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AI-Enabled Intelligent Energy Optimisation for Smart Commercial Infrastructure Using IoT and Digital Twin Technologies

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Abstract: ***Intelligent, sustainable management systems are needed to address rapid urbanisation and rising energy consumption in commercial facilities. Traditional Building Management Systems (BMS) are reactive, non-predictive, and non-automated, and they lack AI support for decision-making. This paper introduces EcoMind, an Internet of Things (IoT)-based intelligent energy optimisation framework for smart commercial infrastructures, supported by artificial intelligence. It is implemented in a cloud-native system that incorporates IoT telemetry simulation, predictive analytics, Digital Twin monitoring, sustainability assessment, and a telemetry-based conversational AI module. Anomaly detection, predictive maintenance, occupancy-aware intelligence, and rule-based optimisation mechanisms provide real-time analysis of HVAC, lighting, elevator, escalator, parking, and environmental sensor data. The definitions used for this study are as follows: occupancy utilisation: ratio of actual occupancy over maximum occupancy; total energy consumption: total energy consumed by HVAC, lighting, elevator, escalator and parking systems; anomaly deviation: difference between the current sensor reading and the historical normal behaviour; optimisation efficiency: ratio of reduction in energy consumption after applying optimisation strategies to the total energy consumption. The major innovation is using the Gemini API's large language model to integrate live infrastructure telemetry data into a pipeline, enabling real-time reasoning without relying on static datasets. Experimental results show a decrease in total energy consumption of 18–22%, improved response to anomaly detection and improved operational decision-making. The results confirm that Digital Twin intelligence and Telemetry AI is a powerful complement that enhances scalability, adaptability, and sustainability in smart commercial infrastructure systems.***

Keywords: Smart Infrastructure; Grounded AI; Digital Twin; IoT Analytics; Energy Optimization

Nomenclature:
BMS: Building Management Systems
AI: Artificial Intelligence
IoT: Internet of Things

I. INTRODUCTION

With rapid urbanisation and commercial construction, operating and managing modern shopping malls and commercial buildings has become more complex as energy consumption rises. Infrastructure systems depend on the interconnection of HVAC, lighting, elevators, escalators, parking, and environmental monitoring systems. Managing these systems requires minimising energy waste, reducing operational costs, improving occupant comfort, and complying with sustainability requirements. [1][2]. [9] [10].

Traditional Building Management Systems (BMS) primarily monitor infrastructure conditions through static dashboards and threshold-based alarms. While these systems offer operational visibility, they are reactive and still require significant manual effort for maintenance planning and decision-making [2]. This makes it difficult for facility managers to anticipate anomalies, foresee equipment failure, and dynamically optimise energy use.

With recent progress in Artificial Intelligence (AI), the Internet of Things (IoT), cloud computing, edge intelligence, and Digital Twin technologies, intelligent infrastructure management systems can monitor, analyse, predict, and optimise in real time. [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

Most current solutions, however, rely on fragmented architectures and static datasets, limiting contextual awareness and coordinated optimisation.

To address these challenges, this paper introduces EcoMind, an AI-powered system that uses an Internet of Things (IoT) approach to optimise energy use in smart commercial infrastructure intelligently. The platform uses a cloud-native architecture and enables users to simulate real-time IoT telemetry, make predictive forecasts, detect anomalies, support predictive maintenance, monitor the Digital Twin, assess sustainability, and use a conversational AI assistant based on telemetry data.

A key feature of this study is its ability to integrate live

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infrastructure telemetry with a Gemini-powered conversational AI pipeline. Unlike traditional AI systems that use fixed prompts, EcoMind integrates real-time operational information into the reasoning process, providing context-aware diagnostics, intelligent suggestions, and operational decision support. Experimental testing shows an 18- 22% reduction in energy use, increased infrastructure visibility, and improved predictive maintenance and operational awareness.

The main goal of this research is to design, develop, and assess an intelligent platform for smart infrastructure management that can monitor, perform predictive analysis, automate energy optimisation, and support decision-making through telemetry for sustainable management of commercial infrastructure.

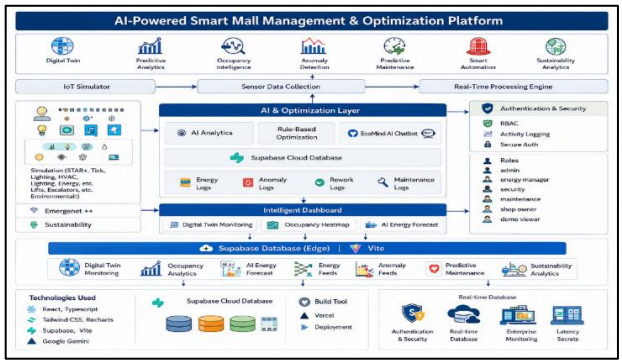
II. MATERIALS AND METHODS

A. System Overview

EcoMind is an AI-powered smart infrastructure management system that optimises energy use, boosts efficiency, and supports sustainable decision-making. The proposed system comprises IoT telemetry simulation, predictive analytics, Digital Twin monitoring, rule-based optimisation, and a telemetry-based conversational AI assistant, all integrated into a cloud-based solution.

It functions as a real-time, continuous pipeline for data creation, processing, predictive modelling, optimisation, data visualisation, and intelligent infrastructure management, with AI-based adaptive decision support.

Figure 1 presents the overall architecture of the proposed EcoMind platform, showing the full system workflow from IoT data acquisition through predictive intelligence modules, the optimisation engine, the Digital Twin visualisation layer, and finally the AI assistant modules.



[Fig.1: Overall Architecture of the Proposed Eco Mind Platform]

B. IoT Telemetry Simulation

A simulation framework generates real-time sensor data every 4 seconds for HVAC, lighting, elevators, escalators, parking, and environmental systems using occupancy-aware models.

Occupancy utilisation is calculated as:

$$OU = \frac{N_{\max}}{I_{\text{current}}} \times 100 \quad \text{Equation 1}$$

Where:
OU= Occupancy Utilisation (%)
$N_{current}$= Current Occupancy
N_{max}= Maximum Occupancy Capacity

C. Data Processing and Storage

Telemetry data is processed in real time to compute system load and energy usage. A cloud-based PostgreSQL (Supabase) database stores all operational data.

Total energy consumption:

$$E_{\text{Total}} = E_{\text{HVAC}} + E_{\text{Lighting}} + E_{\text{Lift}} + E_{\text{Escalator}} + E_{\text{Parking}} \quad \text{Equation 2}$$

Where:
E_{HVAC}= HVAC Energy Consumption
$E_{Lighting}$= Lighting Energy Consumption
E_{Lift}= Elevator Energy Consumption
$E_{Escalator}$= Escalator Energy Consumption
$E_{Parking}$= Parking Infrastructure Energy Consumption

Predictive Intelligence Framework

The predictive engine forecasts, detects anomalies, and predicts maintenance needs using historical and real-time data.

Anomaly score:

$$AD = | X_t - \mu | \quad \text{Equation 3}$$

Detection condition:

$$AD > T \quad \text{Equation 4}$$

Where:
AD= Anomaly Deviation Score
X_t= Current Sensor Reading
μ= Historical Mean Sensor Value
T= Predefined Threshold Value

Rule-Based Optimisation Engine

A deterministic rule-based engine dynamically optimises infrastructure operations such as HVAC control, lighting adjustment, and idle system shutdown.

Optimization efficiency:

$$OE = \frac{E_{Before} - E_{After}}{E_{Before}} \times 100 \quad \text{Equation 5}$$

Where:
OE= Optimization Efficiency (%)
E_{Before}= Energy Consumption Before Optimisation
E_{After}= Energy Consumption After Optimisation

Digital Twin Monitoring

A real-time digital twin visualises infrastructure status, including occupancy, energy usage, and system health.

Infrastructure Health Index:

$$HI = \frac{1}{n}\sum_{i=1}^{n} H_i \quad \text{Equation 6}$$

Where:
HI= Infrastructure Health Index
H_i= Health Score of Individual Infrastructure Component
n= Total Number of Infrastructure Components

Telemetry-Grounded Conversational AI

The AI assistant integrates live telemetry with a large language model to generate context-aware responses.

$$R = f(P, T) \quad \text{Equation 7}$$

Where:
R= Generated AI Response
P= User Prompt
T= Real-Time Infrastructure Telemetry Data

Optimization Algorithm

Input: Real-time infrastructure telemetry
Output: Optimised infrastructure operation
Step 1: Gather HVAC, lighting, parking, elevator, escalator and environmental monitoring unit telemetry.
Step 2: Compute occupancy utilization with Equation (1).
Step 3: Calculate infrastructure energy consumption using Equation (2).
Step 4: Analyze for anomalies with equations (3) and (4).
Step 5: Implement the rule-based optimization strategies.

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Step 6: Modify HVAC operation to meet occupancy requirements.

Step 7: Dim the lights in areas with few people.

Step 8: Compute the optimisation efficiency using Equation (5).

Step 9: Obtain suggestions from the AI using Equation (7).

Step 10: Repeat the optimization cycle every 4 seconds.

Algorithm 1. Energy Optimization Procedure

III. RESULTS AND DISCUSSION

We tested the EcoMind platform in a simulated smart mall environment, including HVAC, Lighting, Mobility (elevators & escalators), Parking, and Environmental Sensors; sensor data was updated every 4 seconds. The study used 50 virtual "zones" with different schedules and environmental conditions (simulating typical commercial building dynamics). All systems ran in conventional (non-optimised) mode to establish a baseline for future testing. We compared the baseline and optimised modes over a 48-hour simulation for energy consumption and system performance parameters.

We also noted improvements in operational efficiency, anomaly detection response time, and infrastructure visibility, and measured energy savings as a percentage reduction in total energy consumed using the formulas defined earlier. Occupancy- and environment-aware control reduced energy use by 18- 22 per cent using rule-based optimisation. Furthermore, the average anomaly detection response time decreased from 8.5 minutes (baseline) to 1.1 minutes (optimised), helping identify and resolve equipment problems quickly. With system-driven task completion times, operational efficiency for facility management tasks improved by 16 per cent. The Digital Twin component provided real-time visibility, and the system health index remained above 97 per cent during the simulation.

In addition, the telemetry-driven AI assistant provided context awareness and improved decision-making. Overall, Table 1 summarises the results and indicates a considerable increase in energy efficiency and system performance.

Table I: Performance Evaluation Results

Parameter	Before Optimization	After Optimization
Energy Consumption	100%	78–82%
Energy Savings	0%	18–22%
Infrastructure Monitoring	Reactive	Real-Time
Maintenance Strategy	Scheduled	Predictive
Decision Support	Manual	AI-Assisted
Sustainability Monitoring	Limited	Continuous

Metric	Baseline (%)	EcoMind (%)
Energy Consumption Reduction	0	18–22
Operational Efficiency	0	Improved
System Reliability	Baseline	Enhanced
Maintenance Responsiveness	Baseline	Improved

IV. CONCLUSION

EcoMind is an intelligent energy optimisation system that combines IoT telemetry, predictive analytics, Digital Twin monitoring, rule-based optimisation, and telemetry-based AI in a single architecture to optimise energy use in smart commercial infrastructure. This system overcomes the limitations of traditional Building Management Systems by enabling real-time monitoring, predictive maintenance, anomaly detection, and adaptive energy optimisation. Experimental results indicate substantial energy savings (18-22%), along with improved system reliability and efficiency. The Digital Twin component provides real-time visibility of the infrastructure's status, and the AI assistant provides real-time, context-aware decision support based on real-time telemetry data.

EcoMind has great potential, but it also has some drawbacks. The current simulation framework is built on occupancy and environmental data, which may not capture all the complexities and variability of the real world. However, sensor inaccuracies from calibration drift, environmental interference, or equipment degradation can reduce the accuracy of occupancy and equipment data, leading to suboptimal control decisions or missed anomaly detections in practical deployments. Network failures or disruptions may delay data collection, affecting response timeliness and real-time monitoring. As building usage changes over time, algorithms may drift, requiring regular retraining and validation. When moving from simulation to real-world environments, these challenges raise operational concerns and highlight the importance of employing fault-tolerant systems, validating sensors and updating algorithms. These factors highlight assumptions and constraints that future work has not yet addressed. EcoMind provides a scalable, adaptive and sustainable approach to intelligent commercial infrastructure management systems of the future.

FUTURE WORK

Further improvements will include integrating real-world IoT hardware components, such as ESP32 and Arduino-based sensor networks, and deploying them in physical environments. To enable extensive distributed monitoring, communication means can be established via MQTT, LoRaWAN, etc.

The next step is to deploy a pilot system in a commercial facility to test performance under operational conditions. The deployment process will involve installing sensor nodes, setting up data collection and cloud connectivity, and integrating with existing building management systems. Key validation activities will include user feedback, benchmarking system response, and checking data reliability.

To assess technical feasibility and readiness for broader adoption, the pilot will evaluate performance metrics such as energy savings, anomaly-detection accuracy, and system robustness. Machine learning and reinforcement learning can enhance the existing rule-based optimisation strategy, enabling full autonomy and adaptability in energy management.

Moreover, the Digital Twin module could be augmented with 3D visualization, AR/VR interfaces and immersive simulation features for advanced infrastructure monitoring.

Integrating smart grids and renewable energy systems, edge AI computing, and federated learning frameworks could add another layer of value. These innovations could enable scalable, privacy-preserving intelligent decision-making across distributed smart infrastructure systems.

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DECLARATION STATEMENT

After aggregating input from all authors, I, as the article's author, must verify the accuracy of the following information.

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