MSc AI Technology Portfolio Project

AIoT Smart Home ESP32-S3

Edge-AI Smart Home Simulation for Comfort, Privacy, Security and Environmental Safety

Author: Alberto Reyes Castro

Technologies: ESP32-S3, Wokwi, Blynk, Edge AI, Sensors

Focus Areas: AIoT, TinyML, Embedded AI, Smart Home Automation

Portfolio adaptation of an MSc Artificial Intelligence Technology project

Contents

1 Introduction

Artificial Intelligence of Things (AIoT) is an important area within embedded systems, smart environments, and edge computing. Rather than only connecting sensors and actuators, AIoT combines sensing, local reasoning, and real-time response to create context-aware behaviour (Al-Fuqaha et al., 2015; Shi et al., 2016). Smart homes are one of its clearest applications because they bring together comfort, privacy, safety, energy management, and user-focused automation (Stojkoska and Trivodaliev, 2017; Ray, 2018).

This project develops a modular smart home prototype using ESP32-S3 room controllers. Each room works as an independent embedded module with its own sensors, actuators, local logic, and remote monitoring interface, while still forming part of a wider house architecture. This room-level approach improves modularity, explainability, and scalability without relying on a single central controller.

The prototype focuses on a bedroom and a kitchen/living room. Both follow the same overall design philosophy but serve different priorities. The bedroom emphasises comfort, privacy, rest, and support for vulnerable users, whereas the kitchen/living room prioritises functional control, environmental monitoring, gas safety, and emergency response. This reflects a core principle of the project: smart-home behaviour should adapt to the role of each domestic space rather than apply identical logic everywhere.

Technically, the project combines low-cost embedded sensing, explainable rule-based control, Blynk-based IoT interaction, and an Edge Impulse workflow. The bedroom remains mainly rule-based because its behaviour can be expressed through clear comfort and privacy rules. The kitchen/living room extends this with an environmental safety classifier trained in Edge Impulse using gas score, temperature, and humidity. The model predicts five states: `NORMAL`, `COOKING_FUMES`, `GAS_DANGER`, `HEAT_ANOMALY`, and `GAS_HEAT_EMERGENCY`.

The main aim is to design and prototype a modular AIoT smart home that supports local decisions for comfort, privacy, safety, and security. To achieve this, the project develops room-specific embedded logic, integrates sensors and actuators, evaluates behaviour through simulation, and demonstrates an initial embedded machine-learning workflow for environmental safety classification in the kitchen/living room.

2 Literature Review

2.1 AI in IoT Systems

AIoT extends the Internet of Things by moving part of the decision process closer to the device. In conventional IoT systems, sensors often send data elsewhere for processing; in AIoT, more reasoning can happen locally. In domestic environments, this is valuable because latency, connectivity dependence, and privacy concerns can reduce the usefulness of a smart system. The literature shows applications in occupancy detection, environmental control, anomaly monitoring, adaptive lighting, and assisted living. However, the degree of intelligence varies widely, from threshold-based automation to full cloud or edge machine-learning pipelines (Al-Fuqaha et al., 2015; Ray, 2018).

2.2 Edge AI and Local Reasoning

A key distinction is between cloud-centred and edge-centred intelligence. Cloud-based AI supports stronger remote computation and easier large-scale management, but can introduce latency, connectivity dependence, and privacy concerns. In domestic systems, responses to motion, comfort, privacy, or gas-related events are often most useful when they occur locally and immediately. For this reason, edge AI has become increasingly important in smart environments. Even when a full learned model is not deployed, the same principle still applies: room-level local reasoning can make the system faster, more resilient, and easier to trust (Shi et al., 2016).

Recent reviews of edge AI and edge machine learning reinforce this design choice. Edge AI is increasingly used to move inference towards resource-constrained devices, reducing latency and cloud dependence while improving privacy and resilience (Merenda et al., 2020; Singh and Gill, 2023). In the IoT context, TinyML is also presented as a practical way to run lightweight models close to the sensor source, which matches the ESP32-S3 and Edge Impulse direction of this project (Dutta and Bharali, 2021).

2.3 Smart Home Automation and Environmental Control

Smart home literature often treats lighting, thermal control, assisted care, and security as separate functions. Lighting is commonly based on occupancy or brightness thresholds, thermal control on temperature and humidity ranges, and security on simple intrusion alarms. These approaches are useful but can become limited when context is ignored. A stronger design should allow the same input to produce different responses depending on room purpose, time, and user profile. This supports the modular room-specific structure used in this project (Stojkoska and Trivodaliev, 2017).

2.4 Gas and Domestic Safety Monitoring

Gas and smoke sensing is especially relevant in kitchen environments. However, low-cost gas sensors do not always separate harmless vapour, cooking fumes, and dangerous gas-related events clearly. The practical design challenge is therefore to remain sensitive to risk without becoming too reactive during everyday use. A common response is to combine thresholds with persistence over time, contextual interpretation, and secondary environmental signals. This directly informs the gas-safety logic used in the kitchen/living room module.

2.5 Machine Learning for Embedded Safety Classification

TinyML and embedded machine learning are useful when a system must classify patterns from several sensor values without sending data to a remote service. However, safety-related machine learning must be introduced carefully. A learned model should not replace deterministic protection logic unless it has been tested thoroughly in the target environment. For this reason, the project adopts a hybrid approach in which Edge Impulse provides environmental safety classification while rule-based gas escalation remains available as a deterministic fallback (Warden and Situnayake, 2019). This also explains why the project uses a small tabular classifier rather than a heavier model. In embedded IoT systems, model choice must consider memory, latency, energy use, and deployment reliability, not only predictive accuracy (Merenda et al., 2020; Dutta and Bharali, 2021).

2.6 Research Gap

Many smart-home projects remain either too generic or too centralised. They often apply similar logic across all rooms, rely heavily on cloud services, or prioritise novelty over explainability. There is therefore value in a modular edge-oriented architecture where each room keeps its own priorities while still contributing to a coherent house-wide design. This project addresses that gap through two differentiated room modules built around a shared control philosophy.

3 System Design

3.1 Overall House Architecture

The proposed smart home uses a modular architecture in which each room is represented by an ESP32-S3 controller. Each controller gathers room-specific sensor data, interprets the local context, and applies local decision logic without depending on a permanent cloud service. The current prototype includes a bedroom module and a kitchen/living room module. They are implemented as separate subsystems but share common ideas: operating modes, user profiles, occupancy awareness, local alerts, and safety overrides. This creates house-level consistency while still allowing each room to behave differently according to its function.

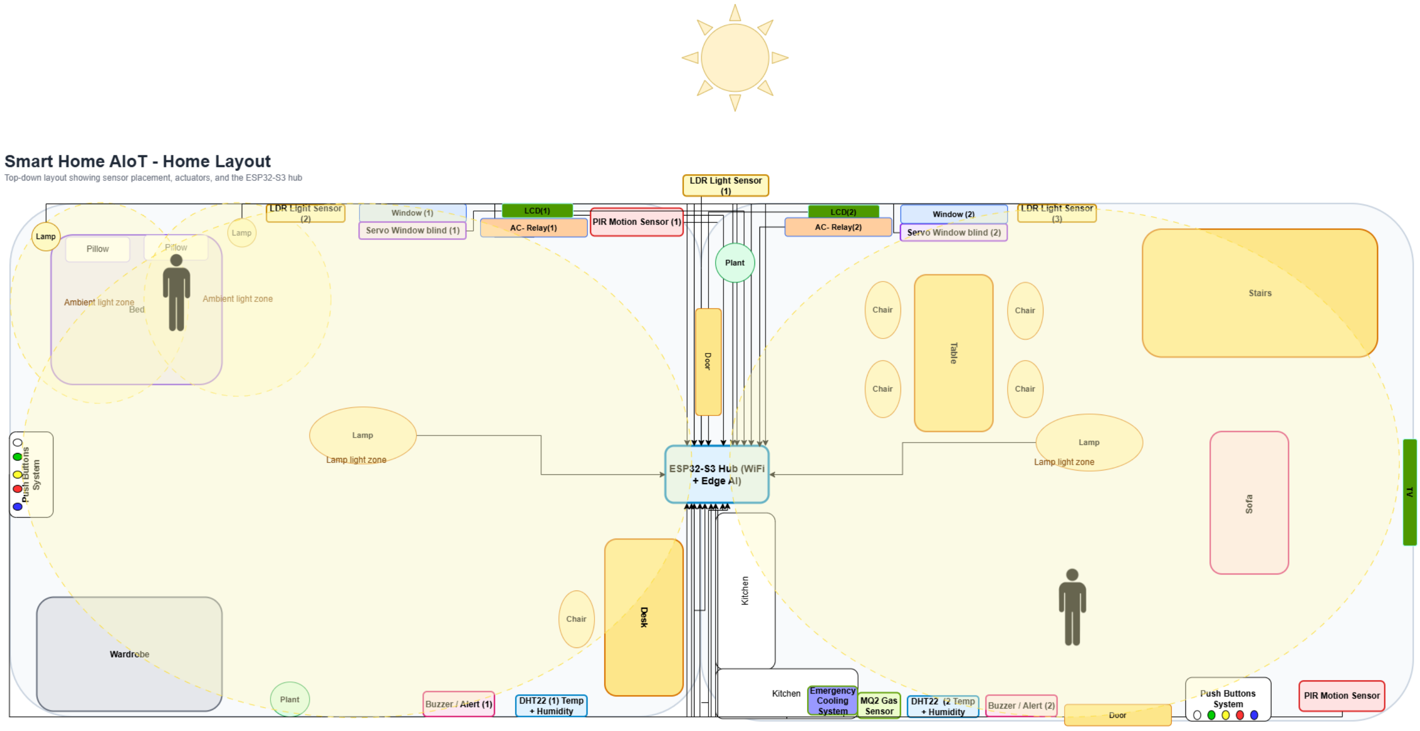
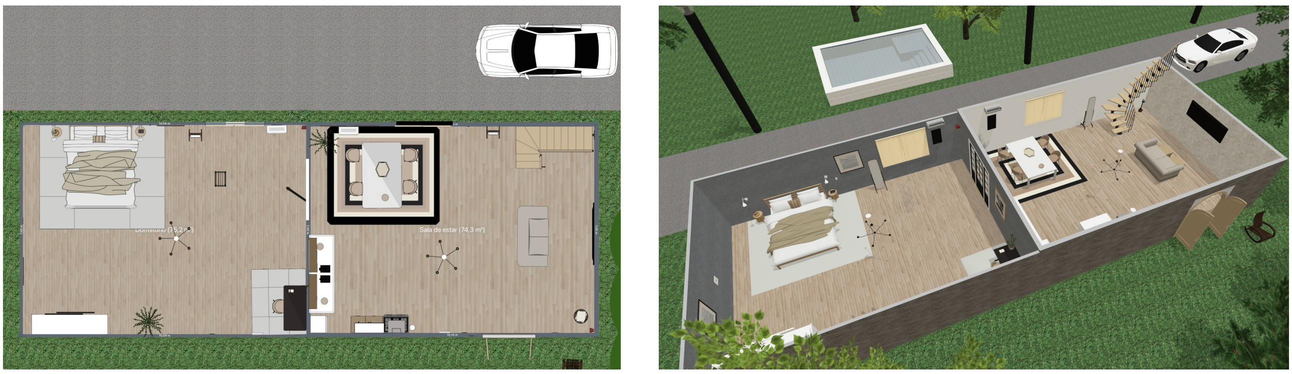


Figure 1: Overall house architecture and room distribution designed in draw.io.



(a) 2D plan view.

(b) 3D plan view.

Figure 2: House visualisation created in Planner 5D, showing the 2D plan and the 3D view. Available at: Planner 5D.

3.2 Common Control Philosophy

The house follows a shared logic based on three common room modes (*Normal*, *Privacy*, and *Eco*), three user profiles (*Standard*, *Elderly*, and *Child*), and a wider *Home/Away* house state. *Sleep* is kept only for the bedroom because it is primarily relevant to rest-oriented behaviour. This framework gives the system consistency while still allowing room-specific responses.

3.3 Away Mode Security Logic

Unlike the comfort-oriented room modes, *Away* is treated as a house security state. When the system is armed, comfort behaviour is reduced and the priority becomes monitoring, intrusion escalation, authenticated recovery, and energy saving. Motion is evaluated within a security window so that the system can distinguish between passive monitoring, suspicious motion, and confirmed intruder alert. The design also includes pet-aware behaviour to reduce false alarms caused by small domestic movement.

AWAY Mode – Security Behaviour (General Logic)

Decision table for HOME vs AWAY security behaviour

Purpose: protect the home when no authorized users are present

Sensors used: PIR motion sensor, Door/Window sensor, Camera (optional), System status

Condition	Bedroom Response	Kitchen / Living Response	Why this behaviour?
AWAY mode + no motion detected	• Blinds: CLOSED • Ambient light: OFF • AC: OFF • System status: Armed	• Blinds: CLOSED • Ambient light: OFF • AC: OFF • System status: Armed	Mantains the house in a secure state, minimizing energy use and preventing unauthorized access.
AWAY mode + first motion detected	• Keep blinds: CLOSED • Ambient light: OFF • AC: OFF • Record/Log event	• Keep blinds: CLOSED • Ambient light: OFF • AC: OFF • Record/Log event	A single motion can be normal (e.g., pet). The system monitors before escalating.
AWAY mode + repeated motion (suspicious)	• Keep blinds: CLOSED • Ambient light: OFF • AC: OFF • Trigger intruder alert • Notify user	• Keep blinds: CLOSED • Ambient light: FLASH / ON • AC: OFF • Trigger intruder alert • Notify user	Repeated motion suggests intrusion. The system raises an alert and notifies the user.
AWAY mode + pet mode enabled	• Keep blinds: CLOSED • Ambient light: OFF • AC: OFF • Ignore small/pet motion	• Keep blinds: CLOSED • Ambient light: OFF • AC: OFF • Ignore small/pet motion	Reduces false alarms caused by pet movement.
AWAY mode + intruder alert active	• Blinds: CLOSED • Ambient light: ON (for visibility) • AC: OFF • Sound alarm (if available) • Continuous notifications	• Blinds: CLOSED • Ambient light: ON (for visibility) • AC: OFF • Sound alarm (if available) • Continuous notifications	Maximizes deterrence and user awareness until the situation is resolved.
AWAY mode + correct authentication	• Return to previous mode (Normal / Sleep / Privacy / Eco) • Blinds, lights, AC restored according to that mode • System status: Disarmed	• Return to previous mode (Normal / Sleep / Privacy / Eco) • Blinds, lights, AC restored according to that mode • System status: Disarmed	The system returns to normal operation once the user is authenticated.

AWAY Mode – AC Behaviour (All Profiles)

Decision table for bedroom AC control in AWAY mode

Purpose: minimize energy consumption and avoid unnecessary cooling

AC behaviour in AWAY mode: AC is kept OFF for all profiles (Standard, Elderly, Child) regardless of temperature or humidity.

Scenario	Standard	Elderly	Child	Why this configuration?
AWAY mode + any temperature / humidity	AC OFF	AC OFF	AC OFF	When the house is empty, the AC remains OFF to save energy and reduce wear. Comfort is restored when the user returns and selects the desired mode.

Note: When the system leavees AWAY mode (correct authentication), AC behaviour follows the selected room mode (Normal, Sleep, Privacy or Eco) and the corresponding profile thresholds.

Figure 3: Away mode security logic across the implemented smart room modules. As shown in this figure, Away mode works as a security layer above the normal room modes. In this state, blinds remain in a defensive position, ordinary comfort functions are reduced, and repeated motion can escalate from monitoring to suspicious motion and then to intruder alert. After authentication, the system returns to Home state instead of staying armed, which helps avoid a repeated alarm loop.

3.4 Bedroom Module

3.4.1 Design Rationale

The bedroom is designed around comfort, privacy, rest, and support for vulnerable users. It therefore includes adaptive blinds, ambient support lighting, a manual lamp state, thermal monitoring, AC output, and occupancy-aware logic. Compared with the kitchen/living room, it requires finer behavioural distinctions, especially at night and across user profiles.

3.4.2 Hardware Structure

The bedroom module includes an ESP32-S3, PIR motion sensor, indoor and outdoor LDR sensors, a servo-controlled blind, smart ambient light output, manual lamp state indicator, DHT22 temperature and humidity sensor (Aosong Electronics, n.d.), AC relay, buzzer, control buttons, and an LCD interface.

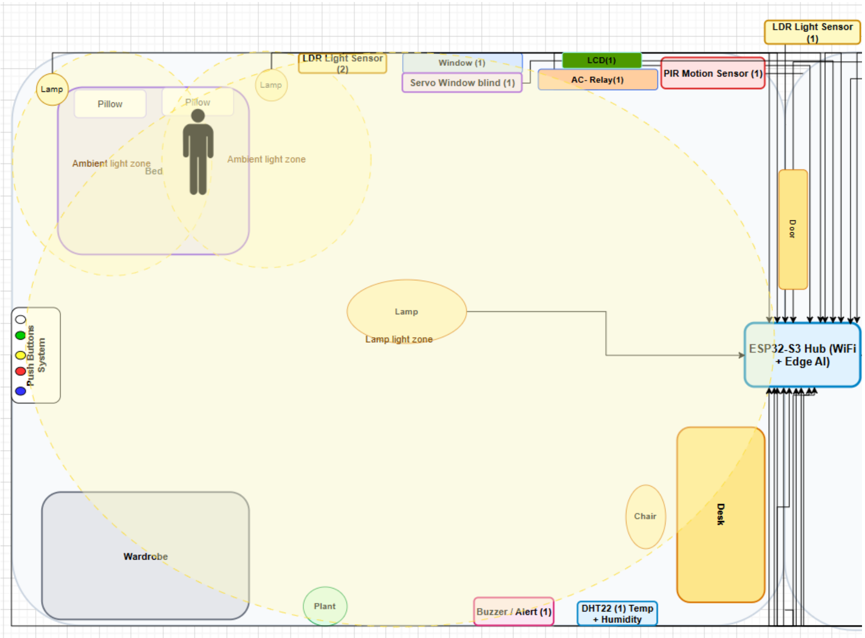


Figure 4: Bedroom hardware layout and logical arrangement in draw.io.

(a) 2D plan view.

(b) 3D view 1.

(c) 3D view 2.

(d) 3D view 3.

Figure 5: Bedroom visualisation created in Planner 5D, including the 2D plan and three dimensional views. Available at: Planner 5D.

3.4.3 Bedroom Behavioural Logic

The bedroom uses four modes. *Normal* supports balanced everyday behaviour, *Sleep* prioritises rest, *Privacy* restricts visibility and daylight exposure, and *Eco* reduces unnecessary energy use while keeping basic support available. Profiles refine this behaviour further: *Standard* provides the default response, *Elderly* extends presence hold time and favours gentler night support, and *Child* adds similarly protective behaviour together with protected deactivation through PIN logic.

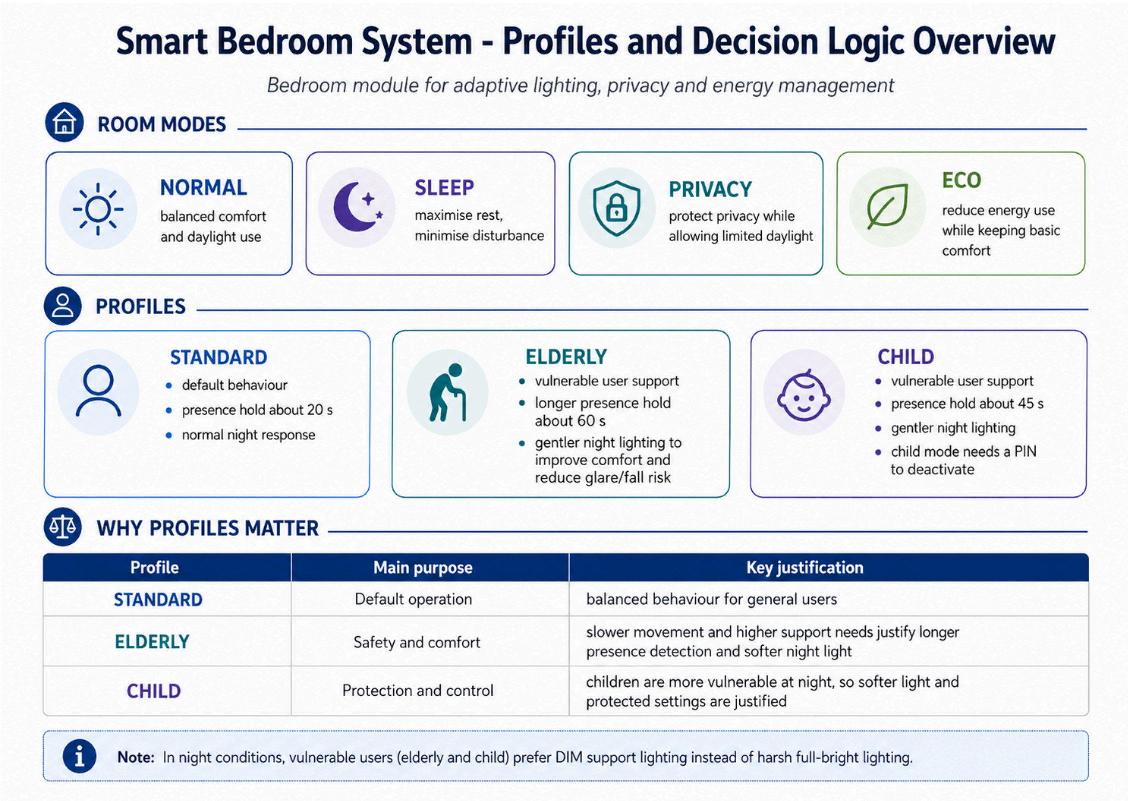
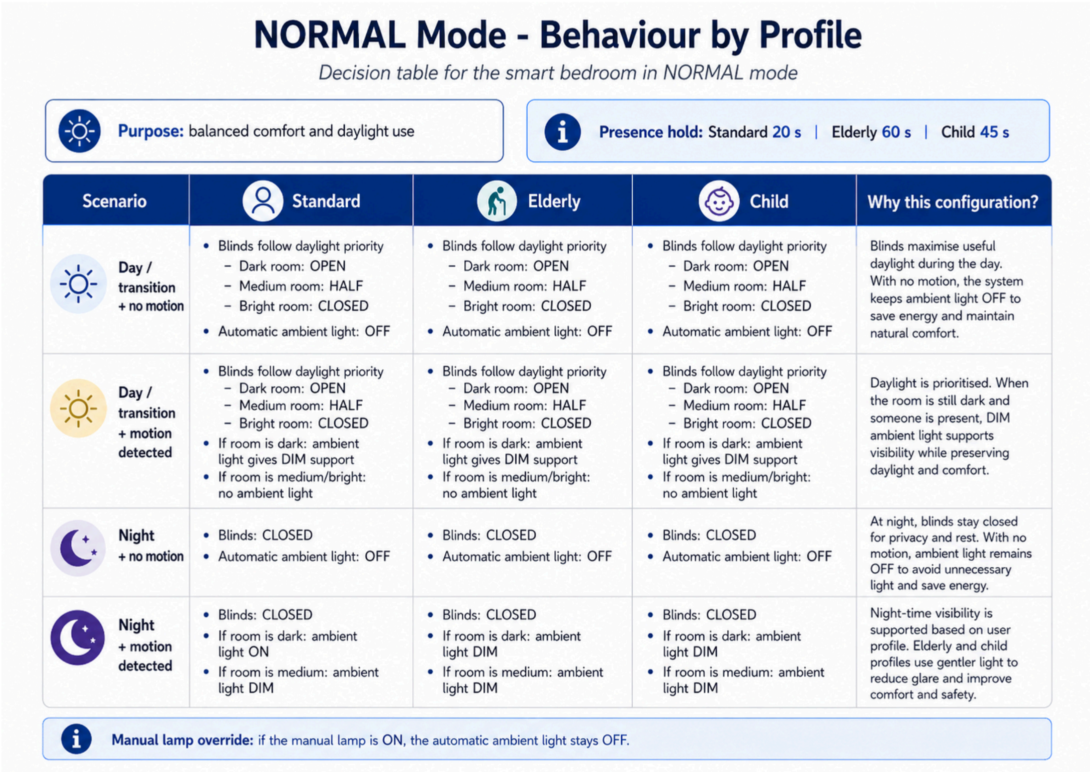


Figure 6: Bedroom profiles and overall control logic overview.

3.4.4 Bedroom Lighting and Blinds Logic

Lighting and blind behaviour are central to the bedroom design. *Sleep* mode keeps the room as dark as possible, while the *Elderly* and *Child* profiles still allow limited night support in selected motion situations. The detailed decision tables below summarise the designed responses.



NORMAL Mode - Behaviour by Profile

Decision table for the smart bedroom in NORMAL mode

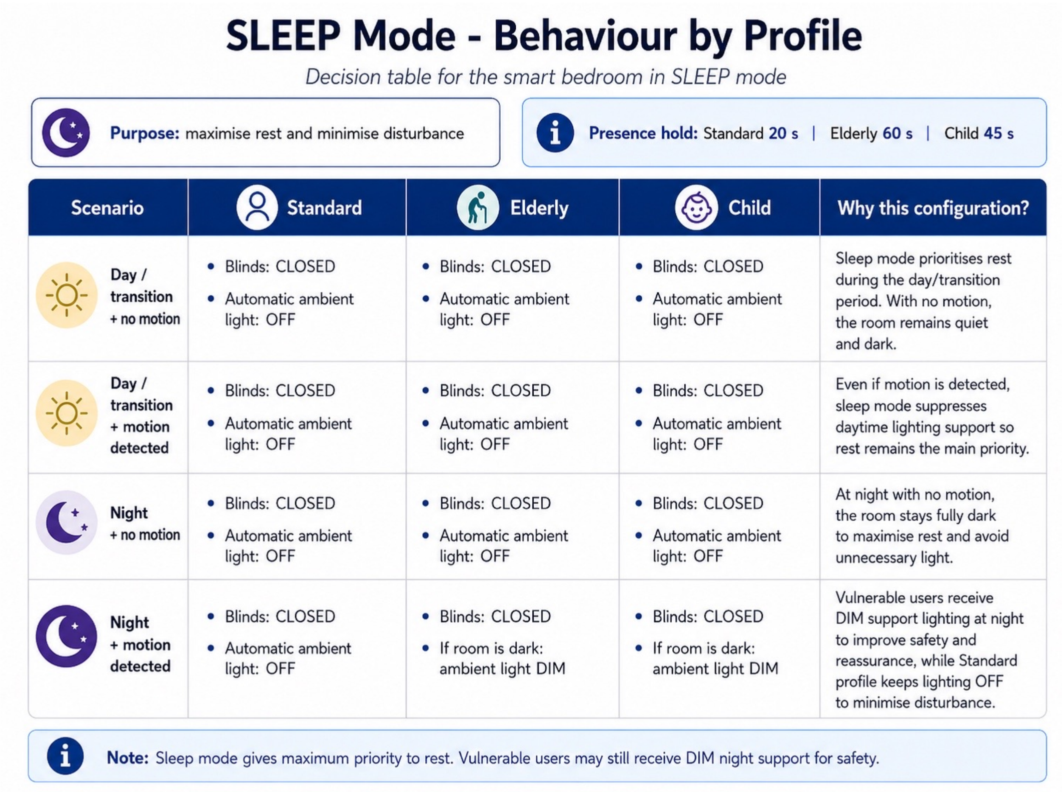
Purpose: balanced comfort and daylight use

Presence hold: Standard 20 s | Elderly 60 s | Child 45 s

Scenario	Standard	Elderly	Child	Why this configuration?
Day / transition + no motion	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	Blinds maximise useful daylight during the day. With no motion, the system keeps ambient light OFF to save energy and maintain natural comfort.
Day / transition + motion detected	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light gives DIM support • If room is medium/bright: no ambient light	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light gives DIM support • If room is medium/bright: no ambient light	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light gives DIM support • If room is medium/bright: no ambient light	Daylight is prioritised. When the room is still dark and someone is present, DIM ambient light supports visibility while preserving daylight and comfort.
Night + no motion	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	At night, blinds stay closed for privacy and rest. With no motion, ambient light remains OFF to avoid unnecessary light and save energy.
Night + motion detected	• Blinds: CLOSED • If room is dark: ambient light ON • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	Night-time visibility is supported based on user profile. Elderly and child profiles use gentler light to reduce glare and improve comfort and safety.

Manual lamp override: if the manual lamp is ON, the automatic ambient light stays OFF.

Figure 7: Bedroom Normal mode decision table for lighting and blinds.



SLEEP Mode - Behaviour by Profile

Decision table for the smart bedroom in SLEEP mode

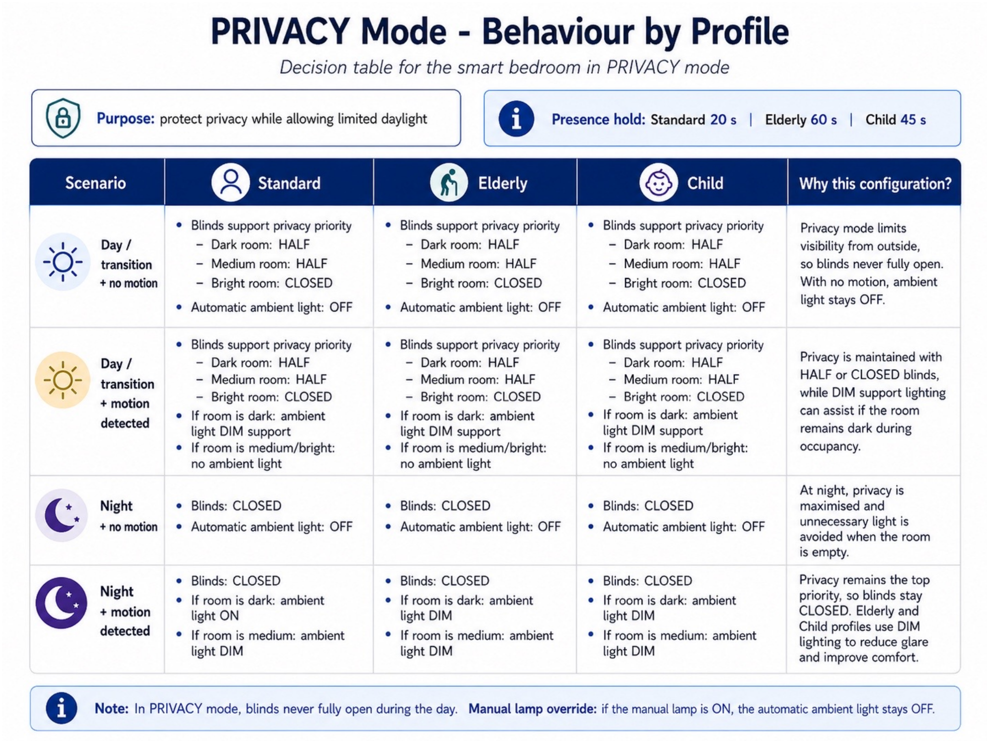
Purpose: maximise rest and minimise disturbance

Presence hold: Standard 20 s | Elderly 60 s | Child 45 s

Scenario	Standard	Elderly	Child	Why this configuration?
Day / transition + no motion	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	Sleep mode prioritises rest during the day/transition period. With no motion, the room remains quiet and dark.
Day / transition + motion detected	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	Even if motion is detected, sleep mode suppresses daytime lighting support so rest remains the main priority.
Night + no motion	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	At night with no motion, the room stays fully dark to maximise rest and avoid unnecessary light.
Night + motion detected	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • If room is dark: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM	Vulnerable users receive DIM support lighting at night to improve safety and reassurance, while Standard profile keeps lighting OFF to minimise disturbance.

Note: Sleep mode gives maximum priority to rest. Vulnerable users may still receive DIM night support for safety.

Figure 8: Bedroom Sleep mode decision table for lighting and blinds.



PRIVACY Mode - Behaviour by Profile

Decision table for the smart bedroom in PRIVACY mode

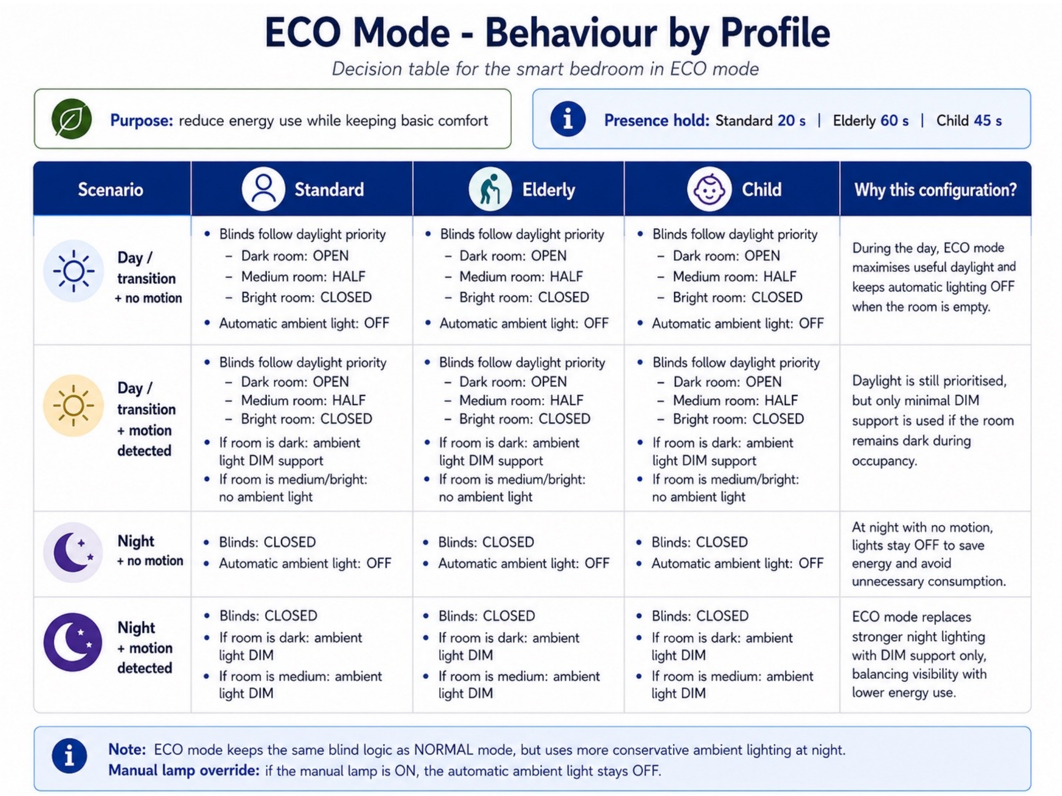
Purpose: protect privacy while allowing limited daylight

Presence hold: Standard 20 s | Elderly 60 s | Child 45 s

Scenario	Standard	Elderly	Child	Why this configuration?
Day / transition + no motion	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	Privacy mode limits visibility from outside, so blinds never fully open. With no motion, ambient light stays OFF.
Day / transition + motion detected	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	• Blinds support privacy priority – Dark room: HALF – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	Privacy is maintained with HALF or CLOSED blinds, while DIM support lighting can assist if the room remains dark during occupancy.
Night + no motion	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	At night, privacy is maximised and unnecessary light is avoided when the room is empty.
Night + motion detected	• Blinds: CLOSED • If room is dark: ambient light ON • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	Privacy remains the top priority, so blinds stay CLOSED. Elderly and Child profiles use DIM lighting to reduce glare and improve comfort.

Note: In PRIVACY mode, blinds never fully open during the day. **Manual lamp override:** if the manual lamp is ON, the automatic ambient light stays OFF.

Figure 9: Bedroom Privacy mode decision table for lighting and blinds. In Privacy mode, half-open blinds allow natural light to enter the room while still preventing visibility from outside. This ensures that indoor illumination can be maintained without compromising privacy at any stage.



ECO Mode - Behaviour by Profile

Decision table for the smart bedroom in ECO mode

Purpose: reduce energy use while keeping basic comfort

Presence hold: Standard 20 s | Elderly 60 s | Child 45 s

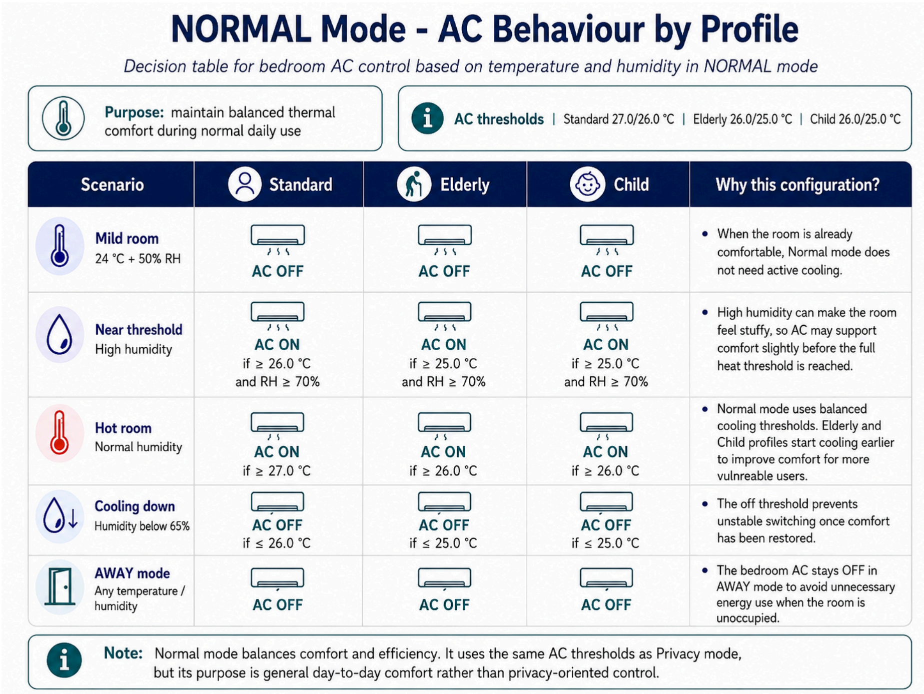
Scenario	Standard	Elderly	Child	Why this configuration?
Day / transition + no motion	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • Automatic ambient light: OFF	During the day, ECO mode maximises useful daylight and keeps automatic lighting OFF when the room is empty.
Day / transition + motion detected	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	• Blinds follow daylight priority – Dark room: OPEN – Medium room: HALF – Bright room: CLOSED • If room is dark: ambient light DIM support • If room is medium/bright: no ambient light	Daylight is still prioritised, but only minimal DIM support is used if the room remains dark during occupancy.
Night + no motion	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	• Blinds: CLOSED • Automatic ambient light: OFF	At night with no motion, lights stay OFF to save energy and avoid unnecessary consumption.
Night + motion detected	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	• Blinds: CLOSED • If room is dark: ambient light DIM • If room is medium: ambient light DIM	ECO mode replaces stronger night lighting with DIM support only, balancing visibility with lower energy use.

Note: ECO mode keeps the same blind logic as NORMAL mode, but uses more conservative ambient lighting at night.
Manual lamp override: if the manual lamp is ON, the automatic ambient light stays OFF.

Figure 10: Bedroom Eco mode decision table for lighting and blinds.

3.4.5 Bedroom Thermal Logic

Bedroom thermal comfort is managed through DHT22 sensing and AC relay control. The response varies by profile and mode: vulnerable user profiles justify slightly earlier intervention, while *Eco* delays activation to reduce energy use. The following figures summarise the designed AC behaviour.



NORMAL Mode - AC Behaviour by Profile

Decision table for bedroom AC control based on temperature and humidity in NORMAL mode

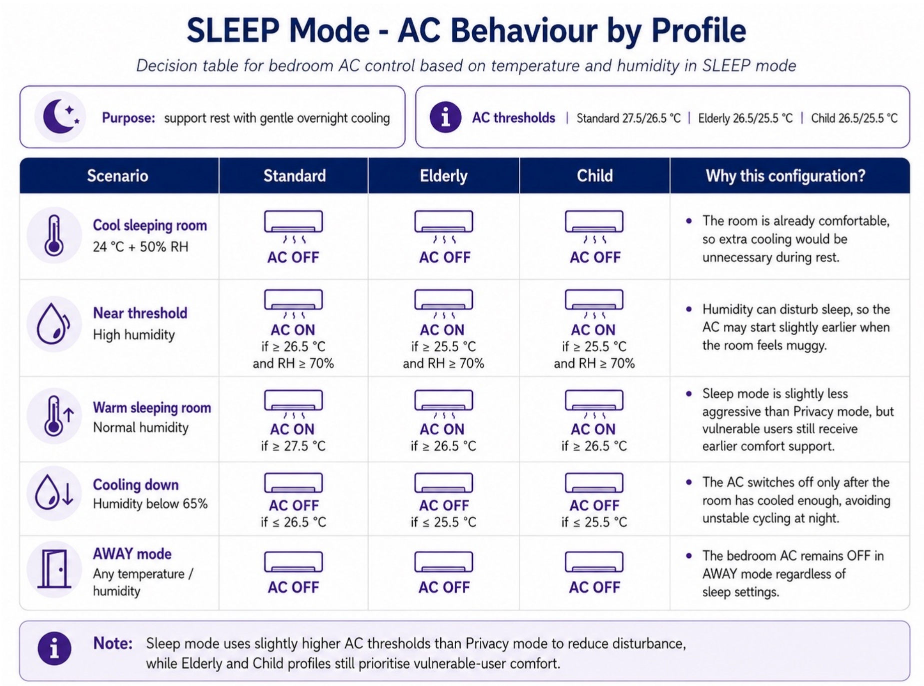
Purpose: maintain balanced thermal comfort during normal daily use

AC thresholds | Standard 27.0/26.0 °C | Elderly 26.0/25.0 °C | Child 26.0/25.0 °C

Scenario	Standard	Elderly	Child	Why this configuration?
Mild room 24 °C + 50% RH	AC OFF	AC OFF	AC OFF	• When the room is already comfortable, Normal mode does not need active cooling.
Near threshold High humidity	AC ON if ≥ 26.0 °C and RH ≥ 70%	AC ON if ≥ 25.0 °C and RH ≥ 70%	AC ON if ≥ 25.0 °C and RH ≥ 70%	• High humidity can make the room feel stuffy, so AC may support comfort slightly before the full heat threshold is reached.
Hot room Normal humidity	AC ON if ≥ 27.0 °C	AC ON if ≥ 26.0 °C	AC ON if ≥ 26.0 °C	• Normal mode uses balanced cooling thresholds. Elderly and Child profiles start cooling earlier to improve comfort for more vulnerable users.
Cooling down Humidity below 65%	AC OFF if ≤ 26.0 °C	AC OFF if ≤ 25.0 °C	AC OFF if ≤ 25.0 °C	• The off threshold prevents unstable switching once comfort has been restored.
AWAY mode Any temperature / humidity	AC OFF	AC OFF	AC OFF	• The bedroom AC stays OFF in AWAY mode to avoid unnecessary energy use when the room is unoccupied.

Note: Normal mode balances comfort and efficiency. It uses the same AC thresholds as Privacy mode, but its purpose is general day-to-day comfort rather than privacy-oriented control.

Figure 11: Bedroom Normal mode AC behaviour by profile.



SLEEP Mode - AC Behaviour by Profile

Decision table for bedroom AC control based on temperature and humidity in SLEEP mode

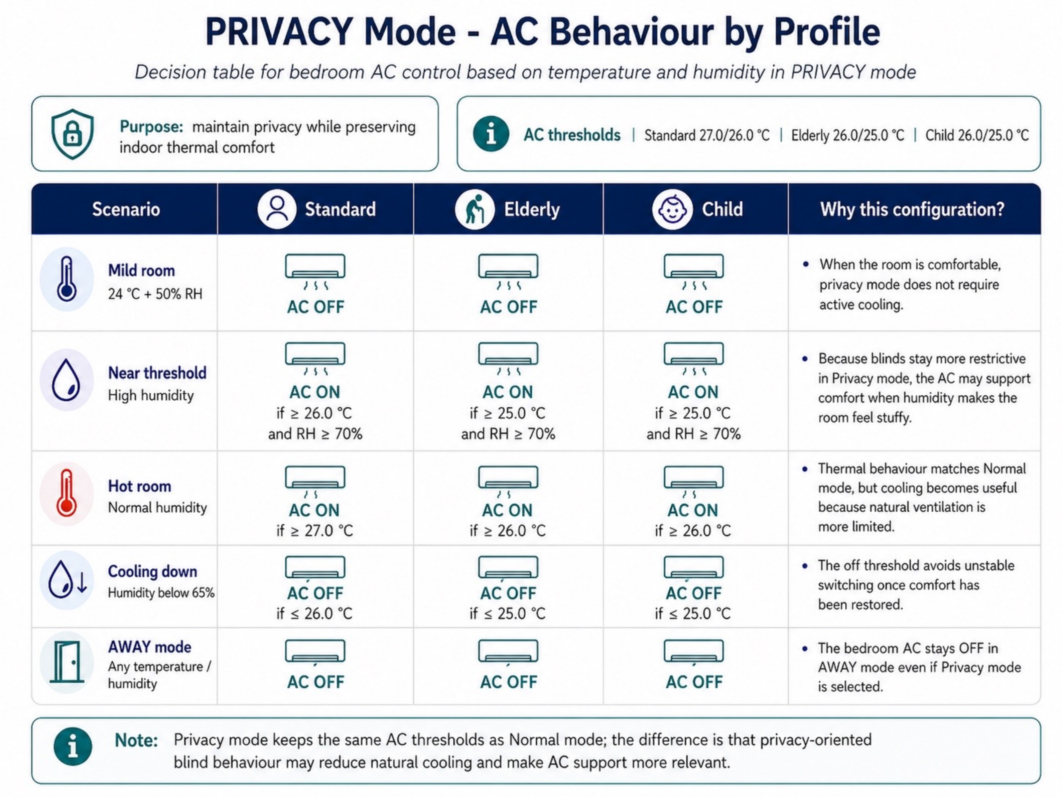
Purpose: support rest with gentle overnight cooling

AC thresholds | Standard 27.5/26.5 °C | Elderly 26.5/25.5 °C | Child 26.5/25.5 °C

Scenario	Standard	Elderly	Child	Why this configuration?
Cool sleeping room 24 °C + 50% RH	AC OFF	AC OFF	AC OFF	• The room is already comfortable, so extra cooling would be unnecessary during rest.
Near threshold High humidity	AC ON if ≥ 26.5 °C and RH ≥ 70%	AC ON if ≥ 25.5 °C and RH ≥ 70%	AC ON if ≥ 25.5 °C and RH ≥ 70%	• Humidity can disturb sleep, so the AC may start slightly earlier when the room feels muggy.
Warm sleeping room Normal humidity	AC ON if ≥ 27.5 °C	AC ON if ≥ 26.5 °C	AC ON if ≥ 26.5 °C	• Sleep mode is slightly less aggressive than Privacy mode, but vulnerable users still receive earlier comfort support.
Cooling down Humidity below 65%	AC OFF if ≤ 26.5 °C	AC OFF if ≤ 25.5 °C	AC OFF if ≤ 25.5 °C	• The AC switches off only after the room has cooled enough, avoiding unstable cycling at night.
AWAY mode Any temperature / humidity	AC OFF	AC OFF	AC OFF	• The bedroom AC remains OFF in AWAY mode regardless of sleep settings.

Note: Sleep mode uses slightly higher AC thresholds than Privacy mode to reduce disturbance, while Elderly and Child profiles still prioritise vulnerable-user comfort.

Figure 12: Bedroom Sleep mode AC behaviour by profile.



PRIVACY Mode - AC Behaviour by Profile

Decision table for bedroom AC control based on temperature and humidity in PRIVACY mode

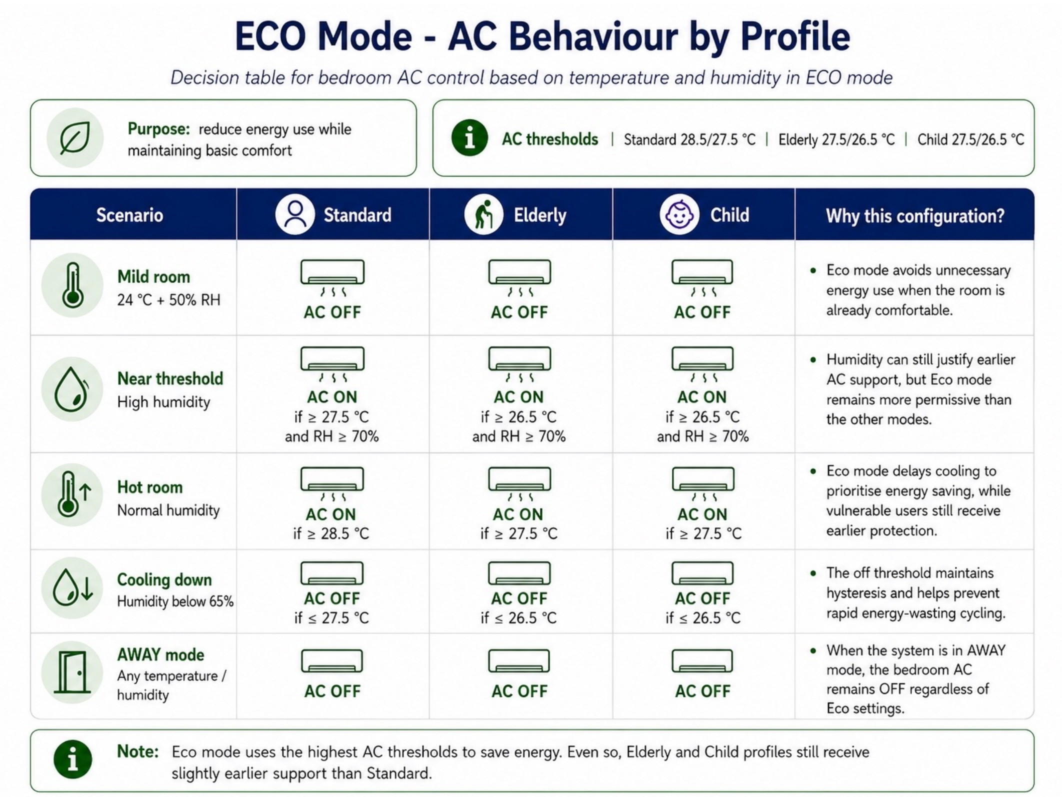
Purpose: maintain privacy while preserving indoor thermal comfort

AC thresholds | Standard 27.0/26.0 °C | Elderly 26.0/25.0 °C | Child 26.0/25.0 °C

Scenario	Standard	Elderly	Child	Why this configuration?
Mild room 24 °C + 50% RH	AC OFF	AC OFF	AC OFF	• When the room is comfortable, privacy mode does not require active cooling.
Near threshold High humidity	AC ON if ≥ 26.0 °C and RH ≥ 70%	AC ON if ≥ 25.0 °C and RH ≥ 70%	AC ON if ≥ 25.0 °C and RH ≥ 70%	• Because blinds stay more restrictive in Privacy mode, the AC may support comfort when humidity makes the room feel stuffy.
Hot room Normal humidity	AC ON if ≥ 27.0 °C	AC ON if ≥ 26.0 °C	AC ON if ≥ 26.0 °C	• Thermal behaviour matches Normal mode, but cooling becomes useful because natural ventilation is more limited.
Cooling down Humidity below 65%	AC OFF if ≤ 26.0 °C	AC OFF if ≤ 25.0 °C	AC OFF if ≤ 25.0 °C	• The off threshold avoids unstable switching once comfort has been restored.
AWAY mode Any temperature / humidity	AC OFF	AC OFF	AC OFF	• The bedroom AC stays OFF in AWAY mode even if Privacy mode is selected.

Note: Privacy mode keeps the same AC thresholds as Normal mode; the difference is that privacy-oriented blind behaviour may reduce natural cooling and make AC support more relevant.

Figure 13: Bedroom Privacy mode AC behaviour by profile.



ECO Mode - AC Behaviour by Profile

Decision table for bedroom AC control based on temperature and humidity in ECO mode

Purpose: reduce energy use while maintaining basic comfort

AC thresholds | Standard 28.5/27.5 °C | Elderly 27.5/26.5 °C | Child 27.5/26.5 °C

Scenario	Standard	Elderly	Child	Why this configuration?
Mild room 24 °C + 50% RH	AC OFF	AC OFF	AC OFF	• Eco mode avoids unnecessary energy use when the room is already comfortable.
Near threshold High humidity	AC ON if ≥ 27.5 °C and RH ≥ 70%	AC ON if ≥ 26.5 °C and RH ≥ 70%	AC ON if ≥ 26.5 °C and RH ≥ 70%	• Humidity can still justify earlier AC support, but Eco mode remains more permissive than the other modes.
Hot room Normal humidity	AC ON if ≥ 28.5 °C	AC ON if ≥ 27.5 °C	AC ON if ≥ 27.5 °C	• Eco mode delays cooling to prioritise energy saving, while vulnerable users still receive earlier protection.
Cooling down Humidity below 65%	AC OFF if ≤ 27.5 °C	AC OFF if ≤ 26.5 °C	AC OFF if ≤ 26.5 °C	• The off threshold maintains hysteresis and helps prevent rapid energy-wasting cycling.
AWAY mode Any temperature / humidity	AC OFF	AC OFF	AC OFF	• When the system is in AWAY mode, the bedroom AC remains OFF regardless of Eco settings.

Note: Eco mode uses the highest AC thresholds to save energy. Even so, Elderly and Child profiles still receive slightly earlier support than Standard.

Figure 14: Bedroom Eco mode AC behaviour by profile.

3.5 Kitchen / Living Room Module

3.5.1 Design Rationale

The kitchen/living room follows the same general philosophy as the bedroom but serves a different role. It is a shared, active, and safety-sensitive environment. For this reason, the design avoids bedroom-style automatic ambient support lighting and instead uses a single manually controlled main lamp. The main priorities are functional control, thermal comfort, occupancy awareness, gas safety monitoring, and emergency response.

This module is also the strongest candidate for machine-learning integration because it combines several environmental signals that can describe risk together. Unlike the bedroom, where most behaviour can be explained through comfort and privacy rules, the kitchen/living room benefits from a hybrid design that combines rule-based safety logic with an Edge Impulse classifier.

3.5.2 Hardware Structure

The kitchen/living room module includes an ESP32-S3, PIR motion sensor, indoor and outdoor LDR sensors, MQ2 gas sensor (Zhengzhou Winsen Electronics Technology Co., Ltd., n.d.), DHT22 temperature and humidity sensor (Aosong Electronics, n.d.), servo-controlled blinds, manual main lamp output, AC relay, buzzer, LCD display, sprinkler or emergency-cooling indicator LED, and buttons for mode, profile, house state, and child mode interaction.

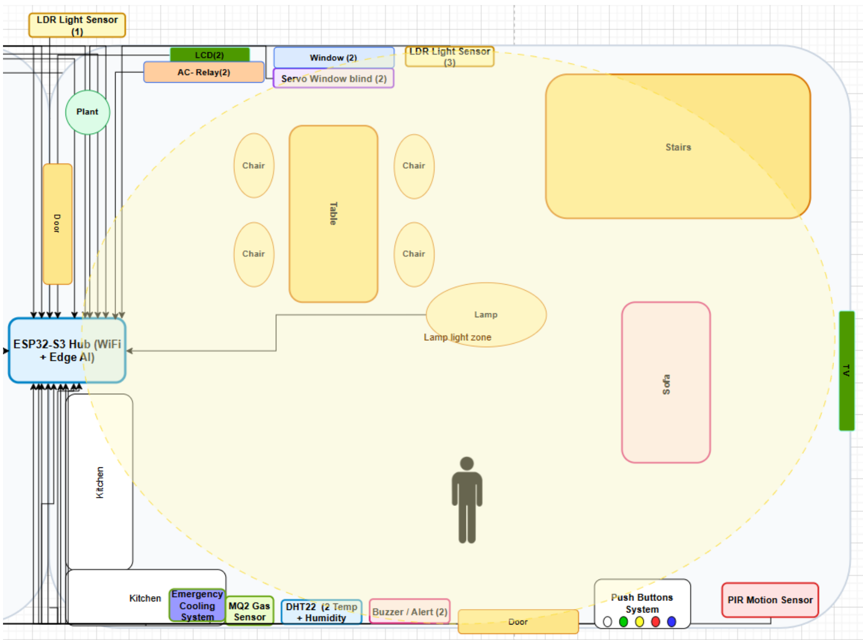


Figure 15: Kitchen/living room hardware layout and logical arrangement in draw.io.

(a) 2D plan view.

(b) 3D view 1.

(c) 3D view 2.

(d) 3D view 3.

Figure 16: Kitchen/living room visualisation created in Planner 5D, including the 2D plan and three dimensional views. Available at: Planner 5D.

3.5.3 Kitchen/Living Behavioural Logic

The final kitchen/living room design uses three room modes: *Normal*, *Privacy*, and *Eco*. *Sleep* was removed because it added little value in a shared functional room. The module still keeps the same profile logic as the rest of the house: *Standard* gives the default response, while *Elderly* and *Child* apply slightly more cautious thresholds and longer response timings. The room also supports the global *Home/Away* state, so repeated motion while armed can escalate from suspicious motion to intruder alert.

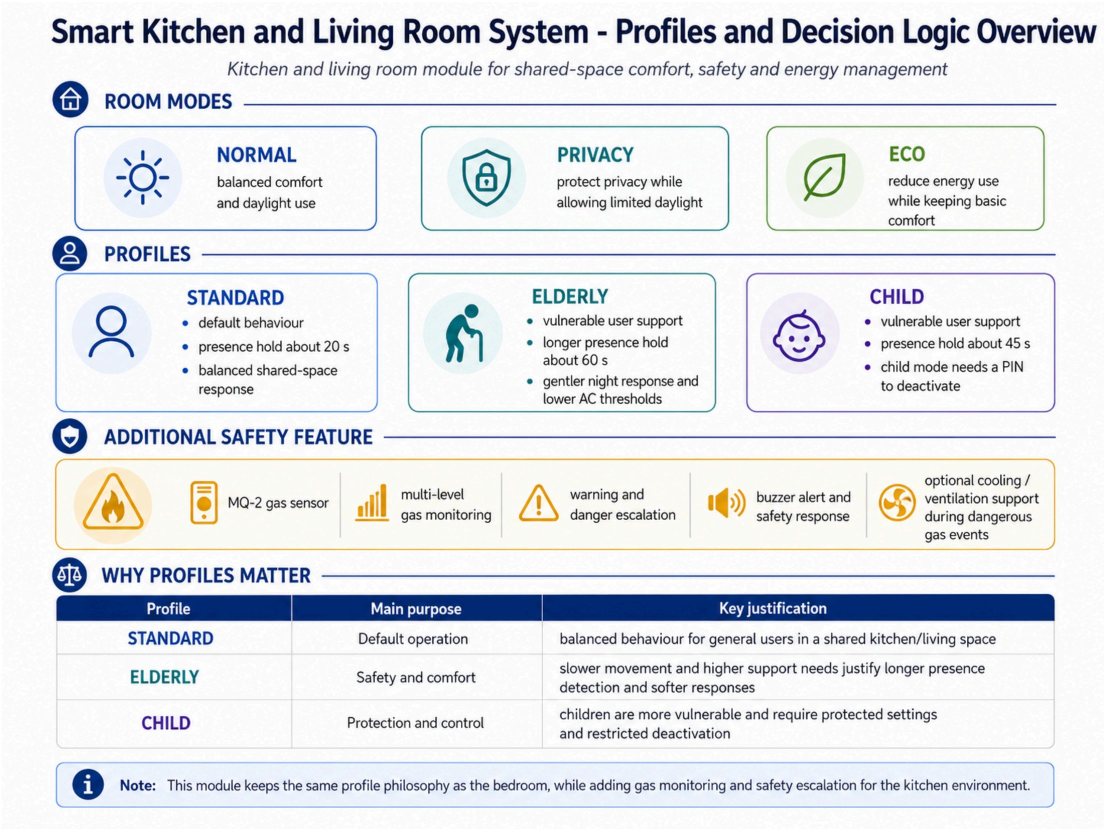


Figure 17: Kitchen/living room system overview. This shared space module follows the same overall house logic used in the bedroom, including the *Normal*, *Privacy*, and *Eco* modes, together with the *Standard*, *Elderly*, and *Child* profiles. However, *Sleep* mode is not implemented in this area, as the kitchen/living room is not mainly intended for night time rest. Unlike the bedroom, this module does not use automatic ambient lighting and relies on a manually controlled main lamp. Alongside blind and thermal control, the module integrates gas monitoring, heat anomaly detection, and emergency cooling response.

3.5.4 Gas and Environmental Safety Logic

The kitchen/living room adds the main safety dimension of the house: gas and environmental risk detection. Because a low-cost MQ2 sensor cannot cleanly separate harmless vapour, cooking fumes, and dangerous events, the system does not depend on one instant reading. This interpretation is consistent with using the MQ2 as a broad combustible-gas sensing element rather than as a precise domestic gas analyser (Zhengzhou Winsen Electronics Technology Co., Ltd., n.d.). Instead, the original rule-based logic uses thresholds, persistence timers, and staged escalation. The final design extends this with an Edge Impulse classifier using three input features:

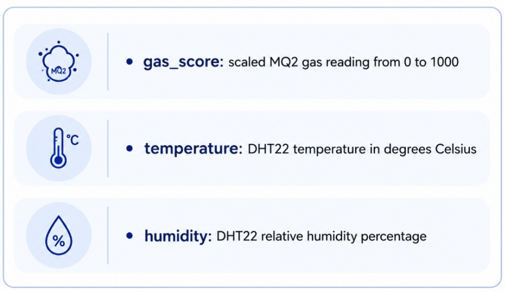


Figure 18: Input features.

The model predicts five environmental safety states:

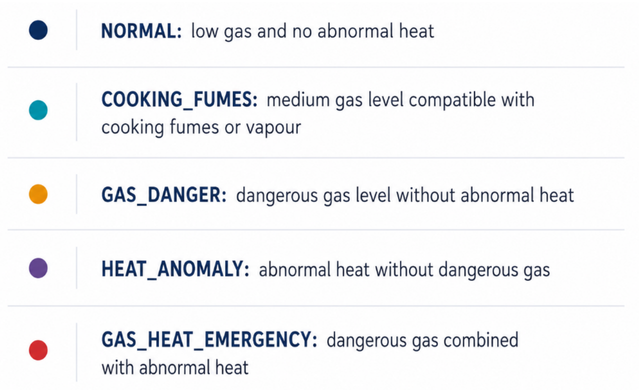


Figure 19: Output classes.

This gives temperature a clearer role in the logic: abnormal heat without dangerous gas becomes `HEAT_ANOMALY`, while dangerous gas combined with abnormal heat becomes `GAS_HEAT_EMERGENCY`. The latter activates the emergency-cooling response represented by a blinking sprinkler LED. The result is a hybrid safety structure in which the gas state machine remains the deterministic fallback while the AI layer provides faster contextual interpretation.

3.5.5 Kitchen/Living Thermal Logic

The kitchen/living room also uses DHT22-based thermal monitoring and AC control. This logic is simpler than in the bedroom because the main focus is shared-space comfort and safety rather than rest support. *Eco* delays AC intervention to reduce energy use, while the *Elderly* and *Child* profiles justify slightly more cautious thresholds. Safety overrides take priority: when cooking fumes or gas danger are active, the AC is switched off so that potentially contaminated air is not circulated through the room.

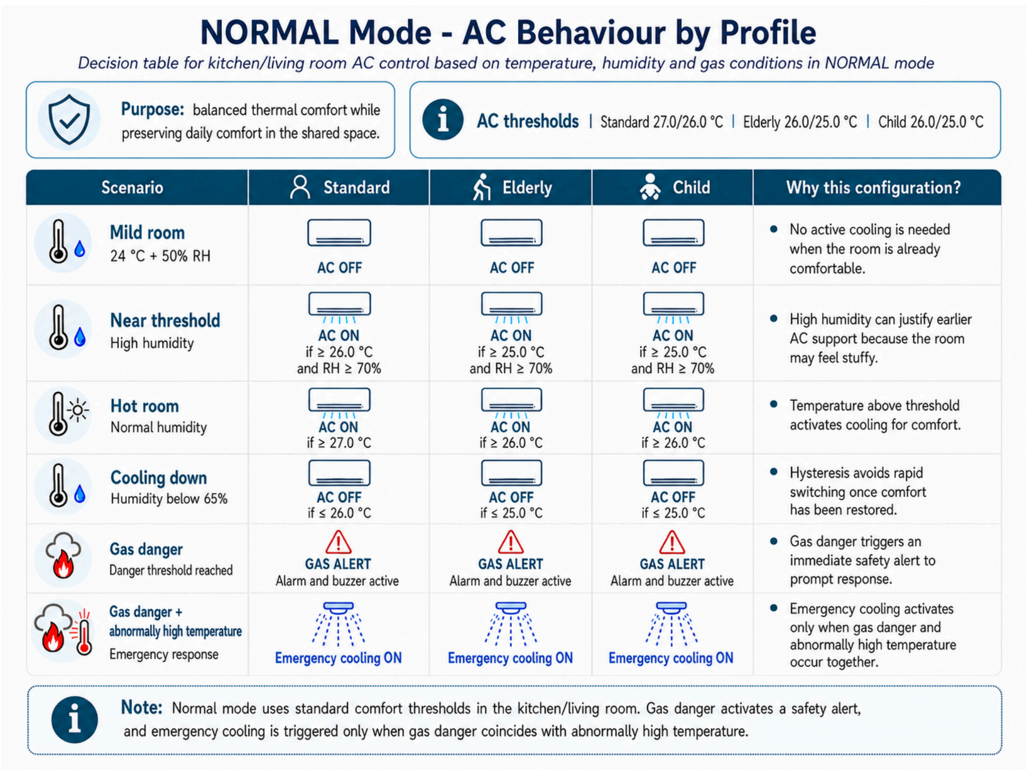


Figure 20: Kitchen/living room Normal mode AC behaviour by profile.

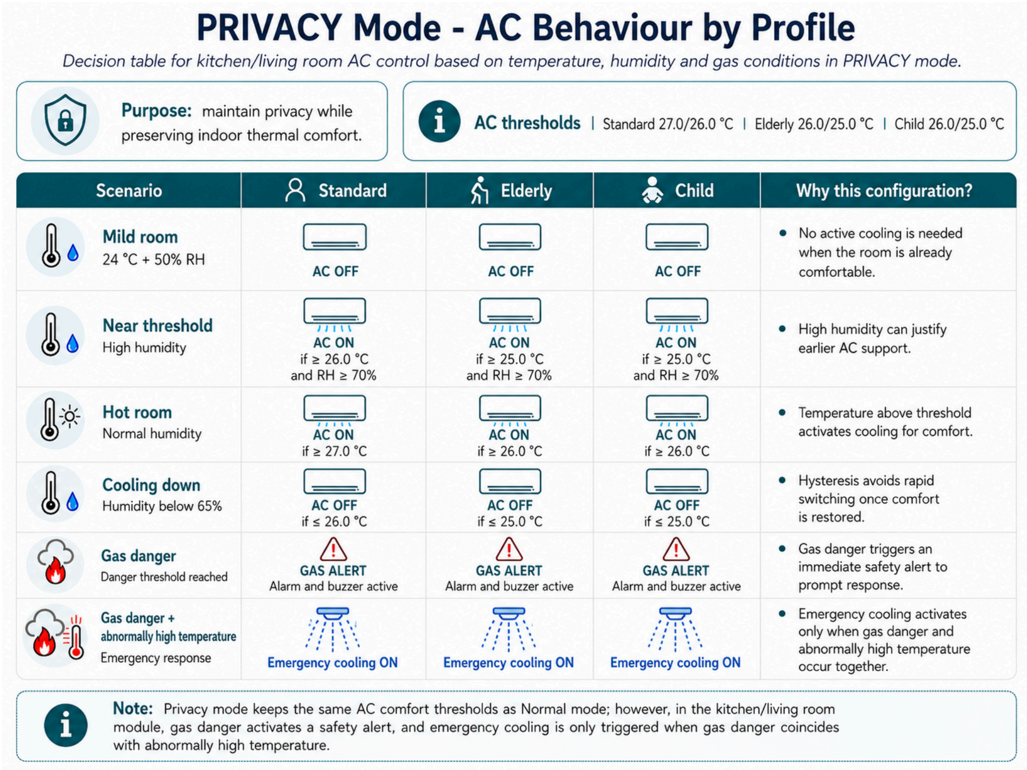


Figure 21: Kitchen/living room Privacy mode AC behaviour by profile.

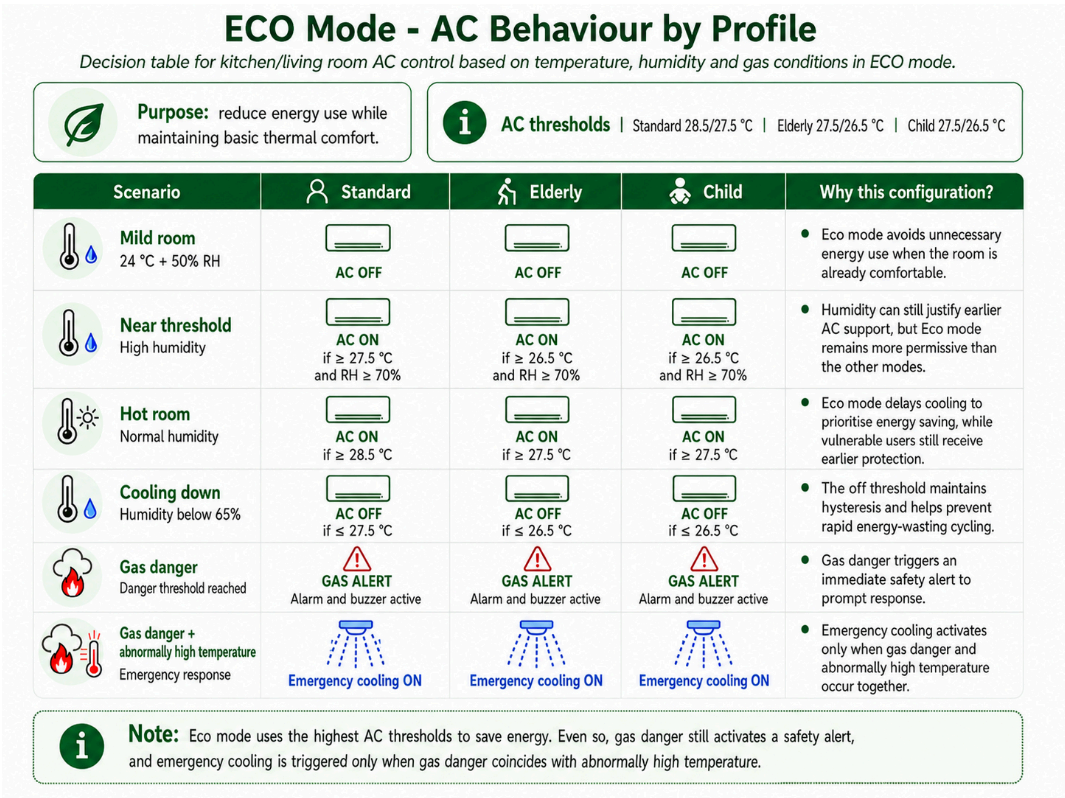


Figure 22: Kitchen/living room Eco mode AC behaviour by profile.

4 AI Model Design & Deployment

The AI part of the project is deliberately limited to the most safety-relevant and data-rich subsystem: environmental safety classification in the kitchen/living room. This keeps the task focused, explainable, and suitable for embedded deployment.

4.1 Role of AI in the Project

The AI component is not intended to replace the rule-based control system. The original rules remain important because they are transparent, deterministic, and appropriate for fallback behaviour in safety-related situations. In the current prototype, Edge Impulse is used to convert the existing environmental logic into a deployable embedded classifier based on `gas_score`, `temperature`, and `humidity` (Edge Impulse, n.d.a). Its role is to add a compact environmental interpretation layer that can be deployed on the ESP32-S3 and connected to the wider room behaviour.

The resulting workflow covers dataset creation, labelling, model training, testing, performance evaluation, and Arduino-library export for ESP32-S3 deployment. Because the dataset in this version is simulated and rule-labelled, the model should be treated as an initial Edge Impulse prototype rather than a certified safety system. The safest interpretation is therefore hybrid: AI supports the existing logic while deterministic rules remain available as fallback.

4.2 Problem Type

The selected problem is a multi-class classification task. The model receives three numerical inputs from the kitchen/living room sensors and predicts the current environmental safety state. As mentioned previously, the input features are:

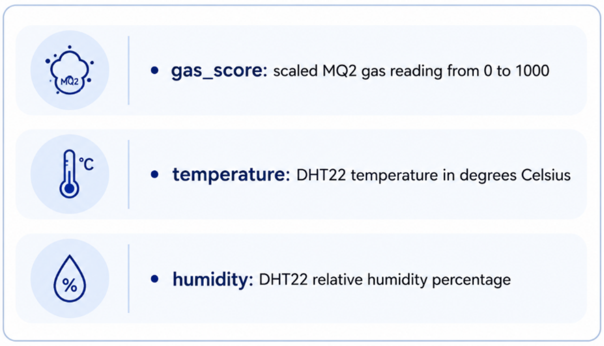


Figure 23: Input features.

The output classes are:

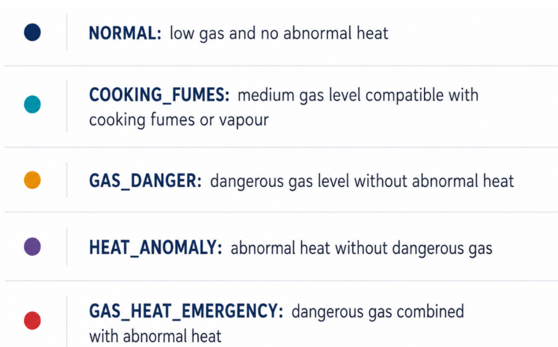


Figure 24: Output classes.

This is more appropriate than a gas-only classifier because it allows the system to distinguish between gas danger, heat anomaly, and a combined gas-and-heat emergency, while also maintaining a direct link between model output and embedded response.

4.3 Dataset Collection and Labelling

A custom dataset was created from the kitchen/living room simulation in Wokwi using the same ESP32-S3, MQ2, and DHT22 setup as the implemented module. This was preferable to a public dataset because the target classes were specific to the environmental safety states defined for this project. Data were collected through a simplified ESP32-S3 sketch that removed Blynk, LCD logic, buttons, and actuator control and printed clean CSV rows in the form:

```
gas_score,temperature,humidity,label
```

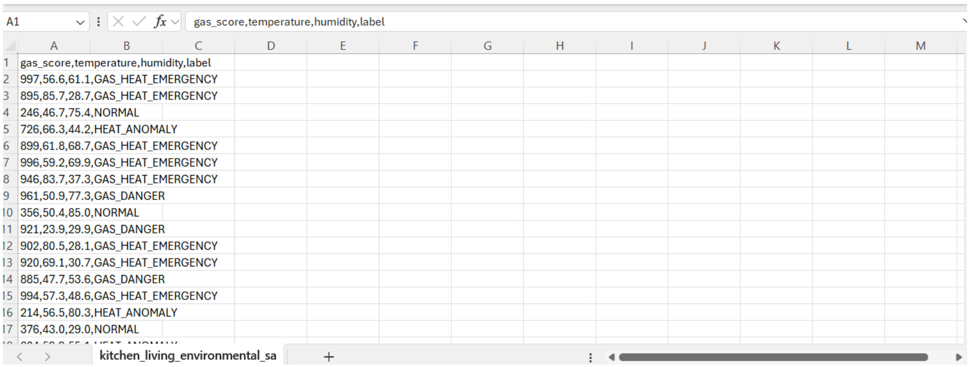


Figure 25: Dataset table used for the environmental safety classifier.

The simulated gas level, temperature, and humidity were varied to produce examples of the five environmental safety states. Labels were generated automatically from the same safety definitions used in the embedded system, which avoided inconsistent manual annotation and ensured alignment between dataset and designed behaviour.

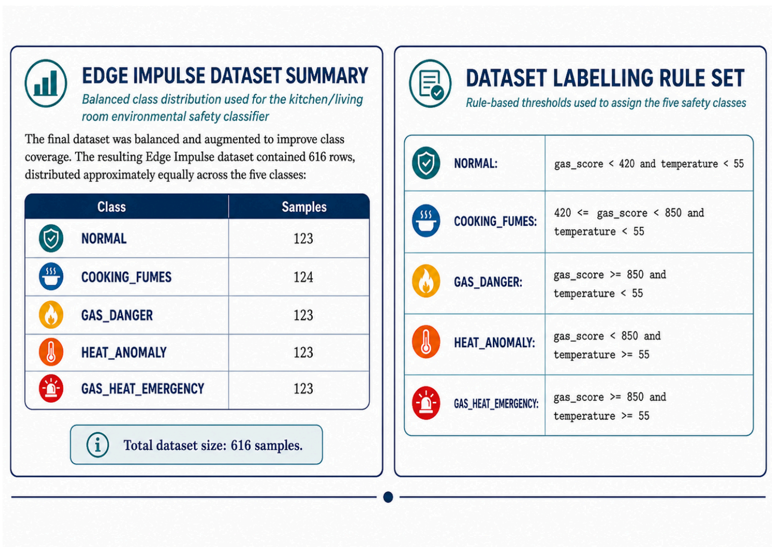


Figure 26: Edge Impulse dataset summary and rule-based labelling criteria for the kitchen/living room environmental safety classifier. The upper panel shows the final balanced class distribution across the five target classes, while the lower panel presents the threshold based rules used to assign labels from gas score and temperature conditions before model training.

Humidity was retained as a contextual feature even though labels were driven mainly by gas score and temperature.

4.4 Impulse Design

The Edge Impulse pipeline was configured as a small tabular classification impulse using the three numerical features `gas_score`, `temperature`, and `humidity`. The processing stage used raw data features with standard scaling, and feature-importance analysis was used to assess the contribution of each input.

The results matched the intended system logic: gas score was the most important feature, temperature the second most important, and humidity a smaller contextual feature. The learning block used a small neural-network classifier with three input features, two dense layers, and five output classes. This was appropriate because the dataset is small, numerical, and low-dimensional, so a larger model would have added complexity without clear deployment benefit.

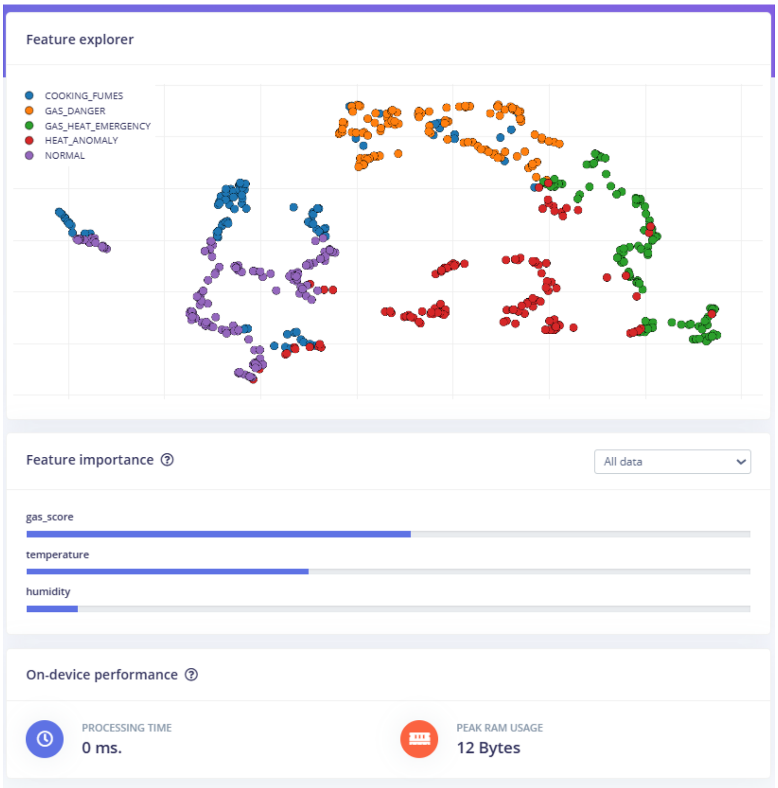


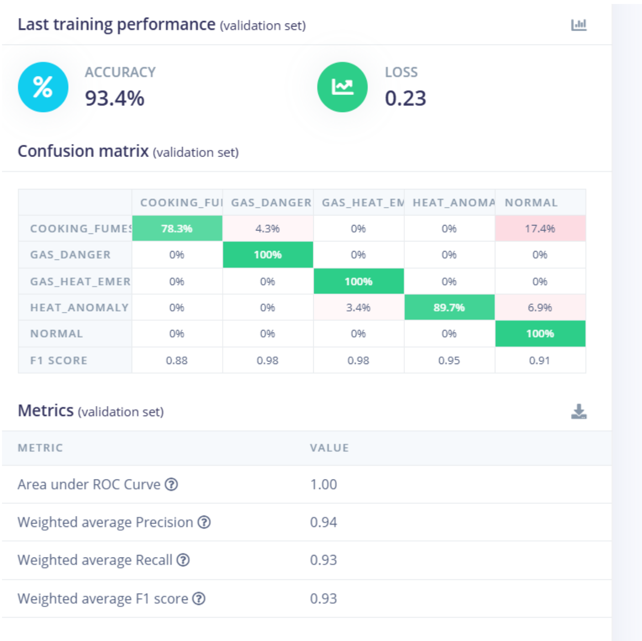
Figure 27: Edge Impulse outputs for the kitchen/living room environmental safety classifier. The upper part shows the feature explorer and the generated feature space for the five environmental safety classes. The lower part shows the feature importance analysis, where `gas_score` is the most influential feature, followed by `temperature` and `humidity`.

4.5 Training and Performance Metrics

The classifier was trained in Edge Impulse using 100 training cycles and a learning rate of 0.0005. Training reached approximately 93.4% accuracy with a weighted F1 score of 0.93, while the held-out test set achieved approximately 85.9% accuracy, an AUC of 0.99, weighted precision of 0.91, weighted recall of 0.89, and weighted F1 score of 0.89. The strongest performance was observed in the most safety-critical classes, especially `NORMAL`, `GAS_DANGER`, and `GAS_HEAT_EMERGENCY`. The main weakness was the intermediate `COOKING_FUMES` class, which is expected because it sits between normal and dangerous gas levels.

Edge Impulse also reported embedded performance estimates suitable for ESP32-S3 deployment: approximately 1 ms inference time, 1.4 KB peak RAM, and 14.4 KB flash usage. These values indicate that the model is lightweight enough for embedded inference.

Figure 28: Edge Impulse training results for the environmental safety classifier. The model achieved approximately 93.4% training accuracy with strong performance on the most safety critical classes.



	COOKING_FU	GAS_DANGER	GAS_HEAT_EM	HEAT_ANOMA	NORMAL
COOKING_FUMES	78.3%	4.3%	0%	0%	17.4%
GAS_DANGER	0%	100%	0%	0%	0%
GAS_HEAT_EMER	0%	0%	100%	0%	0%
HEAT_ANOMALY	0%	0%	3.4%	89.7%	6.9%
NORMAL	0%	0%	0%	0%	100%
F1 SCORE	0.88	0.98	0.98	0.95	0.91

METRIC	VALUE
Area under ROC Curve	1.00
Weighted average Precision	0.94
Weighted average Recall	0.93
Weighted average F1 score	0.93

Figure 29: Training confusion matrix for the Edge Impulse classifier. The matrix shows strong classification performance for `NORMAL`, `GAS_DANGER`, and `GAS_HEAT_EMERGENCY`, with most ambiguity occurring around the intermediate `COOKING_FUMES` class.

METRIC	VALUE
Area under ROC Curve	0.99
Weighted average Precision	0.91
Weighted average Recall	0.89
Weighted average F1 score	0.89

	COOKING_FUMES	GAS_DANGER	GAS_HEAT_EMERG	HEAT_ANOMALY	NORMAL	UNCERTAIN
COOKING_FUMES	60.5%	15.8%	0%	0%	10.5%	13.2%
GAS_DANGER	0%	100%	0%	0%	0%	0%
GAS_HEAT_EMERGEI	0%	0%	92.9%	0%	0%	7.1%
HEAT_ANOMALY	0%	0%	3.4%	82.8%	0%	13.8%
NORMAL	0%	0%	0%	0%	100%	0%
F1 SCORE	0.75	0.88	0.95	0.91	0.95	

Figure 30: Model testing results on the held out test set. The Edge Impulse model achieved approximately 85.9% test accuracy, with an AUC of 0.99 and strong performance on the main safety critical classes.

4.6 Deployment Strategy

The trained model was exported from Edge Impulse as an Arduino library using quantised int8 optimisation and the EON compiler. The generated library was prepared for ESP32-S3 deployment and integrated into the kitchen/living room code as an additional AI layer. The embedded system uses the model output to update an environmental safety state variable that then informs the LCD, Blynk dashboard, buzzer, blinds, AC logic, and emergency-cooling response (Edge Impulse, n.d.b; Espressif Systems, n.d.).

In Wokwi, the full Edge Impulse runtime caused simulator instability when the generated classifier was executed. For that reason, the simulation version uses a Wokwi-safe inference mode that follows the same five environmental safety classes as the trained model. This allows system-level behaviour to be tested in simulation without crashing the virtual ESP32-S3. On real hardware, the exported Arduino library can be enabled for full inference testing. The final architecture therefore remains hybrid: rule-based safety logic stays active as deterministic fallback while the model provides contextual environmental classification.

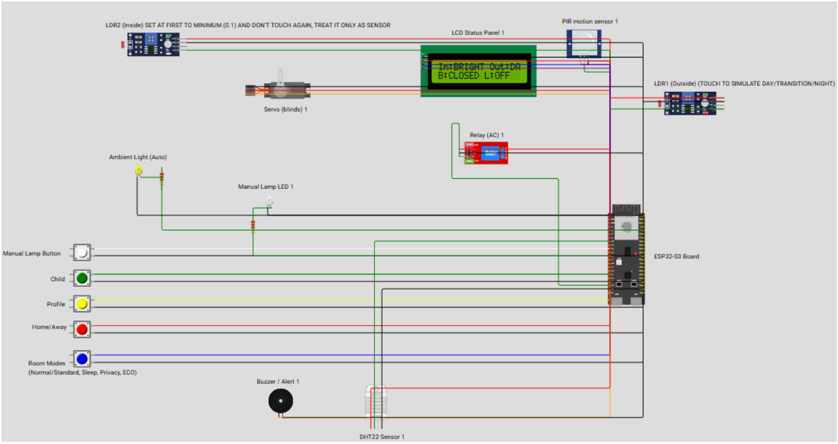
5 Implementation

5.1 Simulation Environment

The practical implementation was developed mainly in Wokwi. This allowed sensor integration, room logic, LCD outputs, serial monitoring, Blynk connectivity, and safety-related behaviour to be tested without full physical hardware assembly. Wokwi was especially useful for iterative debugging, threshold tuning, and controlled testing of gas, temperature, humidity, light, and motion changes (Wokwi, n.d.).

5.2 Bedroom Module Implementation

The bedroom module was the most behaviourally detailed subsystem developed during the earlier stage of the project. It implements light-driven state classification, PIR-based occupancy detection with profile-dependent hold times, adaptive blinds, ambient support lighting, manual lamp integration, AC control through DHT22 readings, and local feedback through the LCD and Serial Monitor. It also supports child-mode protection, Away-mode behaviour, and authenticated state changes.



(a) Wokwi components and circuit connections.

```
======== SYSTEM STATUS (refresh every 5 seconds) =========
Room mode: NORMAL
Profile: STANDARD
House status: HOME
Pet at home: NO
Alert: NONE
AWAY motion count: 0
LDR2 inside raw: 2205 | inside effective brightness score: 711
LDR1 outside raw: 4063 | active outside score: 0 | source: BLYNK_V3
Inside state: BRIGHT
Outside state: NIGHT
PIR raw: 0
Presence active: YES
Manual lamp: ON
Blinds: CLOSED
Smart ambient light: OFF
Temperature: 60.7 C
Humidity: 100.0 %
Thermal state: WARM
AC: ON
Request active: NONE
```

(b) Serial Monitor outputs.

Figure 31: Bedroom implementation in Wokwi, showing the components and the Serial Monitor outputs.

5.3 Kitchen/Living Room Implementation

The kitchen/living room implementation follows the same broad software structure but adapts it to different priorities. Its main additions are gas sensing, emergency safety escalation, and Edge Impulse-based environmental classification. The room keeps a manual main lamp instead of automated ambient support lighting and combines rule-based thresholds with AI-derived environmental state interpretation.

The implementation includes DHT22 thermal sensing, MQ2 gas-score conversion, PIR motion detection, LDR-based brightness interpretation, servo blind control, AC relay behaviour, buzzer alerts, sprinkler or emergency-cooling LED indication, LCD output, Blynk monitoring, and the same Home/Away security logic used elsewhere in the house. The environmental-state pipeline is summarised below.

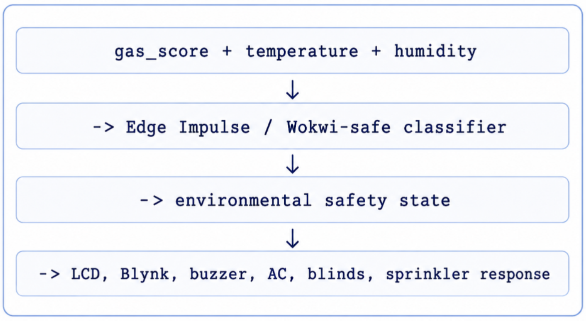
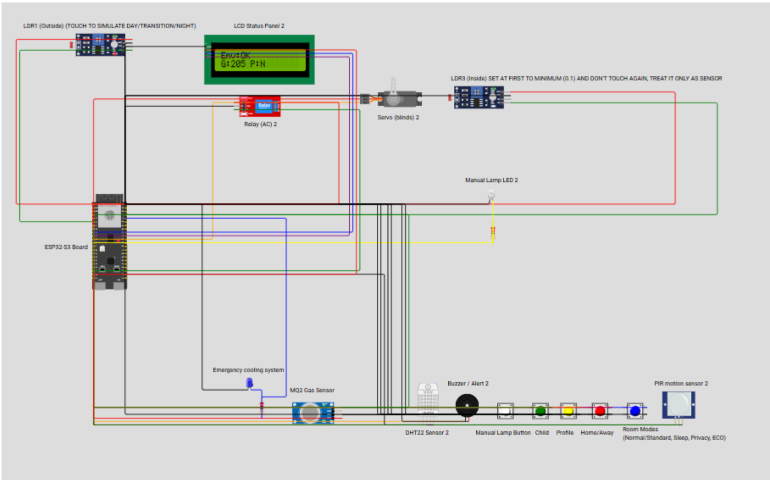
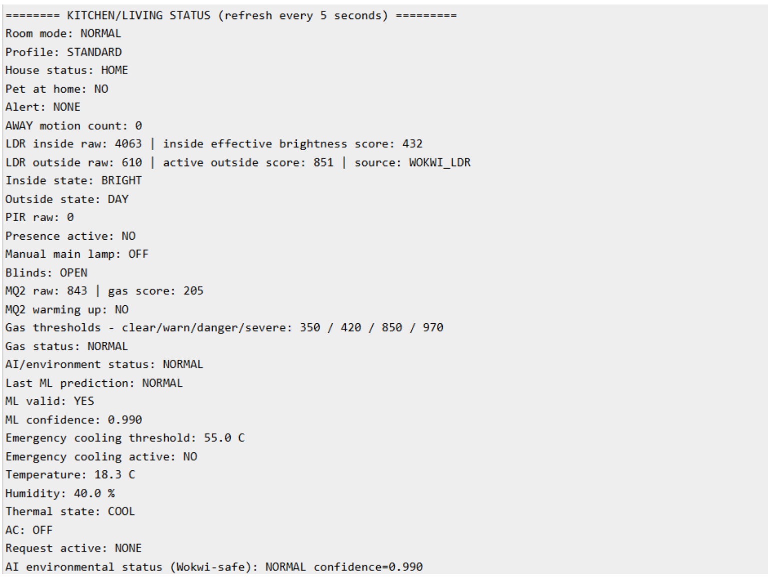


Figure 32: Environmental state pipeline used for the kitchen/living room AI safety layer.

Simulation confirmed the intended hybrid behaviour. For example, when gas score rose to around 885 and temperature to 72.4 °C, the system entered `GAS_HEAT_EMERGENCY`, activated the emergency-cooling state, opened the blinds, turned off the AC, and displayed the alert as *GAS + HIGH TEMP*. When gas later decreased while temperature remained high, the state moved to `HEAT_ANOMALY`, and when both returned to safe values, the status returned to `NORMAL`.



(a) Wokwi components and circuit connections.



```
======== KITCHEN/LIVING STATUS (refresh every 5 seconds) =========
Room mode: NORMAL
Profile: STANDARD
House status: HOME
Pet at home: NO
Alert: NONE
AWAY motion count: 0
LDR inside raw: 4063 | inside effective brightness score: 432
LDR outside raw: 610 | active outside score: 851 | source: WOKWI_LDR
Inside state: BRIGHT
Outside state: DAY
PIR raw: 0
Presence active: NO
Manual main lamp: OFF
Blinds: OPEN
MQ2 raw: 843 | gas score: 205
MQ2 warming up: NO
Gas thresholds - clear/warn/danger/severe: 350 / 420 / 850 / 970
Gas status: NORMAL
AI/environment status: NORMAL
Last ML prediction: NORMAL
ML valid: YES
ML confidence: 0.990
Emergency cooling threshold: 55.0 C
Emergency cooling active: NO
Temperature: 18.3 C
Humidity: 40.0 %
Thermal state: COOL
AC: OFF
Request active: NONE
AI environmental status (Wokwi-safe): NORMAL confidence=0.990
```

(b) Serial Monitor outputs.

Figure 33: Kitchen/living room implementation in Wokwi, showing the components and the Serial Monitor outputs.

5.4 Blynk Mobile Dashboards and Remote Interaction

Blynk provides the remote monitoring and user interaction layer for both ESP32-based modules. The main decision logic remains on the microcontroller, while Blynk allows the user to view real-time sensor values, interpreted room states, alerts, and selected control variables from a mobile or web dashboard.

In the bedroom module, the dashboard displays temperature, humidity, brightness-related values, PIR-based occupancy information, room mode, active profile, house status, blind state, smart-light state, AC state, thermal state, alert state, and additional variables such as pet presence and away motion count. Outside brightness is treated as a unified simulation input that can be controlled either through the physical outdoor LDR in Wokwi or through the Blynk V3 slider, with the most recently changed source becoming the active outside-light reference.

The kitchen/living room dashboard follows the same approach but places greater emphasis on thermal monitoring, manual lighting state, gas score, gas-related safety states, emergency-cooling escalation, and AI-related environmental outputs. It also exposes environmental safety status, model confidence, and the latest raw model prediction. Together, these dashboards provide a practical remote supervision layer while making the internal room logic and the hybrid safety architecture more transparent (Blynk, n.d.).

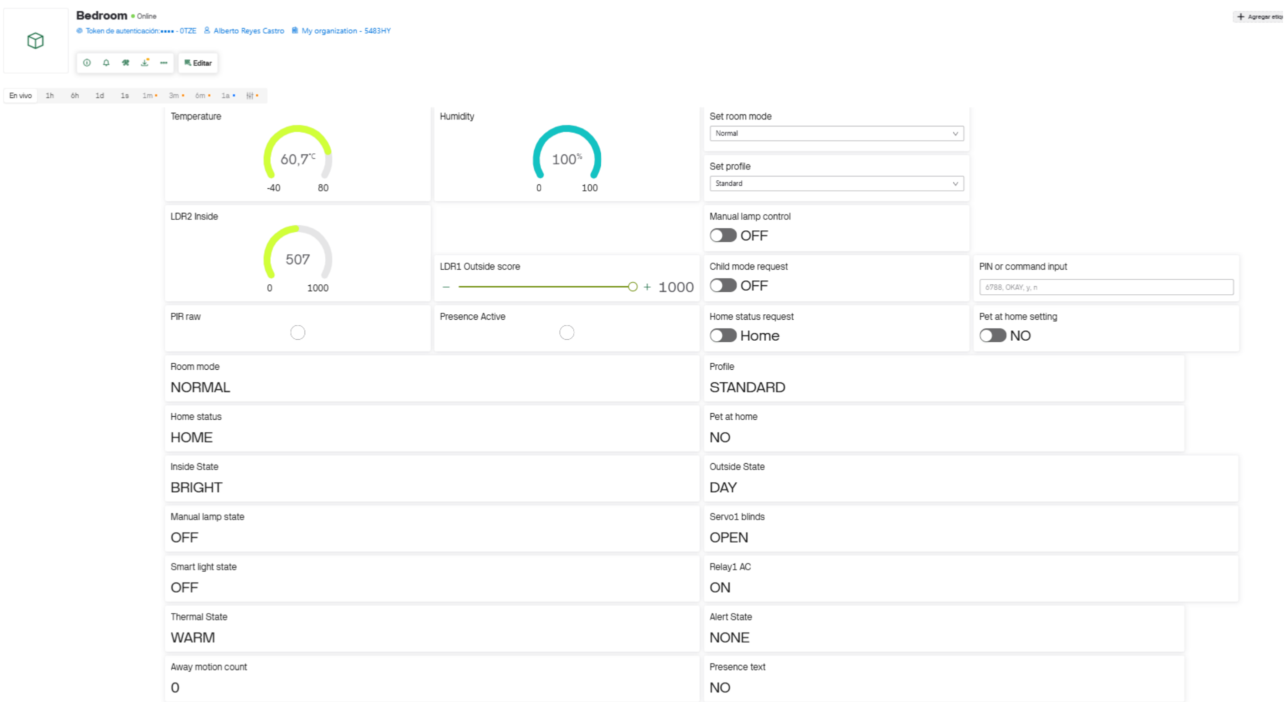


Figure 34: Blynk dashboard for the bedroom module, showing real time sensor values, interpreted room states, and selected remote control inputs for interaction with the smart bedroom system.

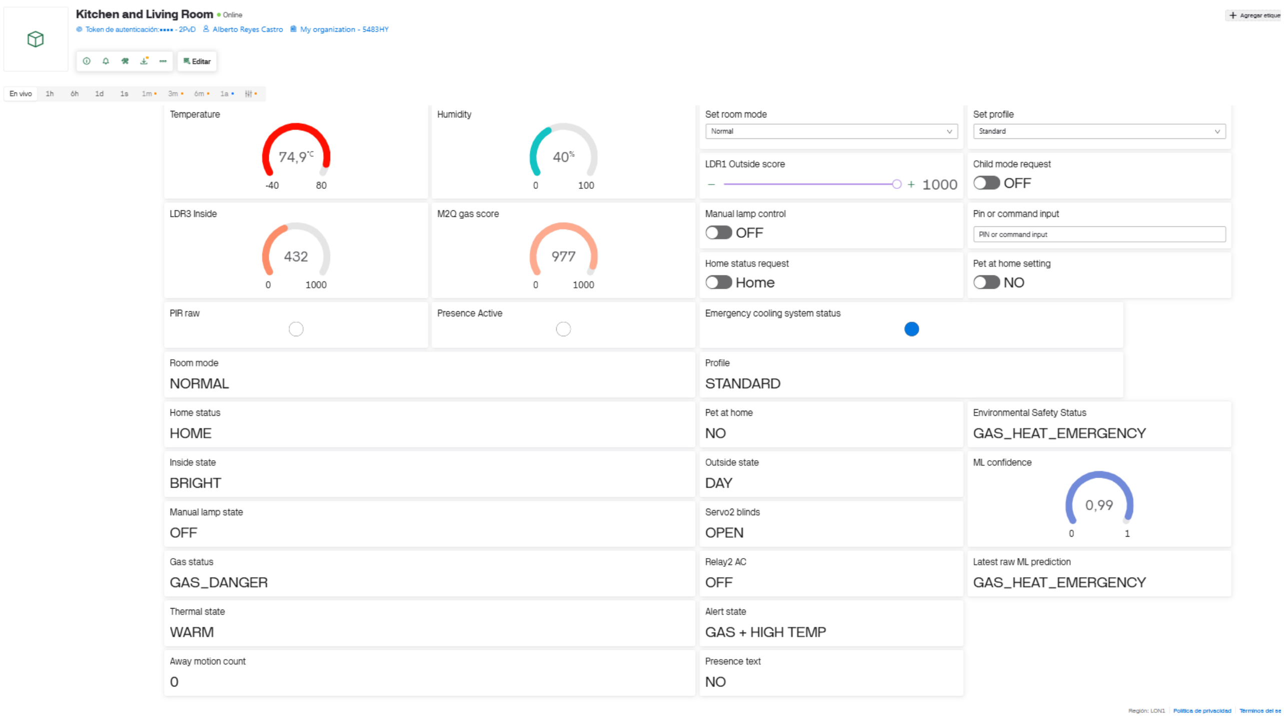
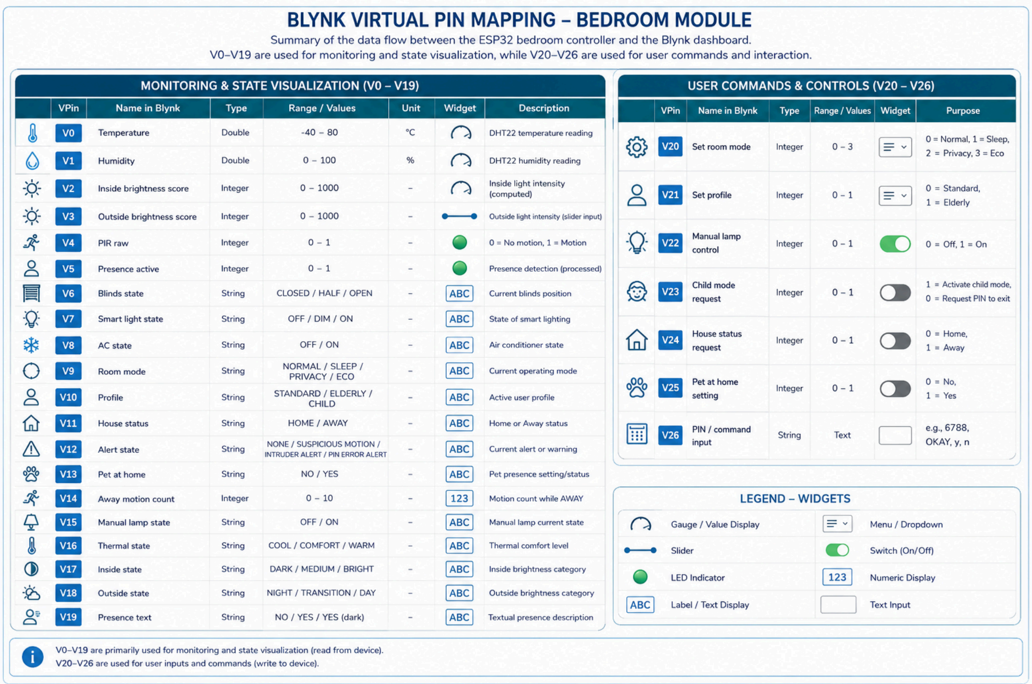


Figure 35: Blynk dashboard for the kitchen/living room module. This interface follows the same remote monitoring approach as the bedroom dashboard, while giving greater emphasis to thermal control, shared space operation, gas safety monitoring, AI environmental safety classification, model confidence, latest prediction visibility, and emergency cooling response.



BLYNK VIRTUAL PIN MAPPING – BEDROOM MODULE

Summary of the data flow between the ESP32 bedroom controller and the Blynk dashboard.
V0–V19 are used for monitoring and state visualization, while V20–V26 are used for user commands and interaction.

MONITORING & STATE VISUALIZATION (V0 – V19)

VPin	Name in Blynk	Type	Range / Values	Unit	Widget	Description
V0	Temperature	Double	-40 – 80	°C		DHT22 temperature reading
V1	Humidity	Double	0 – 100	%		DHT22 humidity reading
V2	Inside brightness score	Integer	0 – 1000	–		Inside light intensity (computed)
V3	Outside brightness score	Integer	0 – 1000	–		Outside light intensity (slider input)
V4	PIR raw	Integer	0 – 1	–		0 = No motion, 1 = Motion
V5	Presence active	Integer	0 – 1	–		Presence detection (processed)
V6	Blinds state	String	CLOSED / HALF / OPEN	–	ABC	Current blinds position
V7	Smart light state	String	OFF / DIM / ON	–	ABC	State of smart lighting
V8	AC state	String	OFF / ON	–	ABC	Air conditioner state
V9	Room mode	String	NORMAL / SLEEP / PRIVACY / ECO	–	ABC	Current operating mode
V10	Profile	String	STANDARD / ELDERLY / CHILD	–	ABC	Active user profile
V11	House status	String	HOME / AWAY	–	ABC	Home or Away status
V12	Alert state	String	NONE / SUSPICIOUS MOTION / INTRUDER ALERT / PIN ERROR ALERT	–	ABC	Current alert or warning
V13	Pet at home	String	NO / YES	–	ABC	Pet presence setting/status
V14	Away motion count	Integer	0 – 10	–	123	Motion count while AWAY
V15	Manual lamp state	String	OFF / ON	–	ABC	Manual lamp current state
V16	Thermal state	String	COOL / COMFORT / WARM	–	ABC	Thermal comfort level
V17	Inside state	String	DARK / MEDIUM / BRIGHT	–	ABC	Inside brightness category
V18	Outside state	String	NIGHT / TRANSITION / DAY	–	ABC	Outside brightness category
V19	Presence text	String	NO / YES / YES (dark)	–	ABC	Textual presence description

USER COMMANDS & CONTROLS (V20 – V26)

VPin	Name in Blynk	Type	Range / Values	Widget	Purpose
V20	Set room mode	Integer	0 – 3		0 = Normal, 1 = Sleep, 2 = Privacy, 3 = Eco
V21	Set profile	Integer	0 – 1		0 = Standard, 1 = Elderly
V22	Manual lamp control	Integer	0 – 1		0 = Off, 1 = On
V23	Child mode request	Integer	0 – 1		1 = Activate child mode, 0 = Request PIN to exit
V24	House status request	Integer	0 – 1		0 = Home, 1 = Away
V25	Pet at home setting	Integer	0 – 1		0 = No, 1 = Yes
V26	PIN / command input	String	Text		e.g., 6788, OKAY, y, n

LEGEND – WIDGETS

	Gauge / Value Display		Menu / Dropdown
	Slider		Switch (On/Off)
	LED Indicator	123	Numeric Display
ABC	Label / Text Display		Text Input

V0–V19 are primarily used for monitoring and state visualization (read from device).
V20–V26 are used for user inputs and commands (write to device).

Figure 36: Virtual pin mapping used for the bedroom Blynk dashboard. The figure summarises the data flow between the ESP32 bedroom controller and the Blynk interface, including monitoring pins, interpreted state outputs, and remote control inputs. In the current design, V0–V19 are mainly used for monitoring and state visualisation, while V20–V26 are used for user commands and authenticated interaction.

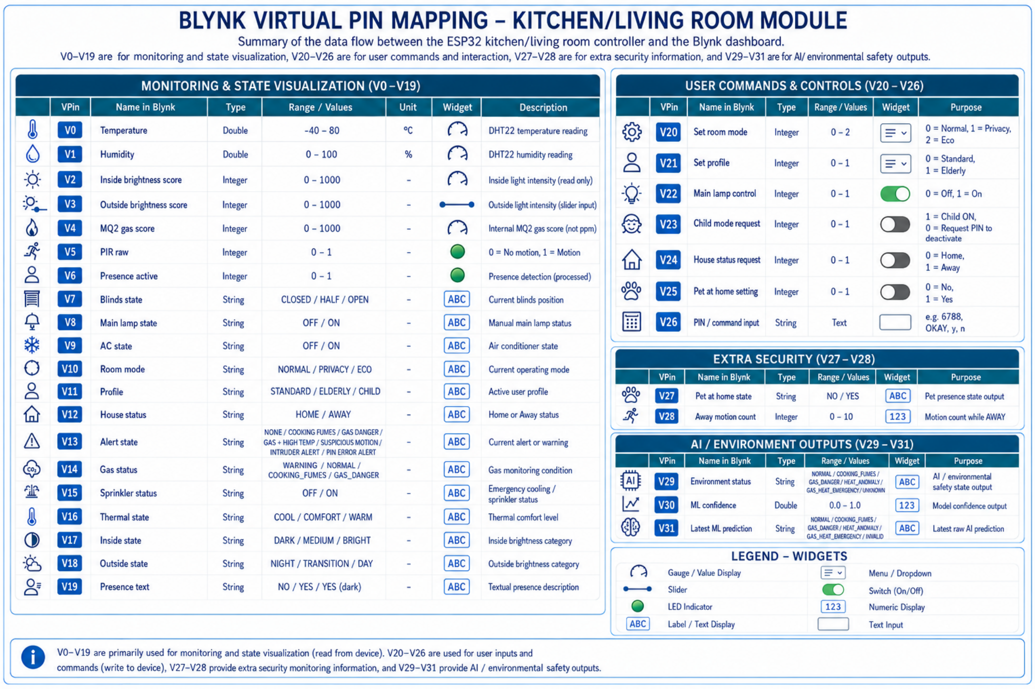


Figure 37: Virtual pin mapping used for the kitchen/living room Blynk dashboard. The figure summarises the data flow between the ESP32 kitchen/living room controller and the Blynk interface, including monitoring pins, interpreted state outputs, remote control inputs, extra security outputs, and AI related environmental safety outputs. In the implemented version, V0–V19 are mainly used for monitoring and state visualisation, V20–V26 are used for user commands and authenticated interaction, V27–V28 provide extra security related information, and V29–V31 are used for AI/environmental safety status, model confidence, and latest raw model prediction.

5.5 Authentication and Security Logic

A recurring feature across the implementation is local authentication for sensitive state changes. Child-mode deactivation and Away-to-Home transition require authentication through the serial interface or Blynk command input, while intruder-alert states use a separate secret-word mechanism for controlled clearance. This adds a modest but meaningful security layer and reinforces the idea that some room states should not be reversible through accidental input.

6 Evaluation

The evaluation is based on scenario testing, simulation behaviour, and Edge Impulse metrics. The aim is not to present a finished commercial product but to assess whether each room behaves coherently under changing environmental and user conditions, and whether the kitchen/living room AI component produces useful environmental classifications.

In the bedroom, the evaluation focused on night-time behaviour, profile-sensitive support logic, occupancy timing, blind transitions, thermal response, and Away-mode alert escalation. Results show that the same room can respond differently under *Standard*, *Elderly*, and *Child* profiles while maintaining a coherent overall behaviour.

In the kitchen/living room, the evaluation focused on gas-reading behaviour, persistence-based safety escalation, AC interaction, emergency-cooling activation, and the relationship between rule-based logic and AI-derived environmental classification. Simulation confirmed the intended behaviour: high gas and temperature produced `GAS_HEAT_EMERGENCY`, activated the *GAS + HIGH TEMP* alert, opened the blinds, turned off the AC, and triggered emergency cooling; when gas fell but temperature remained high, the state moved to `HEAT_ANOMALY`; when both returned to safe values, the system returned to `NORMAL`.

The Edge Impulse model achieved approximately 93.4% training accuracy and 85.9% test accuracy. The held-out test set produced an AUC of 0.99, weighted precision of 0.91, weighted recall of 0.89, and weighted F1 score of 0.89. The strongest results appeared in the most safety-critical classes, especially `GAS_DANGER`, `GAS_HEAT_EMERGENCY`, and `NORMAL`, while most remaining errors occurred around `COOKING_FUMES`. Estimated embedded performance was also suitable for ESP32-S3 deployment, at approximately 1 ms inference time, 1.4 KB peak RAM, and 14.4 KB flash usage.

A key strength of the prototype is that it demonstrates differentiated room logic within a shared architectural framework while also implementing an initial Edge Impulse workflow for environmental safety classification. The main limitation is that the dataset is simulated and rule-labelled rather than collected from physical sensor deployments, so real-world validation would still be required before treating the model as a safety-certified system.

7 Ethical, Privacy & Security Considerations

A main motivation for the project is privacy-aware local decision making. By keeping the main room logic on the embedded controller, the system avoids unnecessary transmission of household behavioural data to external services. This does not remove all privacy concerns, especially because Blynk introduces a cloud-connected dashboard layer, but it reduces the default exposure of raw indoor activity data. This follows a GDPR-style data-minimisation approach: only the information needed for room-state interpretation is processed or displayed, and the main decision logic remains local rather than continuously exporting raw household activity data (Information Commissioner's Office, 2023).

Security is addressed at a basic but meaningful level through protected state transitions, Away-mode alert escalation, local alarm mechanisms, and room-level modularity. The modular structure also reduces dependence on one central controller for the whole house.

Ethically, the project recognises the limits of low-cost sensors and small machine-learning models. This is especially important for gas and safety-related sensing, so the system interprets gas readings carefully through staged escalation rather than claiming chemically precise identification. In the same way, the Edge Impulse classifier is treated as a supportive environmental classifier rather than a certified safety device.

The hybrid architecture is ethically stronger than a fully opaque AI-only approach. Rule-based fallbacks remain active for safety-critical behaviour, while the AI model adds contextual classification. If the learned model is unavailable, uncertain, or unstable in a specific environment, deterministic safety logic still remains.

8 Discussion

This project shows that a smart home can be designed as a set of room-level embedded systems rather than as one undifferentiated automation layer. This is useful conceptually because each room can express its own priorities, and practically because each module can be implemented, tested, and refined separately.

The contrast between the bedroom and the kitchen/living room is one of the main strengths of the design. The bedroom demonstrates profile-sensitive behaviour around timing, support lighting, rest, and privacy, while the kitchen/living room is shaped more strongly by functional comfort, environmental safety, and emergency response.

The Edge Impulse workflow also clarifies the role of AI in the project. The model is not used as a decorative addition or as a replacement for all rules. Instead, it is applied to a specific problem where multi-sensor classification is useful: environmental safety interpretation in the kitchen/living room. Because the dataset was created in simulation and labelled using the project's own safety definitions, the model mainly learns the environmental boundaries designed during development. Its value is therefore not that it outperforms the original rules, but that it demonstrates a complete embedded machine-learning workflow and prepares the system for future real-sensor data. The resulting architecture is hybrid, combining explainable rule-based logic with lightweight learned inference.

At the same time, the prototype remains a staged implementation rather than a finished commercial product. Gas logic still requires real-world calibration, the dataset is simulated and rule-labelled, and the full Edge Impulse runtime could not be executed reliably inside Wokwi. To address this, the Wokwi version uses a simulator-safe inference mode that follows the same five environmental safety classes, while the trained model remains available as an Arduino library for future ESP32-S3 hardware testing.

9 Conclusion & Future Work

This report has presented a modular AIoT smart-home system based on ESP32-S3 room controllers. The project has shown how comfort, privacy, safety, and security can be treated as room-specific behaviours shaped by environment, user context, local control logic, remote monitoring, and lightweight embedded AI.

The bedroom and kitchen/living room modules show that a shared house-wide philosophy can coexist with different room priorities. The bedroom focuses on comfort, privacy, rest, and support for vulnerable users, while the kitchen/living room focuses on shared-space functionality, gas monitoring, heat anomaly detection, and emergency response.

A significant outcome is the Edge Impulse environmental safety classifier for the kitchen/living room. The model classifies five states using gas score, temperature, and humidity, achieves 85.9% test accuracy, and shows suitable embedded performance. The system incorporates this classifier within a hybrid architecture in which rule-based safety logic remains active as fallback.

Future work should focus on five areas: real ESP32-S3 hardware testing with the exported Edge Impulse Arduino library; expansion of the dataset with real MQ2 and DHT22 readings; calibration of gas thresholds and persistence timings using physical hardware; extension of the model with `COLD_ANOMALY` detection and heater response; and further refinement of the Blynk dashboards to improve user feedback, alert history, remote authentication flow, and visual presentation of the already implemented AI-related outputs.

The broader value of the project lies in its architecture. Rather than treating AI as a decorative add-on to conventional automation, the project develops an edge-oriented smart home in which local reasoning is already central, making embedded AI both technically meaningful and conceptually justified.

References

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M. and Ayyash, M. (2015) ‘Internet of Things: A survey on enabling technologies, protocols, and applications’, *IEEE Communications Surveys & Tutorials*, 17(4), pp. 2347–2376.

Aosong Electronics (n.d.) *DHT22 / AM2302 Digital Temperature and Humidity Sensor Datasheet*. Available at: https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf (Accessed: 20 April 2026).

Blynk (n.d.) *Blynk Documentation*. Available at: https://docs.blynk.io/ (Accessed: 20 April 2026).

Dutta, L. and Bharali, S. (2021) ‘TinyML meets IoT: A comprehensive survey’, *Internet of Things*, 16, Article 100461.

Edge Impulse (n.d.a) *Edge Impulse Documentation*. Available at: https://docs.edgeimpulse.com/ (Accessed: 20 April 2026).

Edge Impulse (n.d.b) *Run Arduino library (IDE 2.0)*. Available at: https://docs.edgeimpulse.com/docs/run-inference/arduino-library (Accessed: 20 April 2026).

Espressif Systems (n.d.) *ESP32-S3 Series Datasheet*. Available at: https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf (Accessed: 20 April 2026).

Information Commissioner’s Office (2023) *Principle (c): Data minimisation*. Available at: https://ico.org.uk/for-organisations/uk-gdpr-guidance-and-resources/data-protection-principles/a-guide-to-the-data-protection-principles/data-minimisation/ (Accessed: 20 April 2026).

Merenda, M., Porcaro, C. and Iero, D. (2020) ‘Edge machine learning for AI-enabled IoT devices: A review’, *Sensors*, 20(9), Article 2533.

Ray, P.P. (2018) ‘A survey on Internet of Things architectures’, *Journal of King Saud University – Computer and Information Sciences*, 30(3), pp. 291–319.

Shi, W., Cao, J., Zhang, Q., Li, Y. and Xu, L. (2016) ‘Edge computing: Vision and challenges’, *IEEE Internet of Things Journal*, 3(5), pp. 637–646.

Singh, R. and Gill, S.S. (2023) ‘Edge AI: A survey’, *Internet of Things and Cyber-Physical Systems*, 3, pp. 71–92.

Stojkoska, B.L.R. and Trivodaliev, K.V. (2017) ‘A review of Internet of Things for smart home: Challenges and solutions’, *Journal of Cleaner Production*, 140, pp. 1454–1464.

Warden, P. and Situnayake, D. (2019) *TinyML: Machine Learning with TensorFlow Lite on Arduino and Ultra-Low-Power Microcontrollers*. Sebastopol, CA: O’Reilly Media.

Wokwi (n.d.) *Wokwi Documentation*. Available at: https://docs.wokwi.com/ (Accessed: 20 April 2026).

Zhengzhou Winsen Electronics Technology Co., Ltd. (n.d.) *MQ-2 Manual*. Available at: https://www.winsen-sensor.com/d/files/newpdf/mq-2-%28ver1_6%29---manual.pdf (Accessed: 20 April 2026).

A Appendix A: Additional Simulation Figures (Wokwi)

This appendix includes a small selection of Wokwi screenshots rather than every possible scenario (as there are many of them). The most useful examples are an Away mode alarm, gas alert, and activated smart lights (when inside state is dark, manual lamp is off and motion detected in the dark), as these demonstrate the main behaviours without overloading the appendix.

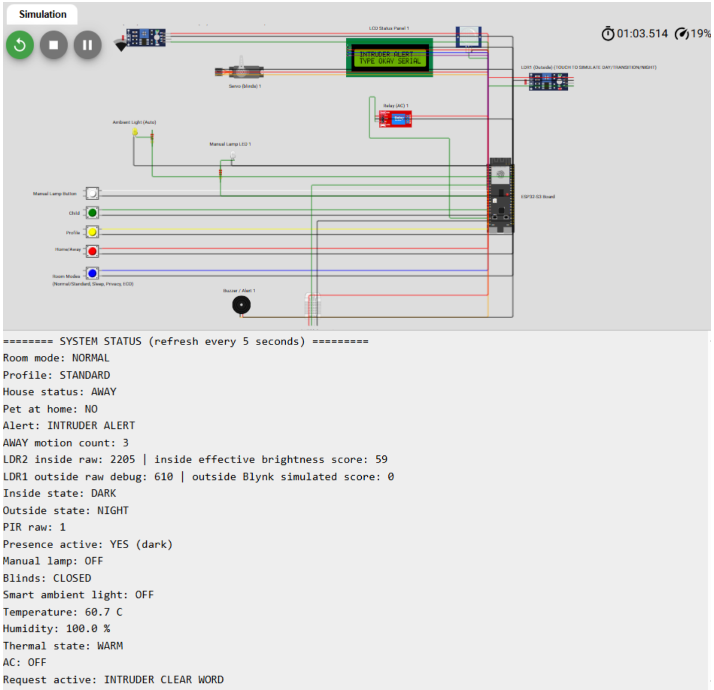


Figure 38: Intruder Alert (bedroom)

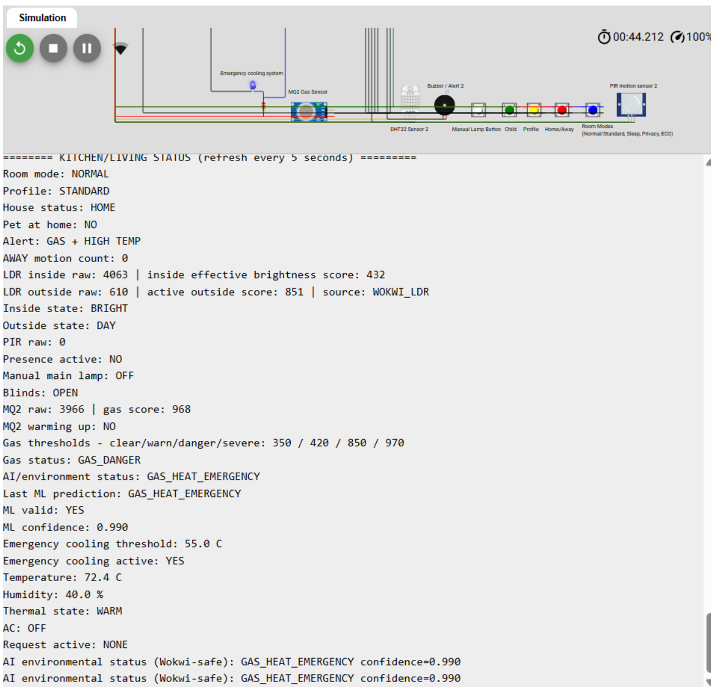


Figure 39: Alert of gas and high temperature (emergency cooling system activated)

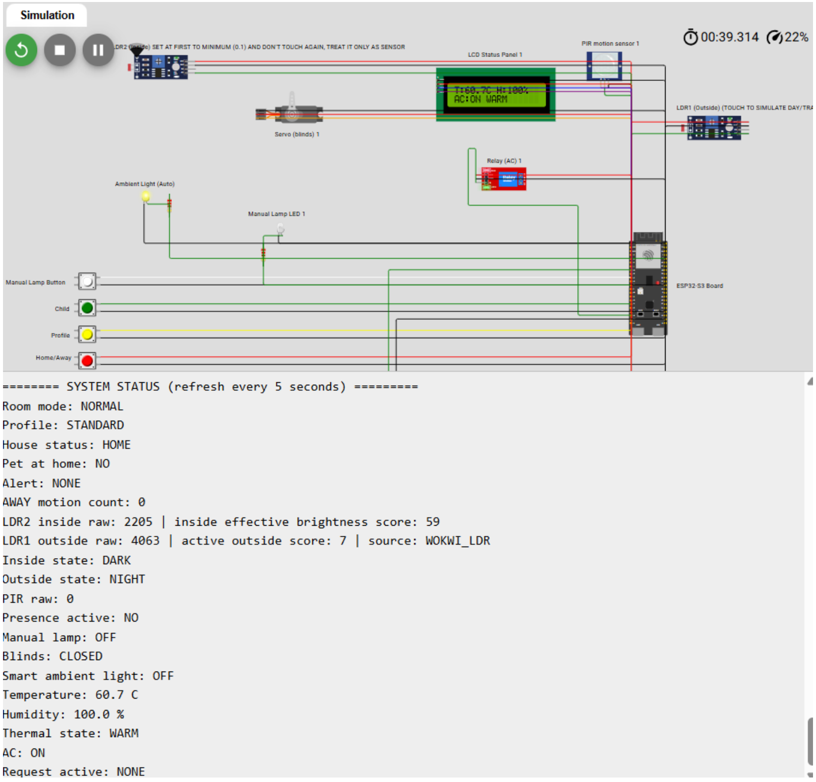


Figure 40: Smart lights ON

B Appendix B: Google Drive Link to Report Material

All links, .zip files, code files, datasets, and supporting materials are available here:

https://github.com/albertoreyescastro/aiot-smart-home-esp32-wokwi.

C Appendix C: Brief User Guide

C.1 Purpose

This project implements a modular ESP32-S3 smart home prototype with two room modules: a bedroom and a kitchen/living room. The system supports local sensing, automated room behaviour, Blynk-based remote monitoring, and an Edge Impulse-based environmental safety layer for the kitchen/living room.

C.2 Required Platforms and Materials

To reproduce the current prototype, the user should have:

- access to the Wokwi simulation links or project files,
- the Arduino/ESP32-S3 source code for each module,
- the Blynk dashboard configuration used during development,
- the exported Edge Impulse Arduino library (for real ESP32-S3 deployment),
- the dataset and supporting screenshots included with the submission materials.

Running the Bedroom Module

1. Open the bedroom Wokwi project.
2. Start the simulation.
3. Use the physical buttons or Blynk controls to change room mode, profile, house state, manual lamp state, and child mode.
4. The outside brightness input is treated as a unified variable. It can be changed either by moving the physical outdoor LDR in Wokwi or by using the Blynk V3 slider.
5. The system uses the most recently changed source as the active outside-light reference.
6. Observe the resulting changes in blinds, smart lighting, AC behaviour, LCD output, Serial Monitor, and Blynk dashboard.

Running the Kitchen/Living Room Module

1. Open the kitchen/living room Wokwi project.
2. Start the simulation.
3. Wait for the initial MQ2 warm-up period before interpreting gas-related states.
4. Adjust gas, temperature, humidity, motion, and brightness conditions in the simulator.
5. As in the bedroom module, outside brightness is treated as a unified input and can be changed either through the physical outdoor LDR in Wokwi or through the Blynk V3 slider, with the most recently changed source taking control.
6. Observe the resulting environmental safety state, gas alerts, AC behaviour, blinds response, buzzer activation, emergency cooling indicator, LCD output, Serial Monitor, and Blynk dashboard.

Important Simulation Notes

- In the final implementation, **outside brightness is treated as a unified simulation input**. It can be controlled either by moving the physical outdoor LDR in Wokwi or by using the **Blynk V3** slider.
- The system uses **the most recently changed source** as the active outside-light reference.
- The **indoor LDR is still used by the embedded logic**, but for consistent demonstrations it is recommended to place it at a low value initially and then leave it unchanged, so that it behaves as a stable internal reference.
- **Sleep mode exists only in the bedroom module**. The kitchen/living room module uses only Normal, Privacy, and Eco modes.
- In the kitchen/living room module, the **MQ2 warm-up period is 15 seconds**. During this period, gas readings should not be interpreted as final environmental states.

Blynk Interaction

Blynk is used for remote monitoring and selected control. The dashboards display key sensor readings, room states, safety-related outputs, and selected control variables. The user can also issue selected commands such as mode changes, profile selection, lamp control, and authenticated requests where supported.

In the bedroom module, Blynk is also used as one of the possible sources for outside-brightness simulation through V3. In the kitchen/living room module, the final dashboard also includes AI-related outputs, allowing the user to observe the environmental safety status, model confidence, and latest raw model prediction alongside the main room variables and safety states.

Edge Impulse / AI Operation

In the kitchen/living room module, the environmental safety logic is based on a hybrid structure combining rule-based gas escalation and a machine-learning-based environmental classifier using gas score, temperature, and humidity. In the Wokwi version, a simulator-safe inference mode is used because the full Edge Impulse runtime caused instability in simulation. On real ESP32-S3 hardware, the exported Arduino library can be enabled for full inference testing.

Main Alerts and Responses

The most important expected system responses are:

- **SUSPICIOUS MOTION / INTRUDER ALERT**: triggered in Away mode after repeated motion detection.
- **COOKING_FUMES**: medium gas level interpreted as likely cooking vapour or fumes.
- **GAS_DANGER**: dangerous gas-related condition requiring defensive response.
- **HEAT_ANOMALY**: abnormal temperature without dangerous gas.
- **GAS_HEAT_EMERGENCY**: dangerous gas combined with abnormal heat; activates emergency cooling indication and defensive room behaviour.

Authentication and Protected Actions

Some state changes require authentication:

- **Child mode deactivation** requires the system PIN (**1234**)
- **Away to Home transition** requires the system PIN (**1234**).
- **Intruder alert clearance** requires the secret word (**OKAY**).

These commands can be entered through the Serial Monitor and, where supported, through the Blynk command input. The PIN and secret-word values used in this prototype are for demonstration purposes only and can be replaced with stronger credentials in a real deployment.

Current Limitations

The current prototype is primarily simulation-based. The dataset used for the Edge Impulse model was generated in Wokwi and labelled according to the system design. The full model runtime was prepared for ESP32-S3 deployment, but Wokwi-safe inference was used in simulation due to simulator instability. Therefore, full hardware validation remains part of future work, even though the current prototype already exposes the main AI-related outputs through the kitchen/living room Blynk dashboard.