www.tssa.com.my e-ISSN: 2636-9133

Automatic Load Control and Energy Optimization in Smart Building Using PLC and SCADA

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Available online 01 July 2026

ABSTRACT

The proposed research project seeks to develop an Automatic Load Control and Energy Optimization system of smart buildings based on the principles of SoftPLC technology and Virtual Commissioning. The system is aimed at recreating industrial automation settings to efficiently control energy use without the limitation of physical device. It has a Web-based SCADA Dashboard (WebVisu) that helps to monitor in real time energy metrics, virtual sensor input, and load status, and it can be viewed using any standard web browser. It requires the backend infrastructure to enable the logging of data (high-frequency data) and historical analysis through the integration of a local MySQL database deployed in XAMPP. This paper will deal with the shortcomings of the already existing passive building management systems by proposing a flexible software-based architecture that has the capability to make intelligent decisions. The switch to the hardware-dependent control to a Digital Twin type of simulation is done through the use of CODESYS Control Win V3, the Modbus TCP/IP communication control, and the Node-RED middleware. The initial testing shows that the software layers have indeed been integrated successfully, which proves that the communication backbone is stable and that the data logging pipeline is correct. Future suggestion also involves application of Fuzzy Logic Control (FLC) and Stochastic Occupancy Profiling to increase more on the flexibility of the system. This thorough research does not just confirm the practicability of Virtual Commissioning to build automation, but it also provides a strong ground on the formation of smart, data driven energy management measures.

Keywords: Energy Optimization, Virtual Commissioning, Fuzzy Logic Control, SCADA

1. Introduction

1.1 Problem Background

The growing need to produce global energy has elevated efficiency to be central to the contemporary infrastructure. With residential and commercial buildings being major sources of electricity and carbon emissions, technologies of Smart Building have been brought into the limelight due to their capability of automating loads like lighting and HVAC [1]. According to recent reviews on Building Energy Management System (BEMS), effective energy management has ceased to be an option, but a need in sustainable development [1], [2]. The incorporation of Internet of Things (IoT) architecture has also made it possible to sense and network layer needed to track such large energy flows in real time [3], [4].

The traditional Building Energy Management Systems (BEMS) often use the fixed option of timer-based controls or manual adjustments. Although they are functional to handle simple activities, such systems do not have the flexibility to act according to real- time variations in the environment conditions and occupancy [5]. The majority of the solutions available can only perform passive monitoring or visualization of power quality, and cannot implement active load control [6], [7]. Moreover, the human comfort as a non-linear dynamic is difficult to control with traditional algorithms like PID controllers and is usually highly inefficient in terms of energy usage including the needless and lighting in empty or lit up spaces [8]

In order to eliminate these shortcomings, this project proposes a smart Automatic Load Control System based on Programmable Logic Controllers (PLC) and SCADA [9]. In contrast to the traditional reactive strategies, the paper utilizes a so-called Virtual Commissioning methodology to test complex control strategies in the simulated conditions before implementation [10]. The proposed system incorporates the Stochastic Occupancy Profiling behavioral prediction and Fuzzy Logic Control multiobjective optimization techniques, enabling the system to be not a passive management system but the active, intelligent control, thus compromising energy efficiency with user comfort [3], [11].

1.2 Problem Statement

Despite the availability of building automation technology, current implementations are hindered by several critical limitations. Primarily, the widespread reliance on time-based or manual controls creates a significant efficiency gap. These static methods fail to adapt to dynamic human behavior, leading to unnecessary energy consumption during low-occupancy periods.

Compounding this inefficiency is the lack of predictive intelligence in standard controllers, such as PID loops and thermostats. These systems are inherently reactive responding only after set thresholds are breached, they lack the stochastic capability required to anticipate demand for true optimization.

Furthermore, addressing these issues through physical prototyping is often cost-prohibitive. Developing and testing complex algorithms, such as Fuzzy Logic, on physical hardware carries financial and safety risks, underscoring the urgent need for virtual commissioning methods that allow for validation in a simulated environment before deployment.

1.3 Research Objectives

The specific objectives of this project are:

(1) To develop a Virtual Data Acquisition testbed that stimulates realistic building physics (Thermal Inertia) and stochastic occupancy profiles to generate virtual sensor data (Temperature, Presence, Power) without physical hardware.

(2) To design an Intelligent Control Logic using Fuzzy Logic Controller (FLC) that automates load shedding and dynamically optimizes energy consumption while maintaining user comfort standards

(3) To integrate a Web-Based SCADA System using Modbus TCP/IP for real time monitoring, alarm management, and data logging, enabling remote system accessibility via standard web protocols.

1.4 Scope of Study

The scope of the project is rigidly outlined as follows to assure the viability and dedicated implementation of the project within final year period:

(1) Software-Based Simulation (SoftPLC): The project itself is carried out as a simulation-based project through the use of SoftPLC technology (in this case CODESYS Control Win V3) to model industrial control logic into a typical computers platform. It explicitly does not involve the assembly of physical hardware, electrical wiring or installation of physical sensors.

(2) Virtual Data & Environment Modeling: Building conditions are modeled through Virtual Data Acquisition (instead of the physical inputs) methods. This includes a building physics modeled mathematically to simulate aspects of building physics like thermal inertia and Stochastic Occupancy Profiles to simulate realistic and random human behavior and presence probabilities.

(3) Communication Protocols: The communication infrastructure is strictly restricted to the Modbus TCP/IP protocol to be industrial standard reliable. This protocol is being used to define the data connection between the Virtual PLC, the WebVisu Dashboard and the Database.

(4) The optimization algorithm uses a Fuzzy Logic Controller (FLC) as opposed to traditional PID or On/Off control. The system is aimed at maximizing two conflicting variables where the first variable is the Energy Consumption (kWh) and User Comfort and the second variable will be Priority-Based Load Shedding algorithm; the non-critical loads automatically get disconnected when the load peaks.

(5) Monitoring and Data Recording: The Human-Machine Interface (HMI) is created with the help of WebVisu which enables remote monitoring of the system through the standard web browser. Also, an external SQL Database (XAMPP) manages system validation and historical performance analysis and records real-time data of the PLC to support long-term reporting.

2. Literature Review

2.1 Theoretical Review

2.1.1 Overview of Building Energy Management Systems (BEMS)

Smart buildings can be characterized as buildings that are designed, built, and operated differently as compared to classic homes or buildings, and have the purpose of energy saving and reducing the use of electricity [1], [4]. They rely on Home Energy Management Systems (HEMS) which utilizes sophisticated connectivity and data infrastructure that integrate a variety of equipment and resources [2], [5]. These buildings are a feedback control system, which uses sensors as indicators to gauge the real-time situation and autonomously to intelligent appliances without involving a person [3], [12]. The automation enables the building to become dynamic to the variable conditions and ensure an efficient operation [12], [13]. The evolution of smart buildings is increasingly relying on artificial intelligence and data-driven methods to achieve higher energy efficiency compared to passive management [14].

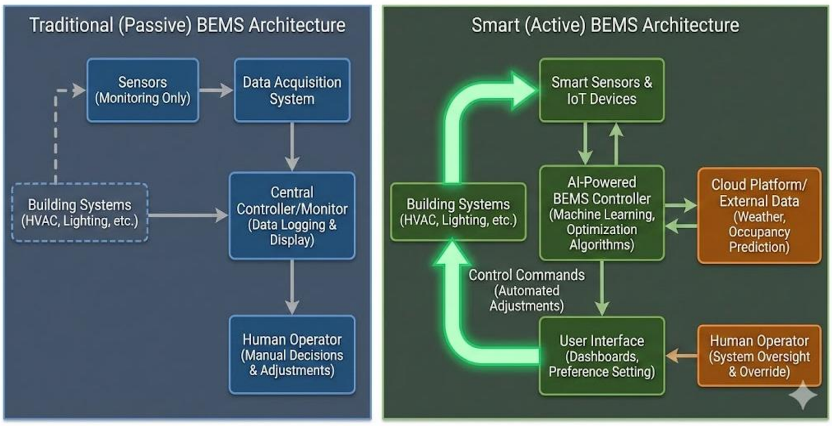

Figure 1. Comparison between Traditional Passive BEMS (Open Loop) and Modern Active Smart BEMS (Closed Loop Feedback).

The structural transition from passive monitoring to active, AI-powered building management is illustrated in Figure 1. The need to reduce the reliance on fossil fuels that harm the environment and increase global warming is what drives energy optimization in these structures [1]. As the energy consumption is likely to rise by over 40 percent over the coming 2 decades, optimization is essential to balance this demand to allow the power grid to remain stable [15]. In addition to environmental and grid reliability, the primary objective to the consumer is to ensure minimum wastage of energy and the cost of utility is minimised [13]. By introducing modern technologies systems and informing the customer about their consumption habits, smart buildings will reduce costs without harming the comfort of the user [4], [6].

The most important approach to this optimization is Demand Side Management (DSM) [5]. DSM strategies are the re-timing or lowering of power consumption in order to alter power consumption profile by the consumer, the key one being to operate appliances when electricity rates are low 13. The idea is based on the ability to differentiate between schedulable devices (like washing machine and electric vehicles) and non-schedulable [12], [15]. Shifting these adjustable loads off peak loads into off-peak loads enables the system to minimize Peak-to-Average Ratio (PAR), which helps save energy by a large margin, in addition to eliminating the load on the power network [13].

2.1.2 Programmable Logic Controller (PLC) Theory

A Programmable Logic Controller (PLC) is an industrial grade computer, which is differentiated by the fact that it is capable of offering hard environment deterministic control unlike any other microcontroller. PLCs are the key in the area of the Building Energy Management System (BEMS), which regulates the utilities of high load (HVAC and lighting) [1], [12]. BEMS will transform into active automation as opposed to passive monitoring; such a sound control architecture is a necessity to optimize energy use, lower carbon emissions [2], [5].

The stability in the operation of a PLC is dictated by its Scan Cycle, which is a continuous loop and involves sensor inputs, control logic, and actuator outputs [10]. The deterministic operational sequence of the controller, consisting of input scanning and logic execution, is depicted in Figure 2.

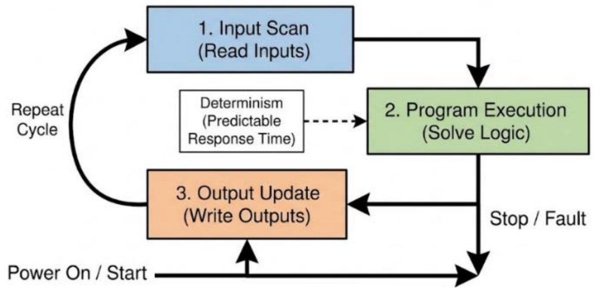

Figure 2. The PLC Scan Cyle

Although this model of implementation is proven, the control algorithms utilized in this model are crucial. PID The conventional Proportional Integral Derivate (PID) controller is not as stable as it needs to be in the face of non-linear dynamics of building environments [8]. Rather, more sophisticated approaches such as Fuzzy Logic are suggested to enable the uncertainties linked with human comfort to be handled better [12], [13].

2.1.3 SCADA Systems Architecture

Supervisory Control and Data Acquisition (SCADA) is a management system based in computers which is commonly applied in industrial plants to measure and monitor the complex processes [12]. Like an intelligent oversight layer, a SCADA system is positioned above equipment at a site to regulate and document physical signalling to execute clever choice-making, based on the real-time data 1. It is mainly meant to receive measurements and equipment status information within local control units and make this information available to a human operator through a centralized dashboard [3]. In this type of architecture, there is a possibility of controlling the whole sites remotely where operators can modify the controls, manage alarms, and make sure that the operations are running well with one central point [12].

The architecture is structured into layers with the Field Level being the first. This layer comprises of physical sensors and actuators, which measure continuously, time-varying measurements of the surroundings, that is, voltage, current, pressure and temperature [3], [7]. I/O connections boxes receive these signals and send them to the Control Level that is commonly controlled by a Central Processing Unit (CPU) or Programmable Logic Controller (PLC) [10]. The PLC is the processing unit that is critical, they receive the signals of the I/O units, store them in their own buffer and execute program logic functions that make field devices directly controlled. The need to have PLCs at this level is usually as a result of flexibility and cost-effectiveness over the need to have special remote units (RTUs).

On the highest level of the structure is the Supervisory Level that consists of the SCADA Server and the Human Machine Interface (HMI). This is due to the SCADA Server that gathers, checks, and automatics data in real-time and takes care of the connection to on-site controllers and the storing of parameters to a central database [3]. The result of this processed data is then visualized as the HMI, which transforms raw data tags into graphical forms of representations like a mimick, schematic and alarm lists [12]. This information is processed by the HMI to give the operator a detailed overview of how the system is performing so that they can make supervisory decisions instantly, like bypassing normal control provisions or being aware of where a problem may exist in order to have more uptime of the system [10], [12].

2.1.4 Fuzzy Logic Control Theory

Fuzzy Logic Control (FLC) is a modern-day approach to computing that simulates human judgment to manage non-linear dynamic systems that are difficult to model in traditional mathematical approaches [8], [12]. As opposed to normal binary logic where exact true or false values (0 or 1) are used, fuzzy logic has added the aspect of partial truth and variables can be ranked using descriptive terms like low, medium or high [13]. This attribute renders FLC especially efficient in its ability to predict and control electricity consumption since human behavior and environmental conditions tend to be random and can be predicted but exhibit non-linear correlation and are hard to model in the shape of strict algebraic equations [8], [13].

A fuzzy logic system has a structure that consists of four operational steps that include fuzzification, rule-based definition, fuzzy inference and defuzzification [12], [13]. Fuzzy sets (membership functions e.g triangular or trapezoidal functions) are used to convert the precise number inputs in the fuzzification phase (time of day, temperature, or current load) into fuzzy sets [12]. The fuzzy rule-based forms the main brain of the systems and applies practical If-Then conditional statements (If outdoor temperatures are low, then electricity consumption is high) to dictate the behaviour of the systems depending on the expertise knowledge [12], [13]. These rules are processed in the logic processor to come up with a fuzzy output, which is ultimately transformed into an accurate digital value in the process of defuzzification, which supply a control signal to the BEMS [8], [12].

Fuzzy logic has been seen to be more favoured than the traditional mathematical models, including Artificial Neural Networks (ANN) or Auto-Regressive Integrated Moving Average (ARIMA) to construct energy management [13], [15]. Whereas mathematical models such as ARIMA need consistent data trends and may be difficult to compute because of errors in calculations, fuzzy logic has got strength and flexibility, wherein complicated information can be transformed into a workable group of guidelines without the need of a precise mathematical model of the structure of the construction [13]. Studies indicate that when fuzzy logic algorithms are applied in energy management systems, a high degree of optimization of the consumption of electricity can be achieved and the studies show that there is a possible peak electricity saving of about 13.5 percent and the reduction in the electricity demand of the system (which has predictive control, as compared to system without predictive control) [13]. The ability to reduce the maximum demand and at the same time retain the comfort of the users justifies the choice of fuzzy logic in the management of the power plan of this project [2] [14].

2.2 Review of Simulation and Virtual Control Architecture

This technological transition in industrial automation from physical hardware to virtualization is examined in this section. It examines the basic ideas of SoftPLC technology as a scalable substitute for conventional microcontrollers. Additionally, it evaluates the simulation environments required to validate control strategies within a "Digital Twin" framework and talks about the methods for mathematically modeling building physics to create "virtual sensors”.

2.2.1 Soft PLC Technology and Virtual Controllers

The Replacement of Hardware with Software-Based Control Microcontrollers such as Arduino or ESP32 are appropriate in the simple home automation, but they do not have the standardization and computational power needed to perform complex industrial calculations [3]. Modern industrial architecture on the other hand is progressively embracing the use of the SoftPLC technology which is a software capable of making a normal Personal Computer (PC) or the Industrial PC (IPC) a fully functioning PLC [10]. Control systems have progressed beyond hardware-based fixed control systems to networked, PC-based control systems in which the CPU is a powerful central server instead of a mere logic gate [3]. This justifies the application of CODESYS Control Win V3 that emulates the industrial CPU design in virtual environment [10].

The operation of a more advanced control strategy, which is Fuzzy Logic, needs a lot of processing capabilities to cope with fuzzification, rule inference, and defuzzification in real time [8], [12]. Strong experimental systems support industrial quality controllers to manage huge observables of consumption data and multifaceted reasoning rules instead of microcontrollers [3]. This project allows the fuzzy inference engine to execute complex floating-point computations required and made possible by the high memory and speed constraints of a programmable processor such as ESP32 without latency by taking advantage of the memory and speed capability of a PC processor running SoftPLC, at least in theory [3], [8].

One of the most important positive aspects of the SoftPLC compared to microcontrollers is that it meets the IEC 61131-3 standard. Although Arduino works with custom C++ libraries, SoftPLC operate on standard languages like the Ladder Diagram (LD) and Structured Text (ST) to allow compatibility of the code and make it deployment-ready across the real-life industries [10]. The automation of the present world is dependent on the open standards to guarantee control logic can be distributed across Wide Area Networks (WAN) and integrated with the SCADA Systems, which is inherent to SoftPLC settings, but necessitates sophisticated middleware on microcontrollers [5], [12].

2.2.2 Mathematical Modeling of Building Physics (Virtual Sensors)

Without physical sensing infrastructure, valid validation of Building Energy Management Systems (BEMS) is dependent on mathematical models to produce real world environmental input [10]. This methodology is called virtual sensing and is used to rigorously test control algorithms in dynamic and stochastic conditions that simulate building physics in the real world [8].

Very conventional simulations Virtual occupancy profiles often make use of unchanging schedules which do not reflect the stochastic nature of human presence and cause major errors in making predictions of energy demand [10]. It is essential to identify a correct occupancy profile to perform thermal and energy simulations since the occupancy will directly affect internal heat gain and the workings of the HVAC and lighting systems [10]. Advanced simulations employ probabilistic models to create the simulated occupancy data of buildings instead of the physical Passive Infrared (PIR) sensors [10]. The conventional schedule of regulations usually does not consider the high uncertainty of human behavior, and hence inaccuracy in estimating peak demand occurs [6], [10]. It is therefore the case that modern studies utilize grounded methods, e.g. Markov Chains or hybrid neural networks (GNN-LSTM), to produce stochastic profiles with correct mapping of arrival and departure patterns [10]. By applying these profiles to the BEMS simulation it is possible to test the system against real and potentially changing load conditions instead of idealised constant inputs [8], [10].

The relationship between occupancy and building physics is mediated by thermal inertia so that the thermodynamic response of a building is not instantaneous [1]. Occupant activities are also important in relation to the internal heat gain which affects building thermal load profile [1], [10]. This relationship is mathematically modelled in a simulation environment in which the virtual room temperature is a (mathematically) dependent variable on the simulated HVAC power and the stochastic occupancy heat gains [1]. This will allow verification of control logic with realistic thermal decay curves so that the system will be responsive to the slow rise and fall of temperature due to human presence, and not just in response to binary on/off signals[1], [5].

Simulated data is a well-known way to test systems in energy research. Occupancy profiles obtained from agent-based models (AnyLogic) to train and validate predictive algorithms, illustrating that simulated datasets can effectively replace physical sensor networks in the development of intelligent control frameworks [10]. This backs up the use of "Simulated Smart Meters" in the SCADA architecture, showing that algorithmic performance can be improved with high-fidelity virtual data before it is used in real life [8].

2.2.3 Simulation Environments for Building Energy Management Systems (BEMS)

Choosing a suitable simulation environment is a decisive factor in BEMS studies because it is necessary to make sure that control measures suggested have both theoretical and practical implementable. Although mathematical modeling tools like MATLAB/Simulink are common in the modeling of complex physical dynamics, the environments often do not directly integrate with industrial hardware [10]. Conversely, a development environment based on the IEC 61131-3 standard, such as CODESYS, provides a so-called SoftPLC, a feature that fills the gap between simulated theory and the real world in the industrial environment [10].

The literature cites MATLAB/Simulink as having the capability to deal with a complicated mathematical model, including the solution of a differential equation (thermal inertia) or the training of Artificial Neural Networks (ANN) [9]. The effectiveness of streamlining energy management systems through meta-heuristic algorithm Particle Swarm Optimization (PSO) [15]. Nonetheless, code written in MATLAB usually needs a lot of transcription or middleware to execute on real controllers (PLCs) in the real world which leads to a lack of a connection between the simulated project and the actual project [10].

This project has picked CODESYS due to the fact that it offers a native industrial control environment, that runs on standard computing hardware using the SoftPLC technology. The contemporary control architectures have changed to PC based systems where the CPU is an all-powerful server, which is what CODESYS Control Win V3 perfectly imitates [3]. Control logic written in CODESYS in either Ladder Diagram (LD) or Structure Text (ST) is also fully compliant with the IEC 61131-3 standard and is deployable to physical PLCs with no alteration at all [10]. This compliance with the IEC 61131-3 standard also allows this fuzzy logic algorithms to not only be an academic exercise but to be designed to fit the high-quality of reliability of the automation industry [10]. Embedded fuzzy-based load scheduling can be successfully integrated directly into such SCADA-connected environments and prove that the CODESYS is a powerful platform to perform both complex logic and real-time visualization [12].

Recent literature highlights that utilizing Digital Twins significantly enhances the efficiency and safety of testing energy systems prior to physical deployment [16] Furthermore, virtual commissioning allows for the rigorous optimization of microgrids and smart building dynamics within a safe, simulated built environment [17]

2.3 Review of Software & Communication Protocols

The fundamental software frameworks and communication standards needed for industrial interoperability are assessed in this section. In particular, it examines the architecture of web-based SCADA for remote visualization, the use of Modbus TCP/IP to guarantee deterministic data exchange between system components, and the IEC 61131-3 programming standards used for control logic development.

2.3.1 IEC 61131-3 Programming Standards (Ladder Logic)

In the field of the development of industrial automation and building control systems, standardized programming language is necessary to ensure maintainability and compatibility with others. IEC 61131-3 standard is the main language of Programmable Logic Controllers (PLCs) Structured Text (ST) and Function Block Diagram (FBD) [10]. In this project, Ladder Logic (LD) was selected as primary language of SoftPLC.

Ladder Logic is graphically based on the electrical relay logic diagrams, so it is the easiest to learn by electrical engineers and facility managers [8]. Whereas in microcontrollers text-based code languages such as C++ or Phyton would be used to express a safety interlock, LD enables the real-time visualization of power flow through a contact and coil to simplify the troubleshooting of safety interlocks and switching sequences [3]. The current SCADA architectures are shifting away on vendor-specific equipment to the the so-called standard software and open rules [8]. As the project employs the CODESYS that adheres to the IEC 611131-3 standard exactly, the control code will not be bound to the hardware but will be moved irrespective of the industrial platform [3], [10].

Although Ladder Logic is perfectly suited to Boolean operations (On/Off control), it can still be used with more complicated math. Application of complex energy management programs to standard PLC equipment (WAGO) with the core switching intelligence doing the physical actuator work with the sophisticated fuzzy logic communicating with the system variables [12]. This mixed methodology of Ladder Logic that controls the real world, and Structured Text that controls the Fuzzy Logic brain is seen as a best practice in the industry. It guarantees that the switching logic which is of safety-critical nature, is visual, verifiable, and is not dependent on the complexity of computational algorithms of the optimization algorithms [10], [12].

2.3.2 Web based SCADA and HMI Visualization

The SCADA system architecture has now changed radically to isolated proprietary systems to the use of PC based systems with standard software-based network protocols and the internet [3]. In the model described as Server-to-Client, the SoftPLC is an embedded web server where a visualization interface can be hosted on it directly [7]. This design eliminates the need of specific HMI hardware or a client-side software installation and instead the Human Machine Interface (HMI) is accessed through any common web browser on a PC or mobile phone [7], [8].

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In addition to direct control, the main aim of HMI is to improve the user interaction by exposing data to transparency. Highlight the importance of the fact that, the Home Energy Management Systems (HEMS) also include feedback systems because the latter will enable consumers to make well-informed decisions about their energy profiles [6], [12]. The web dashboard is a direct feedback loop since it displays real-time information like present power consumption, priority load status, and accrued costs [12]. The combination of real-time SCADA monitoring and fuzzy-based load scheduling can be used to guarantee the instant verification of the automated decisions and hence provide transparency between the user and control algorithms [12]. Advanced SCADA functions are critical for optimizing Energy

Management Center (EMC) operations by centralizing data visualization [18] To bridge the communication gap, studies have successfully demonstrated the use of Node-RED alongside local databases to create low-cost, real-time web-based SCADA systems [19]

2.3.3 Virtualization of Network Protocols: Modbus TCP/IP

Fieldbus protocols are used in the physical Building Energy Management Systems (BEMS), which transmit data between the field devices and controllers. In order to model this infrastructure in simulation, the base is virtualized through using RCP/IP stack on the host workstation, where the Modbus TCP/IP protocol is used as the transport service [4].

It was demonstrated that the Modbus is still the standard of industry of the wired reliable communication of Programmable Logic Controllers (PLCs) and SCADA systems through the open standard architecture because it is simply designed and has a low complexity [4], [5]. Although newer IoT protocols have received greater popularity in supporting cloud connectivity, older protocols such as Modbus TCP/IP have been more popular in supporting local control loops since some deterministic data exchange is required in supporting the stability and response time of the Fuzzy Logic Control [4]. For industrial communication, Modbus TCP has proven highly effective when integrated with predictive control mechanisms for indoor temperature regulation [20]

This project uses Localhost (127.0.0.1) loopback interface instead of physical Ethernet cabling in order to simulate the network medium. The current SCADA systems have evolved legacy serial connections to the "PC-based systems and use standard network protocols where the CPU has to control the distribution of data using Client-Server models [3]. Using CODESYS, the SoftPLC is used as the Modbus Server (Slave), and the Visualization interface is used as the Modbus Client (Master). This architecture is a true representation of the industrial DNP3 or IEC 60870-5-104 architectures and allows verification of system performance in realistic environments with no need to use physical network hardware [3], [5].

2.4 Review of Control for Energy Optimization

The control strategies used for energy optimization in smart buildings are criticized in this section. First, basic Automatic Load Control algorithms used in Demand Side Management (DSM) are examined. It then compares these deterministic methods with sophisticated intelligent control techniques, emphasizing Fuzzy Logic Control's (FLC) greater flexibility in handling non-linear build.

2.4.1 Automatic Load Control Algorithms

The automatic load control is one of the basic functions of Demand Side Management (DSM) that aims at sustaining the energy consumption of buildings within the safe grid levels [2]. Control methodologies are generally classified as Direct Load Control (DLC) which uses remote actuation of appliances by the central authority and Price-Based Control which uses changes in usage by using dynamic tariff incentives [5]. In the case of safety-critical automation architectures, DLC is the design of choice because its assurances, together with real-time and non-real-time reduction in power consumption during peak events, maintain grid stability under all conditions, even in the face of price sensitivity by users [5].

To reduce the effect of disrupting critical services indiscriminately, the industry standard requires a Priority-Based Shedding strategy. In this logic, all building loads need to be grouped into hierarchies depending on their operational criticality [7]. This could be practically applied by dividing loads into "Primary Loads (Critical) and "Secondary Loads (Non-Critical). The most important loads are essential infrastructure like security systems, emergency lightning and server rooms that need to be continuously operating [7]. Secondary loads on the other hand include deferrable equipment such as HVAC equipment or aesthetic lighting that can be temporarily turned off during peak periods without any loss of safety standards [7], [12].

The control logic is achieved through a continuous feedback loop. Based on load scheduling models, the central controller controls Total Instantaneous Power (P_{total}) through real time metering [7]. The algorithm uses a conditional form: in case P_{total} is above preestablished grid threshold (P_{limit}), the controller will start a shedding sequence which will disconnect loads in a systematic order of ranking based on priorities (lowest priority first) [12]. The strategy guarantees the maximum conformity of the demand and the least disruption of the occupants [6], [12]. When applied to this project, this logic is realized with Ladder Diagram (LD) comparators with the help of the SoftPLC, sequentially switching the output coils to secondary load, until the total power usage is restored to a safe hysteresis level [12].

2.4.2 Fuzzy Logic Control (FLC) in Building Automation

Even though priority-based shedding provides useful emergency load curtailment, binary (On/Off) control does not provide the granularity needed to optimize occupant comfort and systems efficiency. Binary controllers are unable to cope with the non- linear behaviour of building physics, including the slow thermal lag of room or the unpredictable variation of human occupancy [8]. Fuzzy Logic Control (FLC) can overcome these restrictions by manipulating imprecise linguistic variables like moderately high temperature or peaking tariff rates to produce continuous, smooth control manipulations, instead of discrete switching [12], [13].

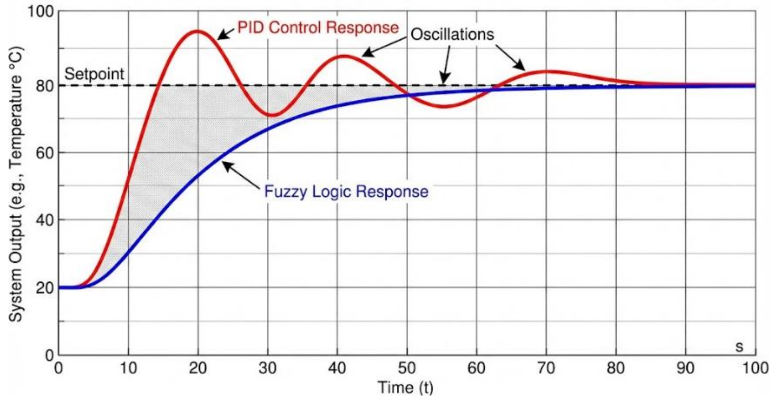


Figure 3. Comparison of System Response: The smooth stability of Fuzzy Logic vs. the oscillation of traditional PID/On-Off control

The superior stability and reduced oscillation of Fuzzy Logic compared to traditional PID control are visualized in Figure 3. The results of numerous simulations conducted have demonstrated the superiority of FLC to conventional controllers in the field of home energy management [13]. The fuzzy logic algorithm was used to forecast and control short-term load consumption (STLC) using historical load consumption and weather data [2]. Unlike the strictly mathematical frameworks that require intricate numerical frameworks, this method with the help of the heuristic rule-based inference engine predicts human behavior in an approximation manner [8], [12]. The outcomes of the simulations revealed that the proposed FLC system would be able to cut down the daily electricity usage by about 13.5% relative to a control scenario where the management is not intelligent [12].

Moreover, the research pointed to the ability of FLC to make a successful operation of the Power profile of the facility when it comes to the execution of proper Peak Smoothing. Comparative simulations indicated that the fuzzy-based management system was able to remove demand excursions which are defined as those cases where the power consumption is above 15 minutes of the safety threshold by reducing the number of cases of excursions in 162 cases to none in diurnal cycle. This proves that FLC especially is well suited to Load Shifting, which automatically transfers consumption to off-peak times to avoid circuit overloads without necessarily having to resort to the severe intervention of total load shedding [12], [13]. The marriage between constant activity and maximum demand decrease is a reason that made it possible to choose Fuzzy Logic as the central control method of the proposed BEMS [5], [12]

Numerous studies advocate for Fuzzy Logic Control (FLC) in Energy Management Systems due to its superior handling of non-linear variables compared to traditional PID controllers [21]. For instance, FLC has been successfully implemented to manage grid-connected residential smart micro-grids and can be developed using standardized interpretable rules such as IEEE Std 1855 [22]. Advanced FLC strategies also allow for weather-adaptive control, dynamically adjusting HVAC setpoints based on external conditions [23], and context-driven building metrics [24]. Finally, integrating stochastic occupant behavior into the fuzzy logic model further refines the optimization, ensuring that energy is only consumed where and when occupants are present [25].

3. Methodology

3.1 Project Workflow

This chapter describes the research process used to create the Automatic Load Control System, which uses industrial simulation rather than actual hardware to validate control logic using a Virtual Commissioning approach. The methodology is split into two main stages: the Control System Architecture, which covers the process and output side and includes the development of the SoftPLC algorithm using Fuzzy Logic, the establishment of Modbus TCP/IP communication, and the integration of a Web-Based SCADA dashboard with a SQL database for real-time monitoring, and the Virtual Environment Framework, which focuses on the input side by mathematically modeling building physics and generating stochastic occupancy profiles to simulate realistic user behavior.

3.2 Framework

Figure 4 presents the execution workflow of project. The paper has started by critically examining the limitations of the conventional PID controllers and the benefits of Fuzzy Logic in non-linear BEMS applications. As a result, the technology of SoftPLC (CODESYS) and Modbus TCP/IP was chosen as the basis architecture to provide compliance with the standards of industry. smart management.

The development stage was concerned with the creation of a Virtual Commissioning Environment. In the framework of physical hardware assembly, this step was aimed at modeling building physics, in particular, Thermal Inertia, and Stochastic Occupancy Profile mathematically to generate realistic sensor data. The current stage also concerned the set-up of the SQL database (XAMPP) and the test of the communication backbone in such a manner that there were no issues in data exchange between the virtual controller and the logging server.

Then, it became devoted to the creation of the Intelligent Control Logic as the brain of the system. Rather than physical mechanical design, in this step, the Fuzzy Logic Controller (FLC) and Priority-Based Load Shedding algorithms were programmed in Structure Text (ST) in the PLC environment. This reasoning is aimed at the dynamical processing of the stochastic inputs and optimisation of the trade-off between the energy consumption and the user comfort.

Lastly, there was the Simulation and Validation of the closed-loop system at the end of the project. The integrated platform including the virtual inputs, SoftPLC and the Web-Based SCADA was thoroughly tested. The benchmarking of the system performance was finally done by comparing the recorded energy data with control baseline using manual control to quantify the efficiency gains.

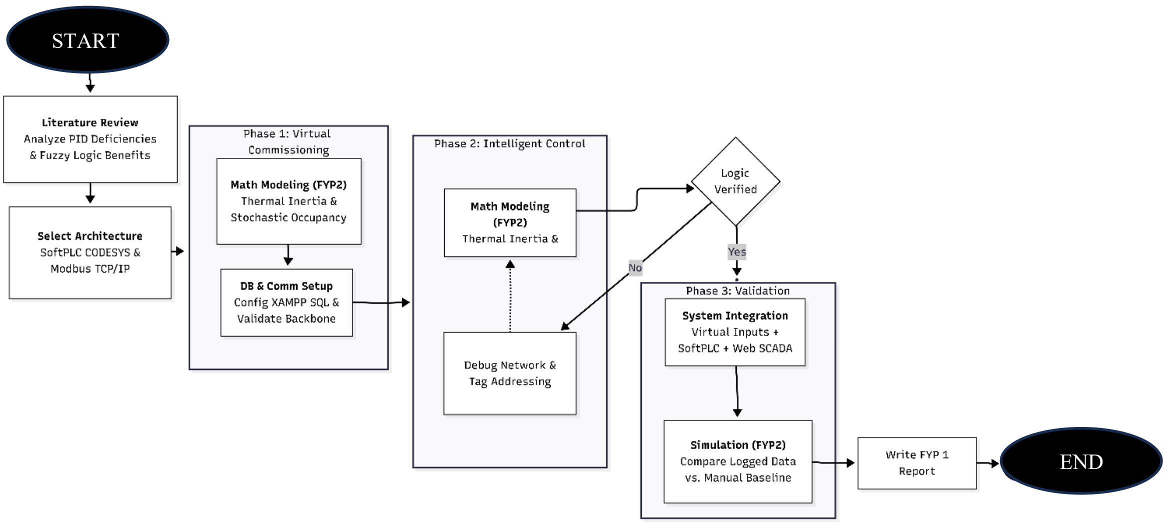


Figure 4. Project Flowchart

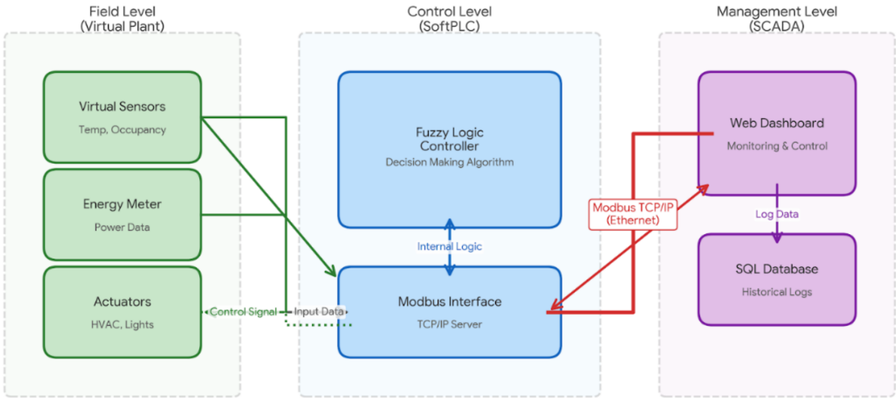


Figure 5. System Architecture Block Diagram

3.3 Proposed Method

The high-level interaction between the field, control, and management layers is detailed in the block diagram in Figure 5. The technical implementation of the suggested system architecture is described in detail in this section. It describes how to set up a data logging infrastructure using MySQL, integrate the middleware layer using Node-RED, and configure the SoftPLC environment using CODESYS. The creation of the Web-Based SCADA interface (WebVisu), which is used for real-time system monitoring and control, is finally covered.

3.3.1 SoftPLC Development Environment (CODESYS)

As per the strategy of Virtual Commissioning, the standard hardware controller gets replaced by a SoftPLC architecture. The CODESYS Control Win V3 was chosen to transform an ordinary workstation into a real time industrial controller. This will help enforce the strict validation of control logic and reduce the risk of electrical failures and the investment cost of physical hardware.

The installation process starts with the installation of the CODESYS Development System (V3.5) and the setup of the so-called Gateway in such a way that the PC can connect with the virtual PLC kernel. In this environment, project is designed as per the IEC 61131-3 standard. Basic switching logic, including manual overrides is written in Ladder Diagram (LD) language, whereas Structured Text (ST) is ready to be used in the future when a more complicated algorithm is needed. This two-language construction guarantees that this system has the strength to perform normal operations to carry out sophisticated mathematical modelling.

3.3.2 Database Setup & Management (XAMPP/MySQL)

A well-developed data logging system is needed to prove the energy-saving performance. Unlike cloud-based solutions that add latency and internet dependences, this project makes use of a localized MYSQL Database that is being hosted through XAMPP. Through this architecture, the speed of the deterministic write operations is very high and can synchronize with the high-cycle times of PLC.

The first step in the implementation is the initiation of the Apache and MySQL modules in the XAMPP Control Panel to establish a local server environment. The PhpMyAdmin is used to create a particular database called energydb, and inside it is created a table that is meant to store Timestamp, Total Power Consumption (kW), as well as the Status of individual zones (e.g. Lobby, Office, Server Room). This organized database is the basis of historical analysis and verification of systems.

3.3.3 Middleware Integration (Node-RED)

This design of the data pipeline is such that real-time power metrics are extracted by having the Node-RED cycle poll particular Modbus TCP/IP registers on the CODESYS SoftPLC. The values are sequentially encoded into the form of JSON objects and systematically inserted as SQL INSERT statements into the MYSQL database. This automated workflow does not involve processing of data manually, so the pipeline will be smoothly automatic and error free in the long-term storage.

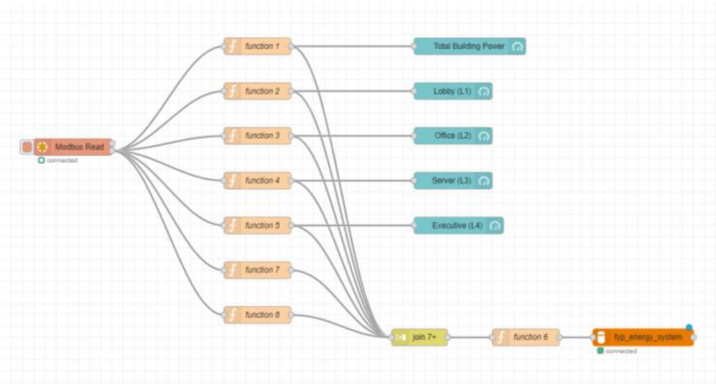


Figure 6. Node-RED Data Flow

3.3.4 SCADA Dashboard Development (WebVisu)

The automated data pipeline and JSON object transformation within the Node-RED middleware are shown in **Figure 6**. CODESYS WebVisu brings about the Human-Machine Interface (HMI) which is based on HTML5 standards that are used to deliver a SCADA dashboard based on the web. This platform-neutral solution makes it support responsiveness by default, meaning that the interface can be opened in any conventional browser on the network without needing to install specific mobile applications.

The interface will allow real-time visualization of the "Digital Twin". It features graphical slides to model Virtual Inputs, including setting the outside temperature or manually turning on occupancy sensors, and gauges to model Virtual outputs, including Power Consumption and Carbon Footprint. Another ability of the data dashboard is that it has an Energy Mix pie chart that the facility managers can use to indicate areas where the facility consumes a lot of energy immediately. Through WebVisu, the control and monitoring interfaces are made under one software environment.

3.3.5 Network Configuration & Tag Mapping (Virtual Wiring)

Since there is no physical electrical circuitry, system connectivity is determined by logical addressing, known as Modbus Tag Mapping, This stage determines the memory map to be used correctly to pass the data between the PLC, Middleware and SCADA layers.

"Virtual Wiring is implemented through settings of IEC 61131-3 variable addresses to particular Modbus registers. Coils (e.g., &QX0.0) are used to control the state of Boolean variables (e.g. Lobby_Light_Status) and analog variables (e.g. Power_Meter_Value) are mapped to 16-bit Holding Register (e.g. %QW0). It has a standardized Tag Database to avoid memory collisions and to ensure that both the WebVisu and Node-RED are using the appropriate memory segments.

Variable	Mapping	Channel	Address	Type	Unit	Description
		Holding Registers	%IW0	ARRAY [0..9] OF WORD		
		Input Registers	%QW0	ARRAY [0..11] OF WORD		
		Input Registers[0]	%QW0	WORD		
Application.PLC_PRG.awModbusData[1]		Input Registers[1]	~~%QW1~~	WORD		
Application.PLC_PRG.awModbusData[2]		Input Registers[2]	~~%QW2~~	WORD		
Application.PLC_PRG.awModbusData[3]		Input Registers[3]	~~%QW3~~	WORD		
Application.PLC_PRG.awModbusData[4]		Input Registers[4]	~~%QW4~~	WORD		
Application.PLC_PRG.awModbusData[5]		Input Registers[5]	~~%QW5~~	WORD		
Application.PLC_PRG.awModbusData[6]		Input Registers[6]	~~%QW6~~	WORD		
Application.PLC_PRG.awModbusData[7]		Input Registers[7]	~~%QW7~~	WORD		
Application.PLC_PRG.awModbusData[8]		Input Registers[8]	~~%QW8~~	WORD		
Application.PLC_PRG.awModbusData[9]		Input Registers[9]	~~%QW9~~	WORD		
Application.PLC_PRG.awModbusData[10]		Input Registers[10]	~~%QW10~~	WORD		
Application.PLC_PRG.awModbusData[11]		Input Registers[11]	~~%QW11~~	WORD		

Figure 7. Modbus Memory Map / Tag Database

3.3.6 System Integration & Manual Testing Configuration

The end of the first development stages is a combination of the three fundamental subsystems, which are the SoftPLC, SQL Database and the SCADA. In order to prove the Digital Twin framework before the deployment of intelligent algorithms, Manual Control Mode is set to overcome automatic logic. The logical addressing and memory allocation required for seamless data exchange are defined in the Modbus Memory Map in Figure 7.

In this validation mode, the slides of simulation dashboard are directly connected to the PLC input variables. This configuration confirms connectivity, or in case the web-based inputs immediately revise the internal state of the PLC. In addition, it also checks the data path validation that ensures that manually generated events are properly time-stamped and documented on the SQL database. This builds a validated foundation, which ensures that the system is prepared to be presented with a sophisticated optimization logic.

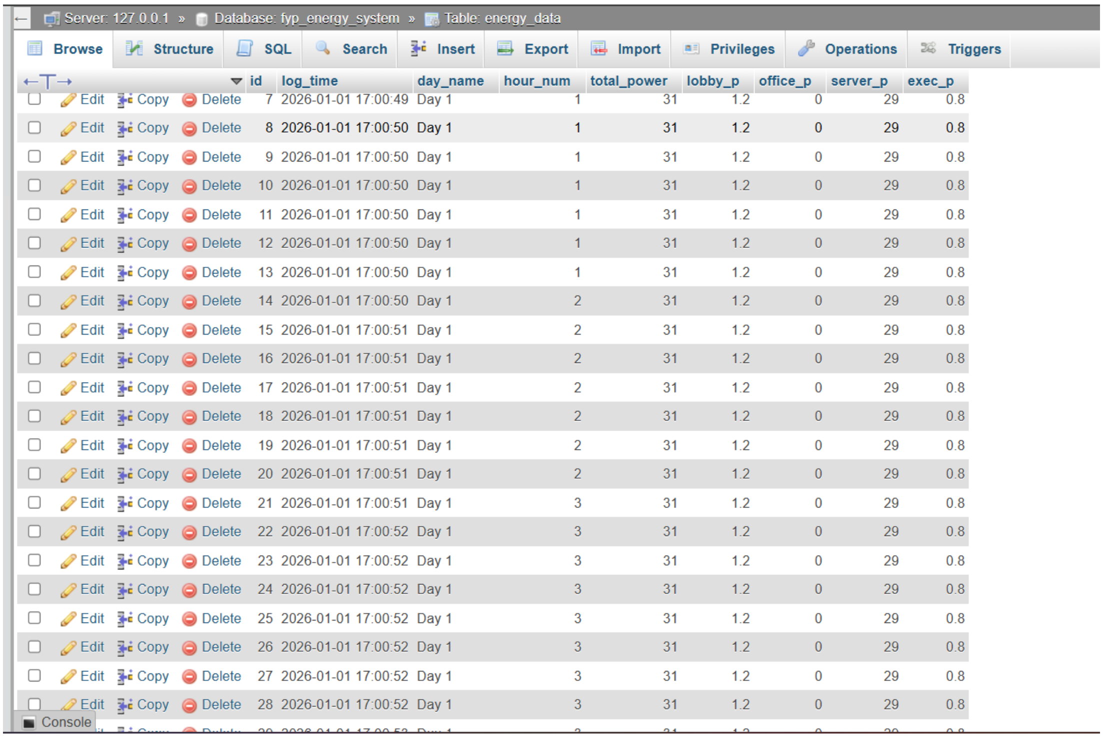
4. Results and Discussion

This part will explain the technical validation of the software architecture that has been designed to the Automatic Load Control System. It shows the working outputs of the three subsystems; the data logging system using MySQL, the industrial communication basis implemented using the Modbus TCP/IP and the real-time monitoring features of the Web-Based SCADA Dashboard.

4.1 Database Integration & Data Logging

The database that was utilized in this Smart Building Energy System is the MySQL database localized through XAMPP. This local solution is also deterministic and high-speed data logging needed by industrial analysis unlike cloud-based solutions which depend on internet latency.

Figure 8 demonstrates the effective data logging within the MySQL database. Configured for real-time performance, the system captures data points every second, recording essential metrics such as the log_time (Timestamp), total_power (kW), and zone-specific metrics (lobby_p, office_p, and server_p) to support historical analysis.



id	log_time	day_name	hour_num	total_power	lobby_p	office_p	server_p	exec_p
7	2026-01-01 17:00:49	Day 1	1	31	1.2	0	29	0.8
8	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
9	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
10	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
11	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
12	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
13	2026-01-01 17:00:50	Day 1	1	31	1.2	0	29	0.8
14	2026-01-01 17:00:50	Day 1	2	31	1.2	0	29	0.8
15	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
16	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
17	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
18	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
19	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
20	2026-01-01 17:00:51	Day 1	2	31	1.2	0	29	0.8
21	2026-01-01 17:00:51	Day 1	3	31	1.2	0	29	0.8
22	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
23	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
24	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
25	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
26	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
27	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8
28	2026-01-01 17:00:52	Day 1	3	31	1.2	0	29	0.8

Figure 8. SQL Database Logging Verification (XAMPP)

4.2 Modbus TCP/IP Connectivity & Tag Mapping

The outcome of the successful building of the Modbus TCP/IP communication loop is evidenced in Figure 9. This is the main nervous system of the project as it connects the CODESYS SoftPlc (Control Layer) to the WebVisu (Supervisory Layer).

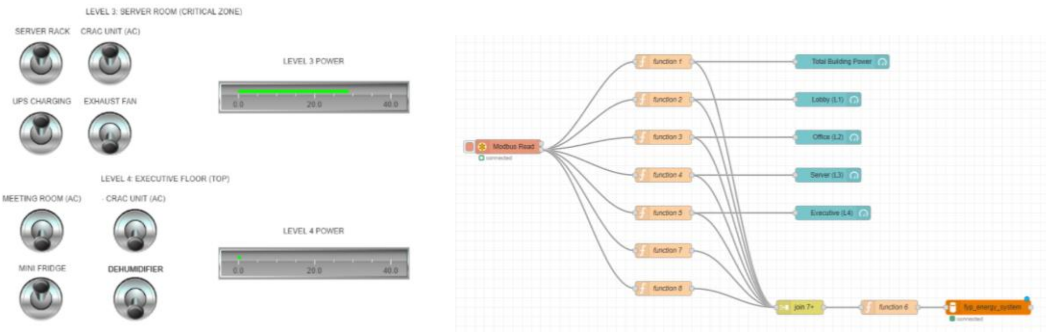


Figure 9. Modbus TCP/IP Connectivity & Tag Mapping

The Figure 9 represents the proof of connectivity. The successful transmission of data packets is observed on the left on the Node-RED/Logic flow. When the dashboard has a toggle switch on, the appropriate signal is relayed to the PLC logic immediately and the feedback loop is used to update the status indicators in real-time. This finding proves the IEC 61131-3 addressing is properly set up, and there is no latency or addressing issues between the software layers.

4.3 Web-Based SCADA Dashboard (WebVisu)

The Web-Based SCADA Dashboard is shown in Figure 10. The interface is the Digital Twin of the building, and with it, facility managers can keep track of energy through any typical web browser.

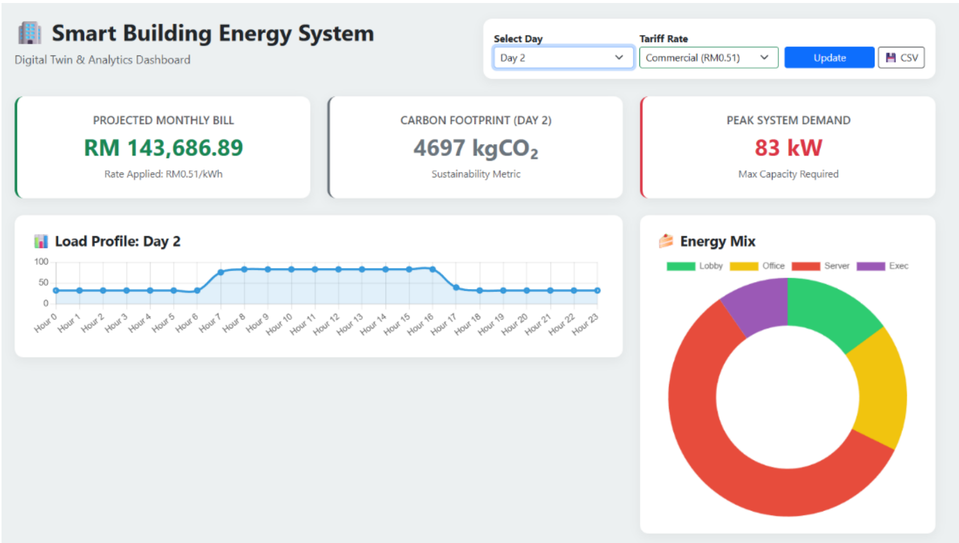


Figure 10. WebVisu Main Dashboard

The SCADA dashboard is designed to be both structurally separated into three critical monitoring areas to provide the overall system monitoring. The upper panel will focus on Key Performance Indicator (KPIs) and will be used to calculate the Projected Monthly Bill and Carbon Footprint using real-time consumption data. This will give the user a real time, practical response on the financial and environmental impact of the current operations.

Below this, there is a central Load Profile Graph where power usage is plotted during a 24-hour working period. This visualization is good in capturing the diurnal patterns that differentiate between unique peak and off-peak states. Filling the layout, the Energy Mix Analysis pie chart disaggregates total consumption by specific zones. This visual hierarchy, as seen in the results of the simulation, draws attention to high-demand zones- like Server Room and Lobby allowing operators to quickly locate targets to optimize or load shedding by priority.

5. Conclusions

5.1 Research Outcomes

The study performed during this stage highlights the revolutionary possibilities of implementing the Virtual Commissioning and SoftPLC technology in the Building Energy Management Systems (BEMS) of the present time. This project has provided a solid framework of the further development of intelligent energy optimization by providing solutions to the key issues that concern system interoperability, data logging latency, and logic validation control. The results demonstrate the viability and advantages of using a so-called Digital Twin strategy to test and prove complex industrial structures with no high-financial risk of using real hardware. To continue, the effective integration of Information Technology (Database/Web) and Operational Technology (PLC/Modbus) that was tested in this paper is key to the realization of the potential of autonomous, data driven smart building.

5.2 Future Works

To make improvements in the development of the Automatic Load Control System in the future, some of the critical developments can be made to make the system smarter, more realistic, and more scaleable to an industrial level. To begin with, there is the direct evolution of the manual control to Intelligent Fuzzy Logic Control (FLC). The system will be in a position to independently strike a balance between conflicting goals i.e. the reduction of energy expenses and employee comfort by applying non-linear reasoning algorithms. This method does not only help remove the possibility of human error in the manual switch but also makes the response process to environmental conditions, e.g. changing temperatures or different electricity tariffs, more dynamic.

To increase the realism and credibility of the simulation, it is necessary to incorporate Stochastic Occupancy Profiling. Presently, the system uses manual feeds to emulate presence, but this task should be done in future with the inclusion of probabilistic models supported by the Random Number Generators (RNG) in the PLC logic itself. This involves the creation of dynamic patterns of user behavior, e.g., people coming into and out of zones at random, with certain probabilities, depending on the time of day. This will stiffly challenge the capability of the controller to address unpredictability making the system sturdy even in the chaotic real-world situations.

Another important consideration to the industrial application is scalability and deployment. Although the current system is running on a PC-based SoftPLC, the next generation should be working on the porting of the logic to physical Edge Controllers, like a Raspberry Pi running the CODESYS Runtime or a specialized Industrial PC. It would be possible to scale the architecture to accommodate a number of Modbus nodes and integrate it with cloud-based solutions (such as AWS or Azure) in addition to the local XAMPP database to have all buildings centrally managed. This feature would greatly improve the commercial feasibility and accessibility of the system by facility managers tracking distributed assets.

Finally, it is essential to adopt the use of technology that is based on data in order to be on the frontline in the smart management of energy. The control strategy could be further optimized with the help of integrating the Machine Learning (ML) algorithms that will study the historical data that will be accumulated in the SQL database. Indicatively, a predictive model might be used to predict high demand hours in advance before they happen so that the system would proactively cool rooms or offload loads. Furthermore, the power signature data may be used to investigate Predictive Maintenance algorithms that will help predict the possible sequence of the equipment failures in order to increase the resilience and durability of the overall electrical infrastructure of the building.

Acknowledgment

This work was supported by the Fundamental Research Grant Scheme (FRGS), Ministry of Higher Education, Malaysia under project No. R.J130000.7851.5F586. The authors would also like to acknowledge Fakulti Kejuruteraan Elektrik, UTM and Fakulti Teknologi dan Kejuruteraan Elektrik (FTKE), UTeM for their support throughout this research.

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