Advance Energy-Efficient Automation of Cold Storage Systems for
Optimal Energy Management Using PLC

Project report submitted in partial fulfillment of the requirement for the degree of

BACHELOR OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

By

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DECLARATION

We hereby declare that the work reported in the B.Tech Project Report entitled **"Advance Energy-Efficient Automation of Cold Storage Systems for Optimal Energy Management Using PLC"** submitted at **Jaypee University of Information Technology, Waknaghat, India** is an authentic record of our work carried out under the supervision of **Dr. Pardeep Garg.** We have not submitted this work elsewhere for any other degree or diploma.

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This is to certify that the above statement made by the candidates is correct to the best of my knowledge.

Dr. Pardeep Garg
Date:

Head of the Department/Project Coordinator

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to everyone who has contributed to the successful completion of our project, **"Advance Energy-Efficient Automation of Cold Storage Systems for Optimal Energy Management Using PLC."**

We would like to thank our project supervisor, **Dr. Pardeep Garg** for their invaluable guidance, support, and encouragement throughout the development of this project. Their expertise and insightful feedback were crucial in navigating the various challenges we encountered.

Furthermore, we would like to express our gratitude to **Mr. Dhirendra Kumar** and **Dr. Ajay Thakur** who has generously provided us with the necessary resources, such as laboratory facilities. Their dedication and hard work were instrumental in bringing this project to fruition.

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ABSTRACT

For perishable agricultural products like fruits and vegetables, cold storage is essential to maintaining their quality and shelf life. However, manual labor or continuous chilling cycles are frequently used in India's traditional cold storage systems, which results in high energy consumption and inefficient operations. Due to severe financial and resource constraints, these restrictions are especially harmful to small-scale farmers and rural storage facilities. This study introduces an intelligent, energy-efficient cold storage automation system that combines the industrial-grade dependability of a Programmable Logic Controller (PLC) with the real-time sensing capabilities of an Arduino microcontroller.

Temperature and humidity are tracked by DHT11 sensors, and the concentration of carbon dioxide (CO_2) within the storage chamber is estimated by a MQ135 gas sensor. Sensor data is processed by the Arduino, which then relays control decisions to the PLC for actuation based on predetermined threshold values. When environmental circumstances diverge from ideal ranges, an exhaust fan is activated. Further improving accessibility and user engagement in rural areas is a Bluetooth-enabled mobile application created with MIT App Inventor that allows real-time remote monitoring of environmental data.

In Waknaghat, Solan, Himachal Pradesh, an experimental validation was carried out in a local cold storage environment simulation. Over the course of a 60-minute test, system performance was tracked while a heat source was employed to simulate temperature rise. In comparison to conventional continuous cooling techniques, the fan only ran for 27 of the 60 minutes, according to the results, resulting in a 55% reduction in energy consumption. The system showed constant communication between components, quick reaction to changes in the environment, and dependable sensor-actuator integration.

This hybrid Arduino-PLC method offers a scalable way to update cold storage infrastructure in rural and semi-urban areas by fusing industrial resilience with low-cost flexibility. The system helps to promote more sustainable farming methods by lowering energy use and post-harvest losses. To further improve autonomy and energy efficiency, future research may investigate the integration of solar-powered operation and AI-based predictive control.

CHAPTER 1

INTRODUCTION

A large part of India's population depends on the agricultural sector for their subsistence, and it also makes a substantial contribution to employment, rural development, and national food security. Fruits, vegetables, and other perishable agricultural products are among the most widely produced in India. However, because of insufficient storage and preservation methods, the nation suffers large post-harvest losses despite high output rates. Among numerous stages of the agricultural value chain, the post-harvest handling of perishable goods is extremely critical. These goods are extremely vulnerable to changes in environmental factors like humidity, temperature, and air quality. Even little changes can cause spoiling, which can result in microbial deterioration, nutrient loss, and financial losses for both suppliers and farmers.

These losses are not only financial; they also lessen the supply of high-quality products for consumers and increase food insecurity. The lack of access to contemporary cold storage facilities disproportionately affects small-scale and marginal farmers in rural and semi-urban locations. Traditional solutions are frequently antiquated, ineffective, and not adapted to the unique requirements of the regional agricultural ecology, even in cases when cold storage is available.

In India, traditional cold storage systems typically utilize continuous cooling systems with manual operation. Despite storage conditions in actual life, these systems are energy intensive and less sophisticated. Further, these systems are scarcely automated, and environmental parameters are not dynamically regulated as a function of real-time feedback. The load becomes uneconomical in regions where electricity is intermittent or has high operating costs, particularly for poor farmers. Further, users have no facility to remotely monitor as well as control the storage conditions using traditional systems since traditional systems lack communication interfaces. This lack of response and awareness will result in delayed action and product life shortening.

There must be intelligent, flexible, and energy-efficient cold storage facilities in such a time of need since we have issues such as climate change, rising energy costs and the worldwide move towards sustainable development. Real-time monitoring and intelligent control systems are key elements that can revolutionize cold storage systems and make it more reliable, cost-effective, and accessible. The combination of industrial-grade control systems and inexpensive microcontrollers gives the promise of designing scalable solutions that can be used even in the most resource-limited situations.

As shown in fig-1 our research suggests the development and deployment of a smart cold storage automation system that integrates a robust Programmable Logic Controller (PLC) with an Arduino microcontroller to overcome such challenges. Temperature, humidity and carbon dioxide (CO_2) levels are three critical environmental conditions that the system is programmed to monitor and manage. An MQ135 gas sensor is utilized to measure the quantity of CO_2 in the cold storages and a DHT11 sensor is employed to measure temperature and humidity. The Arduino gets real-time feedback from these sensors analyzes the input based on current threshold values and determines if ventilation is needed.

The PLC serves as a controller that gets the output signal from the Arduino that also performs decision-making logic. In ideal storage conditions, the signal is taken by the PLC that is designed in ladder logic. On demand, it activates an exhaust fan. This reduces energy consumption and increases the lifespan of system components by making sure that the cooling system operates only when needed, as opposed to running continuously. The performance and reliability are enhanced by the proposed work, which isolates the processing and actuation processes. The PLC provides industrial-grade control, safety and the Arduino performs real-time data processing and transmission.

The most significant feature of the system being proposed is that the system is accessible. A Bluetooth-based smartphone application is utilized, which is developed using MIT App Inventor. Not needing internet connectivity, customers can use the mobile interface to view temperature, humidity, and CO_2 information on their mobile phones. This is especially helpful in rural areas where network coverage is poor. The application makes the user able to make decisions. The data is refreshed every two seconds and provides feedback. There are users who may not be technically competent to use and comprehend advanced hardware interfaces are empowered through this wireless capability, which provides an additional level of accessibility.

Testing was conducted at Waknaghat, Solan, Himachal Pradesh under a mock cold storage setup. A lighter was used as a controlled heat source to progressively increase the inner storage temperature in an attempt to mimic the impact of fluctuating conditions. Sensor readings were captured for 60 minutes. Results indicated that the proposed approach selectively activated the fan, running the fan for merely 27 minutes out of 60 minutes; as opposed to traditional cold storage systems that would run the fan continuously. That is a 55% savings in energy consumption, demonstrating the ability of the design to conserve energy.

There were no failures of actuation and no signal delays and the system reacted to temperature and gas concentration variations consistently. The applicability of hybrid microcontroller-PLC structures to real-world cold storage systems is demonstrated by these results. Future upgrades; for instance, interfacing with renewable energy sources such as solar panels, advanced machine learning-based predictive control, or cloud-based data logging for commercial-scale farming operations, are facilitated by the configurability of the setup. The suggested work offers a cost-effective, practical, and scalable solution to update India's cold storage system. The combination of Arduino and PLC offers a harmonized solution with the industrial ruggedness as well as economy. The suggested work fills the gaps required of conventional cold storage technology with its energy efficiency, real-time monitoring, and mobile interface. The technology offers a significant contribution to the development of infrastructure for smart agriculture, especially in rural and semi-urban areas by preventing post-harvest loss as well as utilizing energy efficiently.

As shown in fig-2 the proposed work offers a realistic, affordable, and expandable strategy for updating India's cold storage infrastructure. The Arduino and PLC combo offers a well-rounded solution that takes advantage of both industrial dependability and economy. The proposed work fills important holes in conventional cold storage technology with its energy efficiency, real-time monitorin and mobile interface. This technology makes a significant contribution in the development of smart agricultural infrastructure, especially in rural and semi-urban areas by lowering post-harvest losses and enhancing energy management.

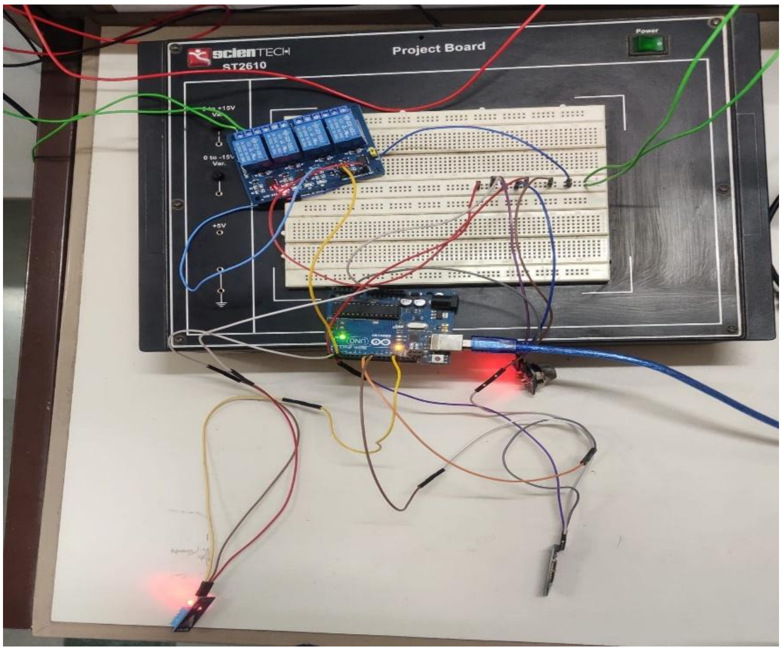

Fig-1 Image of our prototype

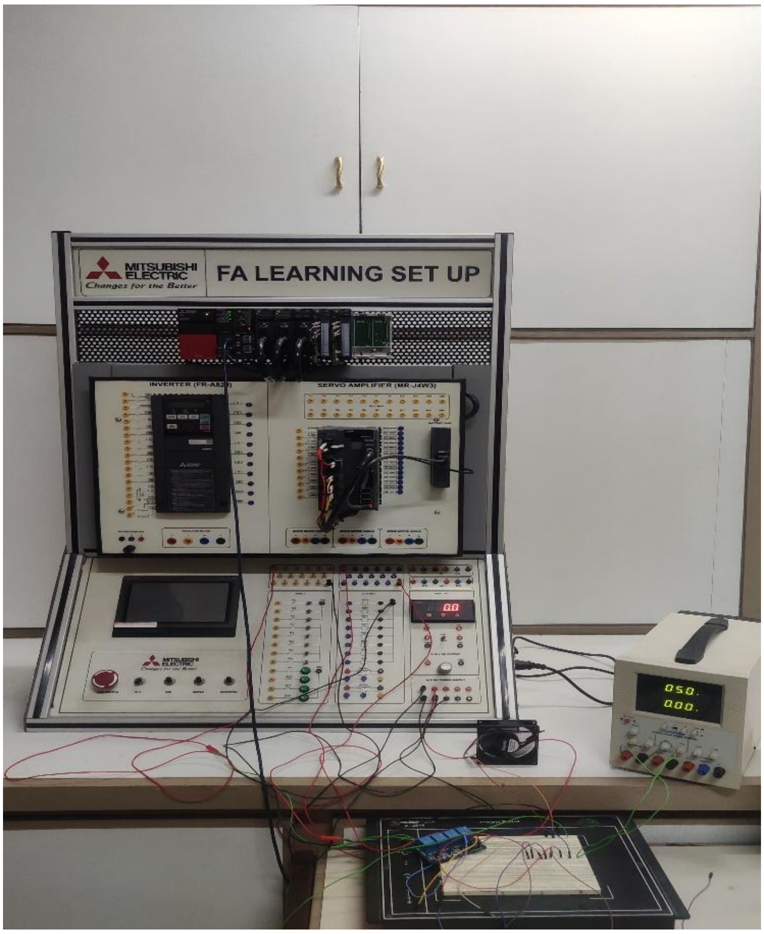

Fig-2 Image of our proposed work

CHAPTER 2

LITREATURE REVIEW

Palaniamy's study [1] illustrated how the versatility of Arduino for sensor integration could improve the reliability of PLCs for control of appliances. In particular, he formulated a home automation system that utilized both PLC and Arduino to illustrate lower costs and better flexibility in the system.

Alhaj [2] emphasized the importance of environmental systems to ensure adequate storage and suggested an Internet of Things based management system for remote management of cold storage applications. The study showed how real time data availability can improve energy efficiency and reduce food waste.

González and Calderón [3] studied the application of open-source platforms with automation systems. Rather than just considering Arduino in isolation, they examined how it can be applied for Smart Grids and Micro-Grids. In a sense, their efforts provide support to using Arduino in energy applications through demonstrating affordable and scalable types of solutions.

Similar to this, Jeong[4] created a Modbus protocol-based communication mechanism between PLC and Arduino that allows for dependable and consistent component interaction in automation systems.

Shaik [5] devised a safety control mechanism for cooling systems in the context of thermal systems, which can be used for cold storage management where perfect environmental regulation is necessary.

Akdemir [6] analyzed the energy consumption of experimental cold storage setups and concluded that intelligent control strategies could significantly reduce operational energy costs.

Zhang [7] created an Internet of Things (IoT)-based jujube fruit preservation system, showing how real-time control and environmental sensing can enhance the quality and shelf life of produce that is stored.

Using wireless modules, Bayindir and Cetinceviz [8] investigated PLC-based water pumping control systems with a focus on dependable actuation in industrial settings—a concept that is just as crucial in cold storage ventilation.

Similar to this, Waluyo [9] shown the potential of industrial automation technologies for energy-efficient climate control by implementing energy-saving control for air conditioners utilizing PLC and SCADA systems.

Kennedy [10] highlighted the suitability of such architectures in rural settings where resource limitations and monitoring accessibility are major concerns by proposing a smart village monitoring system employing PLC and SCADA.

A lab-based Arduino-PLC exercise for students was demonstrated by Orencio and Macalalag [11], who confirmed its efficacy for teaching purposes and real-time sensor-actuator integration.

Khandoker [12] demonstrated how combining the advantages of both platforms improves control accuracy and system flexibility by designing a microcontroller-PLC system for home automation.

Imbrea [13] reinforced the flexibility of PLCs in managing complex systems by talking about PLC integration for grid connectivity of renewable energy sources.

A thorough analysis of energy-efficient cold storage devices for agricultural application was given by Singh [14]. Their research highlighted the pressing need to integrate automation, real-time sensors, and renewable energy sources into the current cold chain architecture. The study found that temperature-based switching, adaptive ventilation management, and hybrid energy systems might reduce a sizable amount of energy use in traditional cold storage facilities.

CHAPTER 3

Foundational Concepts and System Development

3.1 BACKGROUND

Being an agrarian economy, India depends significantly on agriculture for employment, rural development, and national GDP in addition to providing food. Even though the nation is one of the world's top producers of fruits and vegetables, post-harvest management is a major problem, especially for perishable agricultural products. Because of poor storage and transportation, a significant portion of fresh product is lost between harvest and consumption. The absence of suitable and energy-efficient cold storage facilities is largely to blame for the estimated 30–40% post-harvest losses of fruits and vegetables in India, according to studies.

Perishable commodities require cold storage systems to extend their shelf life, preserve their quality, and guarantee their safety. They are essential for stabilizing market supply, cutting down on food waste, and guaranteeing that seasonal product is available all year round. However, typical cold storage facilities have many drawbacks, particularly those that small and marginal farmers in India may use. These include inefficient use of energy, manual labor, a lack of dynamic environmental management, and the inability to monitor remotely. A large chunk of these systems run constantly regardless of the real storage conditions, which causes energy waste and equipment wear.

Upgrading the cold storage facilities with cost-effective and energy-saving technologies is needed in light of the strain on food systems brought about by urbanization, population growth, and climate change. The transformation of conventional to intelligent cold storage facilities illustrates the incorporation of automation, real-time monitoring, and intelligent control systems. With the microcontrollers like Arduino and the widespread use of PLCs in industrial automation, there is a new possibility to create hybrid systems that leverage the strengths of the two platforms.

Role of Cold Storage in Agricultural Sustainability

To enhance the freshness and marketability of perishable commodities such as fruits, vegetables and milk cold storage is a critical intervention. These items are very vulnerable to fluctuations in the ambient humidity and temperature. Besides reducing the spoilage, cold storage enables farmers to store their produce until market prices are favorable. This reduces waste in the agricultural supply chain and enhances economic returns. Also, cold storage infrastructure enhances food supply stability especially during off-seasons.

Challenges in Traditional Cold Storage Systems

The traditional cold storage plants in India function on simple principles with little or no automation. The plants are operated manually or based on predetermined cooling operations that do not adapt to environmental changes in real time. Power consumption becomes avoidable due to this mode of operation. Equipment monitoring systems increases operational costs due to the fact that it leads to both equipment ware and avoidable power consumption. The rise in operations expense occurs alongside increased equipment wear out rate while using energy continues to be inefficient. Running continuous cooling equipment leads to economically unviable high expenses in far-flung rural districts with unstable distribution of power supply.

The development of smart cold storage technology with sensor platforms is an essential solution to address this issue. Integration with automation enables power use systems to work proactively and enhances system life while enhancing quality.

Emerging Trend: Intelligent Cold Storage Systems

Automation with smart control and feedback in real time is increasingly common in contemporary cold storage technology. Sensors, microcontrollers and logic controllers are part of our system. Based on actual data obtained from our results fans and cooling compressors can only be utilized when needed which significantly lowers energy consumption without compromising the quality of the product stored.

Improved decision-making and proactive intervention are further enabled by the ability to remotely to monitor system status, assess environmental data, and record trends. Such advancements facilitate the overall goals of environmental sustainability along with improving operating efficiency.

For smaller-scale businesses, a solution that finds a balance between cost and smart functionality is particularly critical.

Integration of PLCs in Automation Systems

A vital aspect of industrial automation is programmable logic controllers, or PLCs. PLCs are deployed across numerous industries, such as manufacturing, water treatment, and infrastructure automation, and are well known for their reliability, robustness, and real-time operation. PLCs can efficiently control fan actuation, relays, and alarms in cold storage through digital inputs and analog outputs.

In real-world cold storage applications, PLCs can:

- Monitor environmental inputs.
- Activate and deactivate hardware like exhaust fans or alarms.
- Operate autonomously once configured.
- Manage system safety protocols efficiently.

Building a PLC system with all sensors integrated, however, might be expensive, particularly if analog or wireless communication modules are used. PLCs are less suitable for jobs involving mobile communication or direct sensor interface because of their complexity.

Arduino for Sensor Interface

Arduino is a flexible microcontroller platform that is frequently used for rapid prototyping and educational applications, especially the UNO R3 model. It is appropriate for cold storage automation in environments with limited resources due to its low cost and wide support for environmental sensors. The Arduino can compute threshold logic, interact with external systems, and handle real-time data from sensors such the DHT11 (temperature and humidity) and MQ135 (air quality/CO_2).

In the proposed system:

- Arduino reads data from temperature, humidity, and gas sensors.
- It applies logic to detect abnormal conditions.
- Sends control signals to a PLC when thresholds are exceeded.
- Shares real-time data with a mobile application via Bluetooth.

By delegating sensor processing to Arduino, the system offloads non-critical tasks from the PLC, which is then used solely for reliable actuation.

A Hybrid Arduino-PLC Architecture for Efficient Control

This project's system architecture makes use of PLC for hardware-level control and Arduino for logical processing and environmental sensing. This makes it possible to clearly divide up the work: the PLC switches the exhaust fans according to the signals it receives, while the Arduino gathers and analyzes data.

The benefits of this approach include:

- Cost-effectiveness through minimal use of expensive PLC inputs.
- High system reliability via PLC-based actuation.
- Real-time monitoring and feedback using wireless communication.

When a parameter, like temperature or was level, surpasses a predetermined threshold, the Arduino triggers a digital output, which the PLC reads to turn on the fan. The fan is switched off and the signal is reset once the situation has stabilized.

Wireless Monitoring via Bluetooth

Early identification of adverse storage conditions depends on efficient monitoring. This project uses MIT App Inventor to create a basic mobile app interface in place of costly SCADA or HMI solutions. As shown in fig-3 an HC-05 Bluetooth module allows the app to get real-time data from the Arduino.

The app enables users to:

- View live sensor readings (temperature, humidity, CO_2 levels).
- Receive immediate feedback without opening the storage chamber.
- Operate independently of Wi-Fi or mobile networks—ideal for remote regions.

This user-friendly and cost-effective interface ensures accessibility and real-time decision-making for farmers or storage operators, reducing reliance on technical staff and infrastructure.

Fig-3 UI of the app

A scalable and useful way to update cold storage systems in agricultural contexts is with this hybrid Arduino-PLC approach. In order to improve post-harvest management and lower food loss in rural India, it offers the dual benefits of intelligent automation and economic viability.

In the figure-4, the adaptation of a closed-loop controlled system, applicable to smart cold storage, has been illustrated. This captures the way in which sensors, feedback, and programmable logic controllers (PLCs) allow for the creation of near optimal conditions within a cold storage environment. We will next review the functionality of each block, and the ways in which they can meet the requirements for protecting an environment effectively.

Input (Setpoint):

The input will be the desired environmental conditions of the storage, typically through temperature, humidity, or gas concentrations (e.g., CO_2). The cold storage system attempts to maintain the desired reference value for optimal preservation of perishable items. The user is able to specify the setpoint manually, either through PLC.

Error Detector:

The error detector is a comparator that computes the error signal from the input (the desired value) and the feedback signal (the actual condition as determined by the sensors). The discrepancy between the intended value and the cold storage environment's current condition is known as the error signal. The incorrect signal will be +2°C, for instance, if the temperature is set to 10°C but it is actually 12°C. When determining if an adjustment is required, this signal is crucial.

Controller (PLC):

The controller, which in this system is usually a PLC (Programmable Logic Controller), decodes the error signal and chooses the proper course of action. The PLC determines whether to activate or deactivate actuators such as cooling compressors, exhaust fans, or alarms based on programmed logic (either ladder logic or structured text). The actuating signal is produced by the controller, which is the main decision-making entity.

The controller in this smart cold storage application uses sensors and Arduino feedback to function. It lowers human error and increases efficiency by making judgments in real time without human interaction.

Plant (Cold Storage):

The physical system under management, in this example the cold storage unit, is represented by the plant. It consists of hardware that maintains environmental conditions, such as fans, compressors, and relays. The plant reacts appropriately when the controller sends an actuation signal (turn on the fan, for example), bringing the internal environment into line with the setpoint.

Output:

The real environmental condition created by the plant's operation, like the temperature, humidity, or CO_2 level, to the system is termed the output. The output is consistently observed to assess how well the controller has acted to remedy the situation.

Feedback Elements (Sensors):

The feedback system, which determines if an error exists, has some sensors in place, such as the MQ135 (which identifies CO_2 levels) and the DHT11 (which measures temperature and humidity). The error detection unit is receiving real-time data from the sensors (inside the cold storage unit). The cold storage unit can maintain environmental conditions by making effort to continuously monitor the unit, allowing for dynamic correction.

Closed-Loop Functionality:

The advantage of this control model is its closed-loop form, which ensures continuous changes happen via real-time feedback. The feedback mechanism makes the system self-correcting and this is definite because it uses all disturbances in its internal environment (like gas produced by spoilage), and all external changes (i.e. power fluctuations, or background temperature increases), while no feedback control exists in an open-loop system.

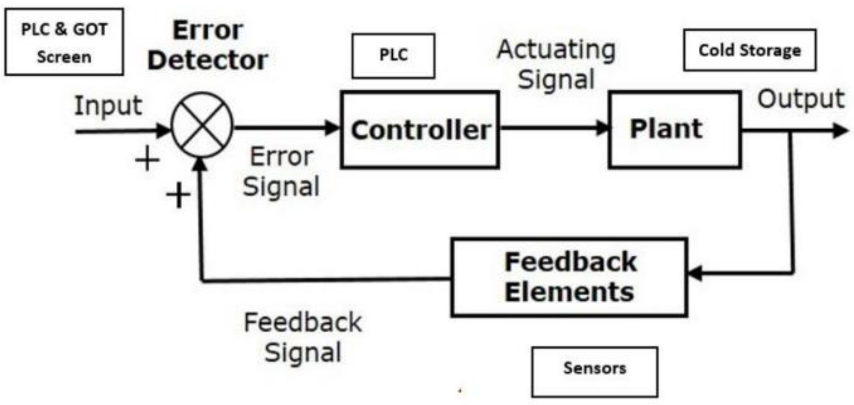

Fig-4 Control loop diagram of our work

3.2 HARDWARE USED

3.2.1 Mitsubishi IQR PLC

As shown in fig-5 Modular high-performance programmable logic controllers, such as the Mitsubishi IQR PLC, are developed for use in industrial automation systems where performance, flexibility, and reliability are critical. The IQR series has been developed by Mitsubishi Electric with extensive integration with a variety of I/O modules and networks, high-speed communication, and advanced CPU processing capabilities. The IQR PLC has deterministic control and real-time response capabilities that ensure devices such as fans and relays can engage promptly based on environmental input. The IQR PLC has been particularly successful in automation systems related to cold storage.

This project will use the Arduino microcontroller to send control signals to the IQR PLC, which activates the fan only when the need arises, using ladder logic programmed in GX Works3. The PLC is suited for challenging environments which require reliable operation due to its industrial-grade reliability which includes 24V digital inputs. Additionally, support for timers and counters improves fidelity for fault management and delays to operate devices only when needed, making it the ideal PLC to be used as part of a responsive automation system that utilizes energy efficiently .

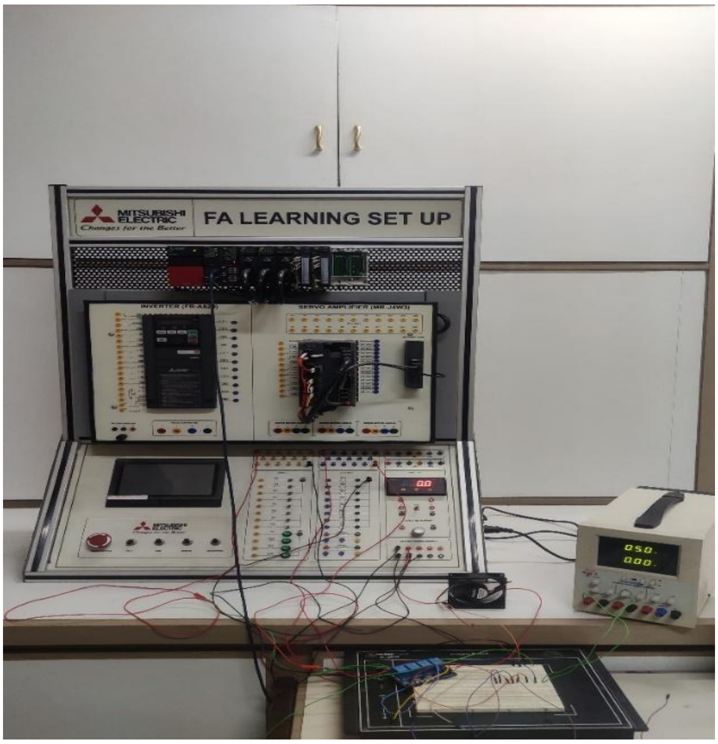

Fig-5 Mitsubishi IQR PLC

3.2.2 Arduino UNO R3

As shown in fig-6 the Arduino UNO R3 is an open-source microcontroller board based on the ATmega328P processor. The Arduino platform is an open and expandable format for a microcontroller board that is commonly desired because of its ease of use, affordability, and flexibility. In academic, scientific, and industrial workspaces, an Arduino is an excellent choice for automating and prototyping a project. With 14 digital input/output pins, 6 analog input pins, a 16 MHz clock, USB connectivity, and 5 volts power supply a wide variety of sensors and modules will work with the Arduino UNO R3.

The Arduino UNO R3 works as a logic controller (acting as a programmable logic controller) and processes the sensor data for the cold storage automation project. The gas and CO_2 data from the MQ135 sensor and the temperature and humidity data from the DHT11 sensor is processed by the Arduino in real time. The Arduino processes the sensor data and sends digital control signals to a PLC based on predetermined thresholds.

It also transmits sensor data to a mobile app via Bluetooth module (HC-05), allowing for remote monitoring. It is ideal for low-energy and rural applications, as it has a low consumption of power and easy programming.

Fig-6 Arduino UNO R3

3.2.3 Relay

As fig- 7 the 4-channel relay module is useful for applications in electronics and automation projects where there is a need to switch high-voltage devices using low-voltage control signals. The four relays on the module act like electrical switches that can be turned on and off by receiving a 5V logic signal from a microcontroller like an Arduino UNO R3.

In this project, the relay module provides voltage level shifting and electrical isolation between the Arduino and Mitsubishi iQ-R PLC by providing an interface of the control side and switching side of the system. The PLC accepts 24V digital inputs, while the Arduino is used with a 5V power supply. The relay module enhances the safety of both the Arduino and PLC as it electrically isolates the two sides of the system.

Each channel can control a variety of devices including fans, alarms and lighting, or whatever can be controlled with relays. The relay module is an ideal module for home automation and commercial applications due to its built in opto-isolators, which removes electrical feedback and enhances safety.

Fig-7 Relay

3.2.4 DHT11 Sensor

As shown in fig-8 the DHT11 sensor has become popular in the home automation and environmental monitoring sector due to its low cost, small size, and compatibility with microcontroller platforms like the Arduino UNO R3. It is suitable for non-critical and hobby based applications since it can measure humidity levels within the range of 20% and 90% reasonably well across a limited temperature range of 0°C to 50°C. The DHT11 has two internal parts; one is an NTC thermistor, which measures the temperature, and the other is a capacitive humidity sensor. From there, the DHT11 has an embedded microcontroller that reads the analog voltages and converts them to digital outputs.

Communication with the host microcontroller is via a single-wire protocol, which is convenient for wiring. The DHT11 is a crucial component of cold storage automation because it monitors the inside environment 24/7.

When it comes time to condition, the Arduino will read the DHT11 sensor every few seconds and use it for determining when to cool or ventilate. Therefore, making sure the proper conditions are maintained for the proper storage of perishable goods.

Fig-8 DHT11 sensor

3.2.5 MQ135 Gas Sensor

As shown in fig-9 the MQ135 is a model of air quality sensor that is often used to detect concentrations of gases such as ammonia (NH3), carbon dioxide (CO_2), smoke, benzene, and many other hazardous gases. The MQ135 relies on a metal oxide semiconductor layer of tin oxide (SnO2) with varying resistance dependent upon the concentration of target gases, which generates an analog voltage out which is dependent on the concentration of gases in ambient air.

The MQ135 requires a supply voltage of 5V and is easy to interface with something like an Arduino UNO R3 (the controller uses an ADC to read the analog value from the MQ135, and the analog value can be converted to parts-per-million (ppm), with a calibration function). The MQ135 has enough precision to measure variance in CO_2 level, or pollution levels, for a low-cost application, but would not provide reliable scientific data without calibration.

The Arduino is able to aid in maintaining air quality and prolonging the shelf life of perishable items in conditioning and agricultural storage, by sending a signal to the PLC to activate the exhaust fan when CO_2 exceeds a specified limit. The MQ135 is excellent for monitoring air quality in real-time within agricultural storage systems due to practical design, low cost, and sensitivity.

Fig-9 MQ135 gas sensor

3.2.6 HC-05 Bluetooth Module

As shown in fig-10 the HC-05 Bluetooth module is a widely used wireless communication component that, (as stated by Duman, 2016). when connected to a microcontroller (like Arduino). facilitates low power, short distance automation and monitoring systems. A robust protocol of Bluetooth 2.0 facilitates communication with devices such as PCs or cellphones, usually up to 10 m in distance.

In this smart cold storage project, the HC-05 module is connected to the Arduino Uno R3 to transmit data collected from the environment using the TX and RX pins as shown in fig-10. The Arduino can send real-time data from the environmental sensors, such as temperature, humidity, and CO_2 levels, to a mobile application that has been designed using MIT App Inventor, to allow customers to monitor storage conditions remotely without internet.

The HC-05 module uses a Universal Asynchronous Receiver / Transmitter (UART) for serial communication, operates at 3.3 volts logic level, and although it is rated for 3.3 volts, the HC-05 module can actually support a rated power of 5 volts. Its relative simple AT command set makes it easy to configure and integrate, even in rural or low-infrastructure scenarios where real-time visibility is important.

Fig-10 HC-05 Bluetooth module

3.2.7 Ventilation Fan

As shown in fig-11 an important aspect of the cold storage automation system is the ventilation fan which controls many indoor environmental conditions such as temperature, humidity, and oxygen concentration as well as providing adequate air circulation. Ventilation fans in traditional cold storage buildings often run continuously without shutting off, resulting in high electrical use. In this case though, the ventilation fan is controlled automatically by the PLC with feedback from the sensor in real-time, obtained through the Arduino.

The ventilation fan operates on 24V DC, which works with the PLC output relays and allows for industrial ratings. The PLC starts the fan when conditions or environmental factors such as temperature exceeds 28 °C or CO_2 exceeds 600 ppm threshold. The fan will then continue to operate only to settle conditions once all factors have remained within threshold limits.

Stopping the fan once conditions have stabilized prolongs efficiency as well as mechanical wear and tear on the fan. Furthermore, this controlled ventilation allows for all factors to settle even if there will be some spoilage occurring, while supporting optimal storage conditions for the goods being stored. The system as a whole benefits from integration and thus is lower maintenance, more reliable, and more energy efficient.

Fig-11 Ventilation fan

3.2.8 Power Supply:

As shown in fig-12 the power supply system is an essential element within the smart cold storage automation system for it provides a consistent and reliable power supply to all electrical and electronic components. The smart cold storage system consists of a variety of electrical components that utilize different voltages to operate effectively because it has both low voltage components (for example: Arduino, sensors and Bluetooth module) and industrial electronics (such as the PLC and exhaust fan).

The operating voltages for the Arduino UNO R3, DHT11, MQ135 and HC-05 Bluetooth module is 5V DC. During testing, this 5V was provided via USB connection or a 5V regulated adaptor. In final installation, a dedicated DC power supply unit or voltage regulator (i.e. 7805) is recommended in order to ensure a reliable voltage free from fluctuations.

In contrast, the ventilation fan and Mitsubishi IQR PLC normally require 24V DC power. These industrial components are powered with a 24V SMPS (Switched Mode Power Supply). The relay module allows for safe signal transmission between the Arduino and PLC. The relay module acts as an interface between the two separate circuits (i.e. 5V and 24V).

A steady and separate power supply is recommended to protect sensitive components against overvoltage or spikes, and to provide a reliable continual operation of the cold storage system.

Fig-12 Power supply

3.2.9 Breadboard

As shown in fig-13 breadboard is a plastic base for prototyping electronic circuits without soldering. It provides a means for testing and experimentation by offering a surface to place electronic components, like resistors, capacitors, transistors, and integrated circuits, to assemble temporary circuits:

A breadboard consists of a grid of holes and internal metal strips that allow for easy connections between components. The metal strips are arranged in rows and columns, the components can be inserted into the metal strips and then connected by jumper wires.

Because they can be reused and are very easy to use, breadboards are very popular with engineers, students, and hobbyists.

They hasten and improve idea testing by removing the need for printed circuit boards (PCBs) in early stages of circuit design. However, because they are unsuitable for high-frequency or high-current applications, breadboards will typically be used in low-power circuit scenarios.

Fig-13 Breadboard

3.3 METHODLOGY

The process used to build and implement a smart cold storage automation system that combines an Arduino microcontroller with a Programmable Logic Controller (PLC) is described in this section. The project's goal is to provide a modular, energy-efficient, and reasonably priced way to monitor and maintain the ideal levels of humidity, temperature, and CO_2 concentration inside a cold storage unit. Small and medium-sized applications in rural and agricultural settings are intended to find the system useful.

3.3.1 System Overview

The hybrid control architecture is used by the suggested model. It combines the sturdy, industrial-grade actuation control provided by the Mitsubishi IQR PLC with the real-time sensing and threshold processing powers of the Arduino UNO microcontroller. The Arduino continuously processes environmental data collected by sensors and relays the results to a PLC and a mobile interface that uses Bluetooth. The PLC controls internal environmental conditions by turning on a fan when it receives the proper trigger signals from the Arduino. Because it is based on modular design concepts, this methodology is minimal maintenance, scalable, and adaptable.

3.3.2 System Architecture

The architecture is composed of three primary subsystems:

• **Sensing Module:** This module collects environmental data using sensors the DHT11 (Temperature and Humidity), along with the MQ135 to detect gas.

• **Processing and Control Module:** The Arduino UNO will receive and process the sensor data using threshold decision logic and then send the control signal to the PLC to process its own logic to actuate and turn on the exhaust fan.

• **Actuation and Interface Module**: Consists of wireless monitoring (Bluetooth (HC-05)), a relay module to connect the Arduino and PLC and fan as the output device.

The entire system is set up as a closed-loop control system, which continuously checks sensor inputs and modifies system behavior to preserve the intended environmental conditions.

A block diagram of this configuration is presented in Fig.-14:

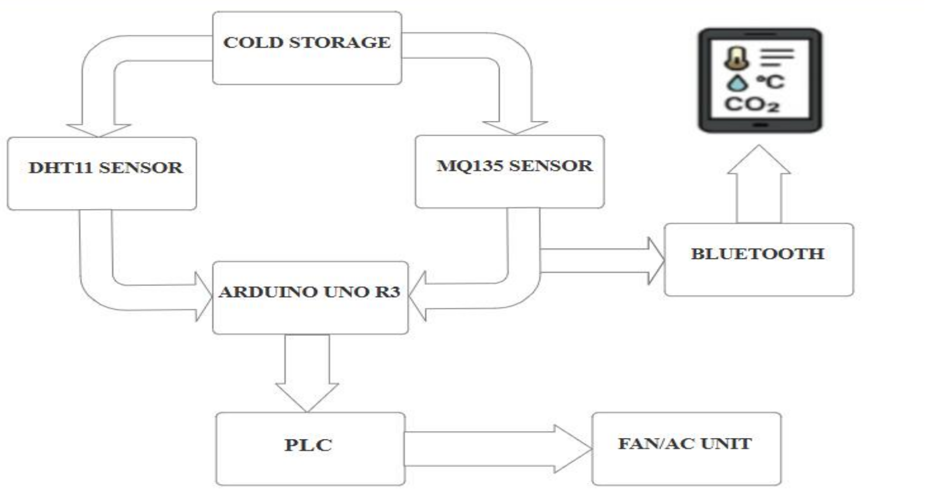

Fig-14 Block diagram of our work

A scheme of a cold storage automation smart system integrating environment sensors, a PLC, a microcontroller in the form of Arduino, and Bluetooth wireless monitoring is shown schematically. A hybrid control mechanism dynamically controls temperature, humidity, and gas content to provide the best storage condition.

The cold storage chamber, where the perishable agricultural goods are stored, is the central part of the system. The MQ135 gas sensor, used for the detection of hazardous gases such as CO_2 and ammonia, and the DHT11 temperature and humidity sensor are the two primary sensors that monitor the environmental conditions in this chamber. The Arduino UNO R3 microcontroller gets real-time readings on a continuous basis from both the sensors.

The Arduino uses preset threshold logic to process this input. The Arduino initiates a control response whenever any parameter surpasses allowable bounds, such as the temperature going above 28°C or the CO_2 levels exceeding 600 ppm. It responds by sending a control signal to the PLC and using the Bluetooth module (HC-05) to relay the sensor readings to a mobile device. Users can remotely monitor the cold storage environment thanks to the mobile interface, which was created with MIT App Inventor and shows the live data.

In order to help return the interior atmosphere to ideal conditions, the PLC reacts to the digital control signal from the Arduino by turning on the fan or air conditioner. This division of labor between PLC (actuation) and Arduino (sensing and logic) guarantees economical sensor integration along with dependable, industrial-grade control.

This system is perfect for rural and semi-urban agricultural applications where energy efficiency, dependability, and affordability are crucial because it essentially offers a closed-loop feedback mechanism with intelligent actuation and real-time monitoring.

3.3.3 Sensor Calibration and Data Acquisition

DHT11 digital sensor was selected for measuring temperature and humidity due to its reliability, affordability, and compatibility with Arduino. It can operate with a good level of precision for small-scale agricultural storage, having an operating range of 0–50 °C for temperature and 20–90% for relative humidity. The digital input pin of the Arduino is employed to interface with the DHT11, and samples are collected every two seconds. This rate was chosen to provide system responsiveness without adding unnecessary processing load. Estimating CO_2 using the MQ135 Sensor: The MQ135 is a versatile analog gas sensor that can detect a range of gases, including CO_2, NH_3, NO_2, and benzene. For simplicity, the Arduino `analogRead()` and `map()` functions are employed to correlate the sensor reading to approximate CO_2 ppm values:

```
float co2_ppm = map(analogRead(A0), 0, 1023, 400, 5000);
```

This approach is sufficient for our prototype's requirements even if it only provides an estimate instead of an exact reading. Later versions can make use of lookup tables or machine learning-based interpolation to include sophisticated calibration for better detection.

3.3.4 Arduino Logic Implementation

The Arduino UNO performs the following logical operations:

I. Collects sensor data every two seconds.
II. Compares the current readings with the predefined thresholds:

- Temperature < 15 °C or > 28 °C.
- Humidity < 20% or > 60%.
- CO_2 > 600 ppm.

III. If any parameter crosses its threshold, the Arduino sets a digital output pin (e.g., D7) HIGH to indicate a breach.
IV. If conditions are within limits, the output pin is set LOW.

Simultaneously, Arduino will send its data, in a formatted way, through serial communication, to the Bluetooth module to be send to the mobile device. The program will also have to time the Arduino to reset it could freeze or hang if not handled properly.

3.3.5 PLC-Based Control and Ladder Logic Implementation

As shown in fig-15 the Arduino sends the HIGH/LOW signal to the Mitsubishi IQR PLC via a digital input (X0). The exhaust fan is powered by the relay output (Y0), which is turned on or off by the PLC. To avoid erroneous triggering from brief spikes in sensor data, a 3-second delay is added.

Ladder Logic Structure:

```
|----[ X0 ]--------------------[  T0 K30 ]---------------------|

(T0 = Timer #0, K30 = 3 seconds)


|----[ T0 ]----------------------------------------------[ Y0 ]--|
```

Fig-15 Ladder logic of our proposed work

Here:

* `X0` is the digital input from Arduino.

* `T0` is a timer with a preset delay of 3 seconds.

* `Y0` is the relay output controlling the exhaust fan.

This logic ensures reliable, deterministic control by the PLC and protects against false positives.

3.3.6 Relay Module as Interface and Safety Layer

The relay module acts as a bridge between the 24V PLC input and the 5V Arduino logic. It provides the following advantages:

1. **Signal Level Matching:** Adjusts the 5V digital output of the Arduino to a PLC-acceptable level.
2. **Electrical Isolation:** Guards against feedback or voltage spikes harming the microprocessor.
3. **Fail-Safe Behavior:** To prevent unintended actuation in the event of an Arduino failure, the relay defaults to an OFF state.

Optocouplers are used in some relay boards to further separate the high-voltage switching side from the low-voltage control side.

3.3.7 Wireless Monitoring and User Interface

To improve usability, a mobile application was developed using MIT App Inventor. The app communicates via the HC-05 Bluetooth module to display real-time sensor values.

Functionality of the App:

- Receives strings of the form `<temperature>;<humidity>;<co2_ppm>`
- Parses and displays the data in graphical and numerical formats
- Uses color codes (e.g., red for threshold violation) for intuitive feedback
- Does not require internet or Wi-Fi, suitable for off-grid deployments

3.3.8 Integrated Workflow and Closed-Loop Operation

The step-by-step operation of the system is as follows:

- Sensors collect data every 2 seconds.
- Arduino processes readings and evaluates conditions.
- If necessary, Arduino activates the relay module.
- The PLC detects the signal and runs its timer logic.
- Upon timer completion, the fan is activated via PLC output.
- Simultaneously, sensor data is transmitted to the user's mobile device.
- As soon as the values return to acceptable ranges, the signal is reset, deactivating the fan.

This control loop is a classic example of a **closed-loop feedback system** that continuously adjusts output based on environmental inputs.

3.3.9 Validation and Experimental Testing

The system was tested under simulated conditions over a 60-minute duration:

I. **Temperature simulation:** A lighter was used to raise internal temperature.
II. **Humidity simulation:** A humidifier was used to elevate humidity levels.
III. **CO_2 simulation:** Incense sticks were used to increase CO_2 levels.

3.3.10 Methodological Advantages

Modularity: System components (sensors, actuators, controllers) are easily replaceable or upgradeable.

I. **Cost-effectiveness:** Arduino handles all sensor logic, reducing PLC resource load and cost.
II. **Energy awareness**: Fan activates only when necessary, saving power.
III. **Accessibility:** User interface via Bluetooth is simple and intuitive, requiring no internet.
IV. **Scalability:** New sensors or actuators can be added with minor code changes.
V. **Rural adaptability**: Designed for minimal infrastructure dependency, ideal for remote locations.

The hybrid Arduino-PLC system outlined in this study provides an effective, scalable, and cost-effective means of automating environmental control in cold storage facilities. Through the fusion of sensor feedback, real-time decision making, and reliable actuation, the system offers optimal storage conditions while reducing energy consumption and operational costs. This system provides an effective means of retrofitting existing cold storage units into intelligent, independent storage facilities those which satisfy today's agricultural needs owing to its modular structure and wireless monitoring feature.

CHAPTER-4

RESULTS AND DISCUSSION

The proposed PLC-Arduino smart cold storage system was experimentally tested in controlled conditions to assess its environmental interactions, adaptabilities and energy efficiencies. The system was set up and tested in Waknaghat, Solan (Himachal Pradesh), where real time monitoring of environmental factors, especially temperature, humidity and concentrations of gases -particularly CO_2 levels -was carried out. To control internal environmental conditions dynamically based on predetermined conditions, the system implements programmable logic, automatic ventilation systems and various types of sensors.

Test Environment and Objectives

Evaluating the effectiveness of the suggested method in controlling internal temperature while reducing power consumption through conditional fan operation was the main goal of the experimental setup. To replicate rising heat circumstances that are comparable to real-world situations, a lighter was utilized.

- Ambient Temperature: 26 °C
- Relative Humidity: 55%
- Duration: 60 minutes
- Monitoring Interval: 5-minute steps
- Sensors: DHT11 (Temperature and Humidity), MQ135 (CO_2 levels)
- Control Devices: Arduino Uno R3, Mitsubishi IQR PLC, 24V DC exhaust fan
- Communication Module: HC-05 Bluetooth module

Comparing the energy efficiency of the suggested adaptive system with a conventional fan arrangement that runs constantly regardless of the real ambient conditions was the aim of the experiment.

Threshold Conditions and System Behavior

The following environmental conditions were programmed into the system to trigger fan activation:

- **Temperature:** ON if >28 °C or <15 °C
- **Humidity:** ON if <20% or >60%
- **CO_2 Concentration:** ON if >600 ppm

Although all three parameters were tracked, the main emphasis of this simulation was on changes brought on by temperature and humidity. However, in order to confirm that the system was prepared for future multi-parameter control, CO_2 levels were simultaneously monitored.

Fan Operation and Energy Analysis

Over the course of the 60-minute test, the fan's ON/OFF status was recorded every five minutes. Whereas the smart system only turned on the fan in response to threshold breaches, the traditional method kept the fan running continuously the entire time.

- **Traditional System ON Time:** 12 intervals × 5 minutes = 60 minutes
- **Proposed System ON Time:** Sum of active durations = 27 minutes
- **Time Saved:** 33 minutes
- **Energy Savings:** (33/60) × 100 = **55%**

As shown in table-1 this outcome shows a significant increase in energy efficiency without compromising the control of internal temperature. This lends credence to the idea that intelligent control logic drastically lowers wasteful power usage.

Table-1 Fan operation and energy analysis

A	B	C	D	E
Time (min)	Temperature (°C)	Time ON (min)	Time OFF (min)	Energy Saved (%)
0	25.5	0	5	100
5	26.8	0	5	100
10	28.3	0.75	4.25	85
15	30.1	2.25	2.75	55
20	32.5	3.5	1.5	30
25	34.8	4.25	0.75	15
30	36.2	4.75	0.25	5
35	35.6	4	1	20
40	33.9	3.25	1.75	35
45	31.2	2.5	2.5	50
50	29.7	1.75	3.25	65
55	27.4	0	5	100
		SUM: 27	SUM: 33	

Graphical Observations

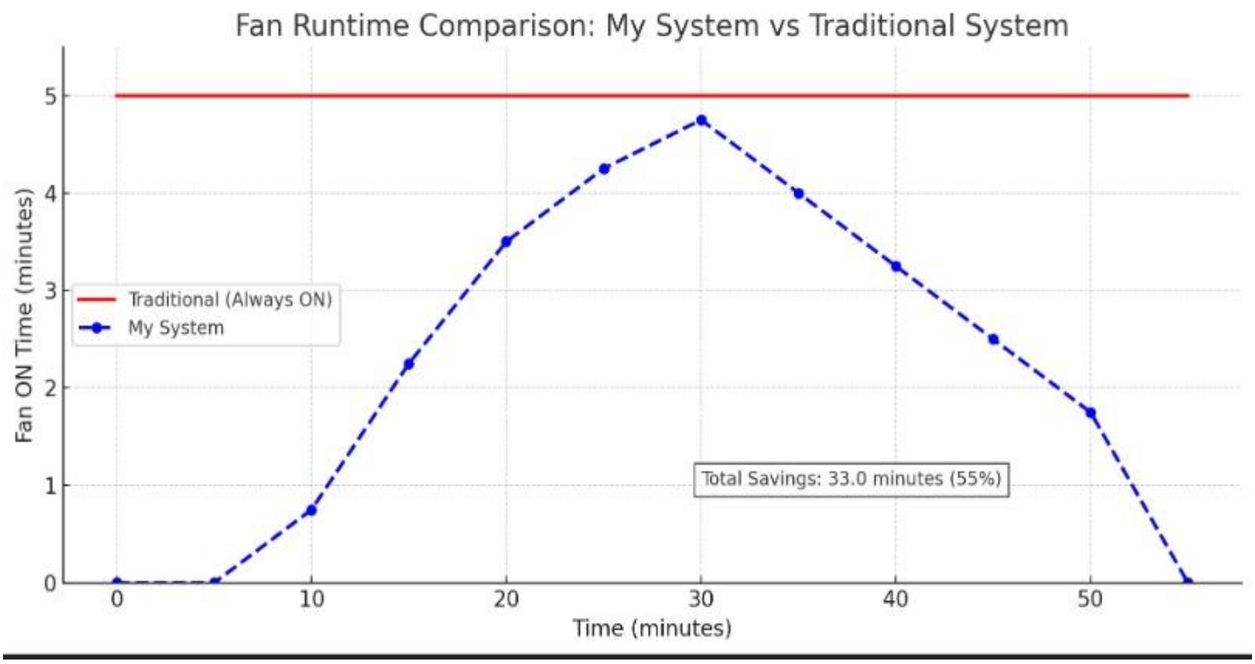

Fig-16 Fan runtime comparison

As shown in fig-16 the operational efficiency achieved by the suggested PLC-Arduino-based cold storage automation system is powerfully illustrated by this graph. In the graph, the stable, uninterrupted red line represents the fan of the traditional system that operates for the entire 60 min test and does not respond or change its operation. In contrast, the smart system exhibited consistent, responsive, intelligent behavior during the rapidly changing 60 min test period.

The flat pattern indicates a fixed approach that included the fan running continuously even if there are variations in the environment and wasting energy, and potentially causing wear on the equipment.

The blue dashed line for the proposed system suggests energy-efficient and intelligent behaviour of the fan operation in that the fan only runs when certain criteria in the environment were exceeded, if ambient temperature rises to above 28°C or other conditions like high humidity or increased CO_2 levels. The fan ran only for 27 of the possible 60 minutes. This was a significant decrease, translating immediately to a 55% savings in energy.

The graph's wavering pattern shows how intelligently adaptive the smart system can be inherently - responding in real time as environmental conditions changed, evidenced by the observation in fan operation. Equipo, both logic and fan operation are adaptive, and intelligent uses of integrated sensor feedback, under a PLC-Arduino design.

The smart system does not merely conserve energy, it also caters for operational efficiency by allowing adjustment of fan operation to actual influence rather than timing. This offers a great opportunity for real-world environments, by aiding in maintaining the best storage, without substantial energy use.

All things considered, the graph not only shows numerical savings but also supports the smart automation system's increase responsiveness and efficiency compared to traditional techniques, signaling a breakthrough in intelligent and sustainable cold storage architecture.

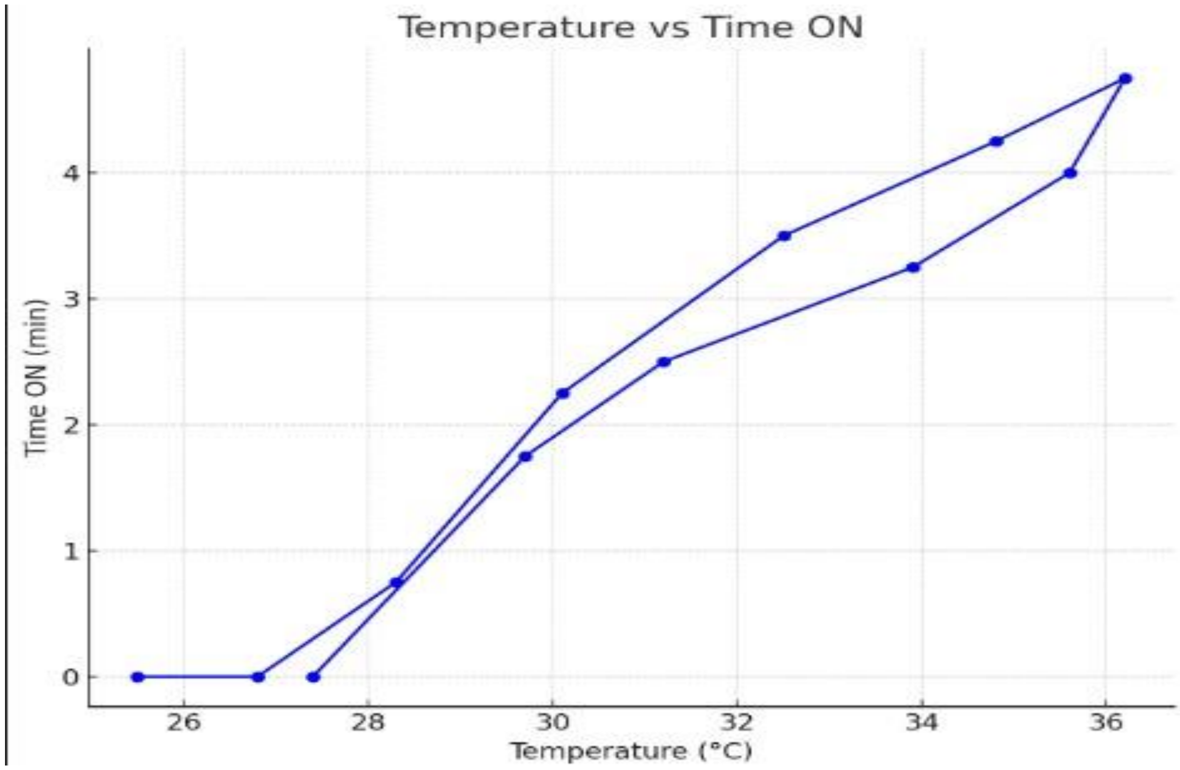

Fig-17 Fan time ON

As shown in fig-17 in the proposed PLC-Arduino-based cold storage automation system, we can see the relationship between increasing the temperature and longer fan ON times. This is shown in a number of ways, mostly seen through the impact that the increase in temperature has on increasing the frequency and length of operation for the fan, after the temperature has crossed the predefined threshold of 28 °C. In contrast, we observe that after all these attempts to activate the fan, with the parameters being steady within the ranges defined as safe, keep the fan dormant. This illustrates the intelligent adaptability of the PLC-Arduino based automation system that we expect to see react in real-time rapidly to changes in the environment.

In this way, with the PLC and Arduino IIoT systems, the PLC and platform can determine based on real-time data from the DHT11 temperature and humidity sensor, if the conditions for the cold warehouse call for ventilation. If the sensor readings reflect that the environment has exceeded the critical threshold temperature, the fan will automatically be activated to let hot air out of the warehouse, and assist in putting the temperature back in range. As long as the temperature readings from the DHT11 remains above the critical threshold, it will allow the fan to turn on more, with the ON time gradually increasing to the maximum time discernible that would have to be used to get a thermal load ventilation process in place.

Next, the intelligent adaptive logic, intended to keep the fan from running when we do not need it to run aimlessly, will ensure that the fan is not running unnecessarily when the temperature readings are steady, even when they do exceed a production level. This means that we are not wasting energy and being poorly managed as we see happening in other control systems.

When thermal stress is at its maximum, the graph indicates that the system responds quickly with longer fan ON durations emulating situations such as open doors, intense ambient heat, or heat from equipment. A brilliant mechanism for efficiently keeping perishables in cold storage with lower energy consumption!

This image speaks to responsiveness as a critical component of sound environmental management. The proposed technology establishes a connection between temperature change and the operation of the fan in order to manage internal conditions; it is able to do that efficiently, by deliberately making an improvement over the conventional static and unresponsive cold storage approach.

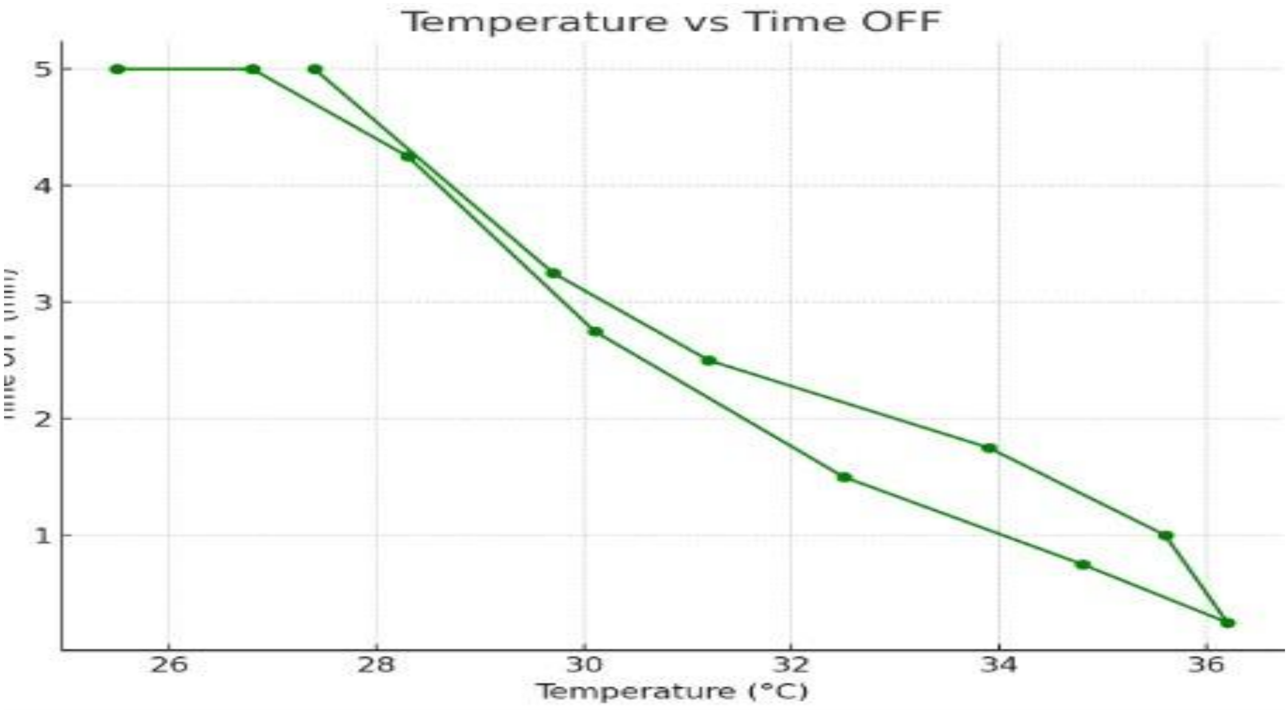

Fig-18 Fan time OFF

As shown in fig-18 in the suggested PLC-Arduino-based cold storage automation system, this graph clearly shows an inverse link between temperature rise and the amount of time the fan is off.

As temperature increases, particularly beyond the top limit of 28 °C, the fan's OFF duration decreased over time. The programmed logic of the system was to promote the operation of the fan under thermal stress conditions to provide an adequate cooling supply and keep temperature levels stable. The opposite trend validates the systems real-time flexibility and ability to react appropriately to changing internal temperatures.

While the fan is stood off to save energy for extended periods of time with the cold storage environment within safe limits, as temperatures exceed safe thresholds (i.e. simulating heat gain by door openings or outside heat influence), the fan's off-time decreased, thus, increasing the duration and intensity of cooling events. This transition is important in order to ensure perishables are kept in storage and temperatures rapidly return back to appropriate levels.

The system's particular logic, which has already been introduced to be able to effectively activate fans based on sensor inputs from the DHT11, ensures a timely action and effortless fan activation along with an empirical approach to using less energy (i.e., only activate cooling when required). More importantly, this intelligent process reduces energy use comparatively to conventional systems, which constantly run the fan and have traditionally used energy when fans are needed due to inside conditions. Thus, in high-temperature situations, short FAN OFF times to maintain the effectiveness and reliability of the system is reasonable.

The proposed solution has the capacity of adaptive controls to sync operation with immediate environmental needs; this capability is suggestive of enhanced performance over traditional means of providing cold storage, as evidenced in this image with an example of the intelligent control operation. The relationship between reduced fan OFF times at high temperatures also shows that the proactive and adaptable control system will likely lead to some overall improvement in energy performance, reduce the equipment life-cycle, and promote environmental conservation in the cold storage context.

Comparative Performance Evaluation

Table-2 Comparative performance evaluation

Metric	Traditional System	Proposed System
Fan Runtime (Total)	60 minutes	27 minutes
Power Consumption	100%	~45%
System Responsiveness	Static	Dynamic
Environmental Adaptability	None	High
Maintenance Complexity	Low	Moderate
Sensor Integration	No	Yes (DHT11, MQ135)

The table-2 shows proposed PLC-Arduino-based cold storage automation system and the conventional cooling system are clearly distinguished from one another in the comparative analysis table based on a number of performance parameters.

The energy efficiency has significantly improved, as evidenced by the fan runtime measure. The fan runs nonstop for the entire sixty minutes in the conventional method. By comparison, the suggested approach reduces operating time by 55% by only running the fan for 27 minutes during the same period. This directly leads to a dramatic reduction in power consumption; whereas the smart system consumes only 45% of the energy, the traditional method uses 100%, resulting in significant energy savings.

The conventional configuration is static in terms of system responsiveness; it does not adjust to changes in the surroundings and continues to run the fan under all circumstances. The suggested system is dynamic and responds to environmental inputs including temperature, humidity, and gas concentration in an intelligent manner. Its great degree of environmental adaptation, which enables it to effectively maintain ideal internal conditions, supports this.

The proposed system has a medium level of complexity because it involves programming and has a number of components that need to be integrated, while the traditional system has a low complexity of maintenance because it is simple. Nonetheless, the additional complexity is justified due to the improved capability and flexibility that the proposed system offers.

Lastly, the old paradigm does not incorporate sensors and therefore cannot monitor the environment in real-time, whereas the proposed system makes use of DHT11 and MQ135 sensors for continuous measurements of temperature, humidity, and air quality (including CO_2 levels) that serves as the basis for intelligent control decisions.

Practical Implications

The deployment of this intelligent cold storage automation system has enormous practical value in regions or remote agricultural hubs of the world with limited and unreliable access to energy supplies. This technology delivers verifiable operational cost savings by reducing fan run time and electricity consumption by large percentages. In remote or off-grid locations, savings on electricity are extremely valuable, as savings in one kilowatt saved per hour results in longer equipment life and lower indirect costs.

Additionally, the system was designed to be connectable to IoT platforms in the future. This means that operators will be able to implement cloud-based monitoring, which would provide automatic alarms for anomalies, real-time environmental data and predictive analytics for service and maintenance. The cold-chain logistics will also become more reliable, with less reliance on manual checks and human error.

The development choice of combining an Arduino (actually an Arduino-compatible board) with a Mitsubishi IQR PLC (an industrial-grade PLC) was a critical design decision. This modular design utilizes the robustness and fail-safe operation of the PLC for critical tasks, and the flexibility of the Arduino for prototyping and feature expansion. Together, they create a programmable, reliable and robust control system.

System Stability and Real-Time Response

The resilience of the smart cold storage system was robust and was consistently assessed under a variety of environmental conditions and performance parameters. One key indicator of system resilience was the complete absence of unintended triggers or unscheduled fan operation. The fan operated only after the environmental parameters were crossed as originally set, especially for temperature as it relates to fan activation, demonstrating the implementation of error-free logic in the developed control program.

This level of resilience was recognized also to have been facilitated significantly through using the Mitsubishi IQR PLC. The PLC had industrial-grade reliability and deterministic operation, the PLC always behaved in a predictable manner and consistently followed sensor input. Predictability and consistency are excellent characteristics to have when responding to rapid temperature (e.g. +4 to +8 degrees Celsius) changes where a faster response is required to avoid any one item in the cold storage unit visual cue of spoilage or being damaged from excess heat in the unit.

The real-time response and monitoring from the integrated Bluetooth connectivity of the HC-05 module enhanced the usability of the system. Users could possess the ability to log and monitor the functioning of the system using their laptops or mobile devices without needing to physically interact with the system. In some applications and environments there were benefits for operators to observe the system's operation from a safe distance or remove themselves from hazardous environments where gas levels or temperature may represent danger.

When everything is working properly, everything from wireless monitoring to responsive control logic to reliable hardware combines to create a very intelligent and stable automation system. In the end, it increases productivity and efficiency in cold storage operations by not only preserving perishable goods, but also minimizing the necessity of watching over things manually.

Limitations and Future Enhancements

The smart cold storage networked system's existing implementation has many benefits; however, there are limitations with this implementation to be acknowledged for future improvements. One of the immediate issues is the choice of DHT11 for temperature and humidity measurement. While low cost, which is a benefit, the moderate accuracy and low sampling rate of the DHT11 could cause the fan not to turn on in cases where there is a critical rise in temperature.

Although Bluetooth communication is easy to set up, the trade-off is that it has a limited range and is susceptible to signal drops especially when considering very noisy industrial environments. More reliable communication modules like Wi-Fi (ESP8266 or ESP32) or GSM (SIM800/900) might be worthwhile additions to improve remote access and remote monitoring. Changing the communication modules will improve the utility of the system in farm locations of remote or far away storage facilities by enhancing access and taking advantage of longs distance control data transmission.

The limitations can lead to subsequent enhancement opportunities (e.g., more accurate DHT22 or BM280 sensors that provide greater accuracy and faster sampling rates) and for any off-grid sites, the added opportunity for solar power could be significant in providing some degree of autonomy, given the remoteness of some sites or risk of disaster recovery.

Ultimately, by utilizing a machine learning model, it may allow the system to become predictive as opposed to reactive. The technology could stop the temperature spikes and improve efficiency by proactively using the fan based on trending environmental behavior. Not only would this improve the functionality of the system, stemming from this work and improvements to the system bring it closer to current trends in Industry 4.0, and smart agriculture.

CHAPTER 5

FUTURE WORK & FUTURE SCOPE

The next generation cold storage automation system that was developed for the project has already made significant advances in energy efficiency, responsiveness, and environmental adaptability when compared to traditional static systems. However, technological development is an ongoing activity. There is still significant opportunity for improvement in the intelligence, connectivity, scalability, sensor efficacy, power consumption and general usability of the system. This section will consider the broader implementation of a similar system in practice and discuss potential future avenues for research.

Sensor Upgradation for Enhanced Precision

DHT11 is used in the current system to measure humidity and temperature. Although it is inexpensive and perfectly fine for a prototype project, the DHT11 has not quite the sensitivity and precision needed in a high-performance environment. Future versions can implement more accurate temperature/humidity solutions like the DHT22 which has a wider measurement range, and faster response times; BME280, or SHT31.

The MQ135 sensor we're currently using for gas sensing is broad spectrum, including CO_2, but doesn't get very specific or accurate. Adding more specific options like NDIR (Non-Dispersive Infrared) CO_2 sensors would provide better detection, and would allow reliable triggers for alarms, or system response.

Expanded Environmental Monitoring

Environmental factors may add to the depth of the study, for example, VOCs, barometer pressure, and light levels. The depth of the study may be furthered by adding of multiple parameters or modules in each. This is very useful when it comes to items stored in cold storage that are delicate in nature verse medications or exotic fruits that require a tightly controlled airspace.

In addition, the same degree of sensors of moisture and UV radiation can be integrated into greenhouse automation or combined facilities for indoor farming and storage.

Integration of Machine Learning Algorithms

The use of machine learning (ML) is one of the most interesting avenues for future research. By training models based on past environmental data, accurate expectations of temperature spike & proactive adjustments to fan operation could be achieved. This type of control method would be proactive instead of reactive. Prediction engines could be built using various machine learning (ML) approaches such as support vector machines, linear regression, and more complex Deep Learning methodologies. Additionally, these prediction engines could develop skills that learn user preferences or seasonal patterns to maximize system performance.

Solar Power Integration for Off-Grid Operation

In some rural or remote areas, the level of power supply can vary greatly. With the addition of solar panels and a charge controller, the system could be self-sustaining. This is especially important for agricultural applications or scenarios with unscheduled grids.

For the purpose of improving food preservation in developing countries, we recommend a solar-powered fan, with the solar-powered control system, for small-scale storage provided by individual farmers or moving cold storage.

Enhanced User Interface and Control Flexibility

Currently, the system engages the user through a serial monitor and simple mobile app. In the future, engaging the user may take the form of a human machine interface (HMI) which could come with touchscreens or vocal activation via a virtual assistant (i.e., Google Assistant or Alexa).

Improved Data Security and Privacy

Data protection is a responsibility you assume when remote control device integration and cloud-based storage occurs; this is particularly important to secure APIs and user authentication and the secure transmission of data using encryption systems like TLS/SSL. Access control and the protection of data integrity is very sensitive when dealing with the storage of sensitive information (ie. vaccinations).

CHAPTER 6

CONCLUSION

This project showcases the power of hybrid control systems to address key issues in cold storage facilities—namely energy inefficiency, manual intervention, lack of real-time monitoring, and limited intelligent response to environmental changes. By integrating a Mitsubishi IQR PLC with an Arduino microcontroller, the system harnesses industrial-grade reliability alongside flexible, cost-effective programmability. Real-time environmental control is achieved using DHT11 and MQ135 sensors to monitor temperature and gas levels, triggering dynamic fan actuation based on sensor feedback. Bluetooth-based monitoring further enables convenient, wireless system performance tracking.

The hybrid system outperforms conventional static cooling setups. Testing revealed a drop in fan runtime from 60 minutes to 27 minutes, resulting in a power consumption reduction from 100% to about 45%, which not only saves energy but also extends component lifespan and reduces maintenance needs. The PLC's logic programming ensures fast and appropriate response to deviations in temperature and gas concentration, preserving the optimal environment for storing perishables like fruits, vegetables, dairy, and pharmaceuticals.

Beyond technical innovation, this project holds socioeconomic promise—especially for rural areas with inconsistent power supply. Its affordability, scalability, and open-source nature make it well-suited for deployment in underserved regions, reducing food waste and supporting local supply chains. Additionally, its modular design invites future enhancements such as cloud-based remote access via GSM/Wi-Fi, machine learning for predictive control, and off-grid operation using solar power. Ultimately, this system sets a foundation for smart cold storage that is not only technically sound but also socially impactful.

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