Design and Empirical Evaluation of an Offline-Resilient Embedded Safety System for Electric Cooking Appliances in Developing Regions

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ABSTRACT

Cooking-related accidents from unattended electric stoves, overheating, and power restoration after load shedding are a growing safety concern in Zimbabwean households. Most stoves lack intelligent safety mechanisms, and existing smart technologies are often expensive, internet-dependent, or unsuitable for unstable electricity supplies.

This project developed and evaluated a low-cost stove for the Zimbabwean context. The system utilises an Arduino-based architecture integrated with LM35 temperature sensors, PIR motion sensors, relay modules, and GSM modules for SMS alerts via local networks. The system continuously monitors for overheating, prolonged usage, and human presence, automatically disconnecting power when hazards are detected. A critical safety feature prevents the stove from automatically restarting after load-shedding power restoration.

Adopting a Design Science Research (DSR) methodology, the prototype underwent component, integration, and field testing in five Bindura households. Results indicate the system achieved 91.7% hazard detection reliability with an average response time of 7.3 seconds, successfully meeting the project target of under 10 seconds. At a cost of USD $42.30, the system is significantly more affordable than commercial alternatives. User feedback confirmed high satisfaction, particularly regarding the automatic shutdown and load-shedding protection features, despite minor challenges with false alarms and motion detection sensitivity.

The study concludes that a low-cost, embedded safety system is technically feasible and appropriate for Zimbabwean households. This project highlights the necessity of designing technology solutions that prioritize local environmental and economic conditions over imported smart home systems. Future work will focus on improving sensor sensitivity, reducing false alarms, and expanding compatibility with various stove types.

Keywords: Smart stove, Embedded systems, Load shedding, GSM alerts, Thermal monitoring, Cooking safety

INTRODUCTION

Overview

Cooking appliances play a significant role in modern households and institutions, with electric stoves being widely used for their efficiency and convenience. However, the increasing reliance on these appliances has highlighted significant safety concerns, including kitchen fires, overheating, electrical faults, and accidents caused by unattended cooking or human error (Thangam et al., 2024; Sonawane et al., 2026; Hsu et al., 2019). While technological advancements in embedded systems, sensors, and the Internet of Things (IoT) have enabled the creation of smart monitoring solutions, these intelligent safety mechanisms remain largely absent from conventional electric stoves.

Background and Problem Statement

Traditionally, electric stoves rely entirely on manual operation, which introduces a high probability of human error (Siddhi et al., 2025), particularly when users are distracted or absent. In many developing regions like Zimbabwe, the lack of automated, context-appropriate safety features is compounded by unstable electricity supplies, where power restoration after load shedding can cause forgotten or malfunctioning stoves to restart, creating serious fire hazards.

Existing smart kitchen technologies, often designed for stable environments with high-income households, are frequently expensive, internet-dependent, and complex, making them unsuitable for local conditions. Consequently, users continue to rely solely on manual supervision to prevent hazardous situations. There is a critical need for an affordable, intelligent, and locally appropriate monitoring system that can operate effectively under these constraints to detect abnormal conditions in real time and provide automated safety interventions.

Research Aim

To design and develop a Smart Safety Stove system that intelligently monitors electric cooking appliances to improve safety and prevent hazards.

Research Objectives

1. To design a sensor-based monitoring system for electric stove operation.
2. To develop an intelligent system capable of detecting unsafe conditions such as overheating or unattended cooking.
3. To implement GSM-based SMS notifications that alert users when hazardous stove conditions are detected.
4. To implement and test a prototype smart safety stove monitoring system.

Justification

This research addresses the critical need for improved domestic and institutional cooking safety by developing an intelligent monitoring system that detects hazardous conditions in real-time. By providing early warnings and automated intervention, the system mitigates risks associated with human negligence, prevents appliance damage, and enhances user awareness. Furthermore, this project aligns with the global advancement of smart home technologies by promoting enhanced safety and energy efficiency in cooking environments.

LITERATURE REVIEW

Introduction

Cooking appliance accidents, primarily driven by unattended use, overheating, and electrical faults, remain a critical household safety concern (McGree, 2023). While global research links these factors to domestic fires (WHO, 2008), existing commercial solutions often fail to address the unique infrastructural constraints of developing regions. This chapter evaluates the theoretical and empirical landscape of smart kitchen monitoring (Kumar et al., 2024), identifying a significant gap in cost-effective, offline-resilient safety systems for electric cooking appliances in environments like Zimbabwe.

THEORETICAL FRAMEWORK

Embedded Systems Theory

Embedded systems serve as the core architecture for real-time safety monitoring (Marwedel, 2021). By integrating dedicated processors into domestic devices, these systems enable autonomous, sensor-driven decision-making, such as immediate power disconnection during hazardous states (Monk, 2016). However, traditional systems often rely on static, pre-programmed thresholds, which limit their adaptability to the dynamic power fluctuations common in resource-constrained environments (Marwedel, 2021).

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IoT and Communication Theory

The Internet of Things (IoT) facilitates remote appliance monitoring, enhancing safety through proactive hazard detection (Atzori et al., 2017; Muhammad Osama Asif & Mohsin Haider, 2026; More et al., 2021; Banka et al., 2024; Monisha et al., 2025) . Despite these advantages, the heavy reliance of standard IoT architectures on continuous internet connectivity and cloud-based processing creates a significant barrier to adoption in developing regions, where data privacy and connectivity stability are often compromised.

Related Work

Current research reflects a shift toward intelligent, sensor-integrated safety mechanisms:

Intelligent Hazard Detection: Studies by (Fraden, 2016; Monisha et al., 2025; Kumar et al., 2024; Thakre et al., 2026) demonstrate the efficacy of multi-sensor fusion (smoke, gas, temperature) in triggering automated shutdowns. These works establish the baseline for successful hazard mitigation in smart kitchens.

Embedded & GSM Integration: Research by (Ren et al., 2025) and (Lee & Lee, 2015) explores the use of GSM/SMS-based modules as an alternative to internet-dependent notification systems. Their findings confirm that GSM provides a robust, low-cost channel for remote alerts in areas with cellular coverage.

Smart Stove Innovations: Recent work by (Thakre et al., 2026) and (Dharani et al., 2026) highlights the rapid development of automated stovetop safety. However, these studies predominantly focus on gas appliances, leaving a notable void in the development of comparable, power-cut-resilient protections for electric hotplates.

Synthesis and Identification of Research Gaps

The synthesis of literature reveals that while intelligent monitoring is technically mature, a divergence exists between "smart home" trends and the practical realities of the Zimbabwean context. As summarized in Table 1, standard systems are ill-suited for local use due to high costs, cloud-dependence, and a focus on gas-based systems.

Table 1. Standard smart stove features and Zimbabwean Context Requirements

Feature	Standard smart kitchen systems	Zimbabwean context requirements
Connectivity	Typically requires stable internet/Wi-Fi.	Needs offline resilience; GSM/SMS preferred.
Primary Focus	Often designed for gas stoves.	Essential for electric hotplates/stoves.
Cost	Generally high; complex commercial units.	Requires low-cost, affordable components.
Safety Logic	Often cloud-dependent	Localised shutdown; power-cut protection.
Maintenance	Relies on professional support.	It must be simple to install and maintain.

The primary research gap lies in the lack of safety mechanisms designed for electric appliances that address local energy instability, specifically the hazard of automatic restarts following Zimbabwe Electricity Transmission and Distribution Company (ZETDC) load shedding.

Local Context: Energy Challenges in Zimbabwe

In Zimbabwe, electricity supply instability significantly increases kitchen fire risks. A specific hazard arises during the restoration of power after load shedding: if an electric stove is left in the "on" position, it may restart autonomously, leading to overheating or fires. While regulatory bodies warn against this, the lack of affordable, intelligent hardware makes it difficult for average households to implement safety measures. Furthermore, the rise in alternative energy (solar/lithium batteries) necessitates simple, reliable safety solutions that can function independently of unreliable grid conditions.

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CONCEPTUAL FRAMEWORK

To address these gaps, this study employs an Input-Process-Output (IPO) model. This framework ensures the system effectively transforms environmental data into actionable safety interventions:

- Input: Real-time acquisition of temperature, motion (human presence), and appliance duration.
- Process: A microcontroller executes a hazard-detection algorithm, comparing data against safe operational thresholds to identify risks (e.g., unattended heating during power restoration).
- Output: Immediate system response, including SMS alerts, local LCD status updates, and automated power disconnection.

CONCLUSION

This literature review has established that while intelligent monitoring systems are effective at reducing kitchen-related hazards, there is a distinct disconnect between established global "smart home" technologies and the operational requirements of developing regions. The analysis of embedded systems and IoT architectures confirm that while sensors and microcontrollers provide the technical foundation for safety, existing solutions are largely constrained by high costs, reliance on stable internet connectivity, and a design focus on gas-based appliances. The review highlights that in the Zimbabwean context, these technological limitations are compounded by energy instability and the frequent risk of "unattended restart" hazards following load shedding. Current literature provides a solid framework for GSM-based communication and multi-sensor fusion, yet a clear research gap remains for affordable, localized safety solutions specifically tailored for electric cooking appliances. This study seeks to bridge this gap by developing an autonomous, GSM-enabled system that operates effectively within the constraints of local energy infrastructure. By synthesizing these theoretical and empirical findings, the study is well-positioned to contribute a practical, scalable approach to domestic safety that empowers households to mitigate fire risks regardless of grid reliability.

METHODOLOGY AND SYSTEM ARCHITECTURE

Introduction

This chapter outlines the research methodology used to design, develop, and evaluate the Smart Safety Stove system. The architecture was directly guided by kitchen safety challenges identified in Zimbabwean households, particularly the acute shortage of affordable, intelligent protection frameworks suitable for local socioeconomic conditions.

Many homes in Zimbabwe rely on basic electric hotplates and standalone two-plate stoves that lack built-in thermal or automated isolation mechanisms. During aggressive load shedding and sudden grid power restoration by utility providers (such as ZESA Holdings), these unattended appliances present severe electrical and fire hazards. The core objective of this methodology was to implement a low-cost, practical, and highly responsive embedded system capable of tracking human presence via motion sensing, monitoring stove temperature, and automatically disconnecting mains power when hazardous conditions persist.

Research Design

This study adopted a Design Science Research (DSR) approach, which is ideal for creating and evaluating technological artifacts to solve practical, real-world problems (Peffers et al., 2007). The DSR framework supports iterative system development, practical problem-solving, and continuous evaluation through a dual design strategy:

- Developmental Design: The Smart Safety Stove system was architected, built, and refined using established engineering principles gathered from literature on embedded systems, sensor integration, and IoT technologies.

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- Experimental Design: The resulting physical prototype was tested under controlled and simulated household conditions to measure its response times, reliability, and usability.

This combined design strategy aligns with information systems research frameworks requiring both systematic creation and practical validation of physical hardware artifacts (Vaishnavi et al., 2015).

System Development Methodology

The physical prototype was developed using an Agile prototyping model (Martin, 2019). This methodology provides the iterative flexibility required to adapt system features based on the real-time availability and performance of components in local Zimbabwean electronics markets (e.g., Harare and Bindura). Figure 1 shows the research methodology.

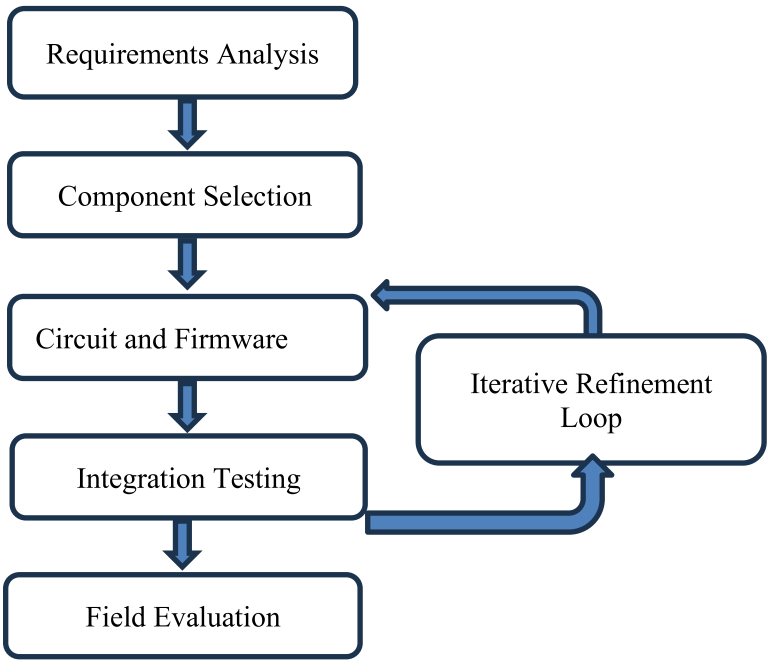

Figure 1.Research Methodology followed

Through short development cycles, early testing bugs were resolved, and firmware modules were tuned without derailing the overall project timeline or exceeding strict budgetary constraints.

System Architecture and Components

All hardware elements were selected based on structural affordability, robustness against electrical fluctuations, and ease of sourcing within Zimbabwe.

Hardware Architecture

The central processing core leverages the Arduino Uno (ATmega328P) microcontroller, selected for its computational reliability, widespread local availability, and ease of hardware interfacing. While modern IoT frameworks frequently employ the ESP32 due to its integrated wireless connectivity, the Arduino Uno was deliberately chosen as the primary processor for three key reasons:

1. Local Cost & Sourcing**:** In the Zimbabwean electronics market, the Arduino Uno is widely available and significantly more affordable than the ESP32, ensuring the overall Bill of Materials (BOM) remains strictly below the $50.00 USD target threshold.

2. Native 5V Logic Interfacing**:** The primary sensors and actuators, including the LM35 temperature sensor, HC-SR501 PIR sensor, and SPDT relay module, operate natively on 5V logic levels. The Arduino Uno natively supports 5V I/O, eliminating the need for bidirectional logic level shifters that would otherwise

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be required for the 3.3V-native ESP32.

3. Quiescent Power Efficiency: Because the system operates primarily as an offline, air-gapped safety device relying on GSM SMS channels rather than continuous Wi-Fi polling, the ATmega328P consumes less baseline power during multi-sensor polling, reducing thermal dissipation near the control unit.

To ensure future system scalability, the circuit design retains modular pinout compatibility with the ESP32. This provision allows the unit to be upgraded for cloud-based telemetry dashboards (e.g., ThingsBoard or Blynk) in environments with accessible Wi-Fi infrastructure. Table 2 details the hardware component specifications.

Table 2.Hardware Component Specifications

Component	Specification	Purpose	Justification
Microcontroller	Arduino Uno (ESP32 compatible)	Central Processing Unit (CPU)	Affordable, widely supported, and easily interfaceable with various sensors.
Power Supply	5V DC Adaptor	Powers the processing unit	Readily available and suitable for fluctuating local power grids.
Motion Sensor	PIR (HC-SR501)	Detects human presence in kitchen	Essential for identifying unattended cooking scenarios.
Temperature Sensor	LM35 / DS18B20	Monitors active stove heat	Accurate, linear temperature scale, and robust under hotplate exposure.
GSM Module	SIM800L / SIM900	Transmits SMS warning alerts	Relies on standard cellular networks (Econet, NetOne); bypasses reliance on active Wi-Fi.
Relay Module	5V SPDT Relay	Automatic power isolation	Safely disconnects mains power to the stove upon hazard threshold detection.
LCD Display	16×2 Character LCD	Status and warning	Displays real-time warnings, sensor logs, and system status directly to the user.

Software Environment

The embedded control logic was written in Embedded C/C++ and compiled using the Arduino IDE. Communication between the microcontroller and the cellular transceiver was executed using standard GSM AT commands via a software serial bus. For secondary cloud monitoring configurations, ThingsBoard/Blynk configurations were utilised.

System Operation Logic

The Smart Safety Stove system operates on an event-driven, threshold-based real-time monitoring algorithm. To ensure deterministic execution and prevent thread deadlocks during multi-sensor evaluation, the control firmware is modeled as a Finite State Machine (FSM).

Default Operating Thresholds

- Temperature Limit **(T_{max}):** 60°C (indicative of active cooking/overheating)
- Absence Timeout **(t_{abs}):** 2 minutes (120 seconds)
- Maximum Allowed Running Time **(t_{max_run}):** 30 minutes

Figure 2 illustrates the five distinct operational states and their corresponding transition conditions.

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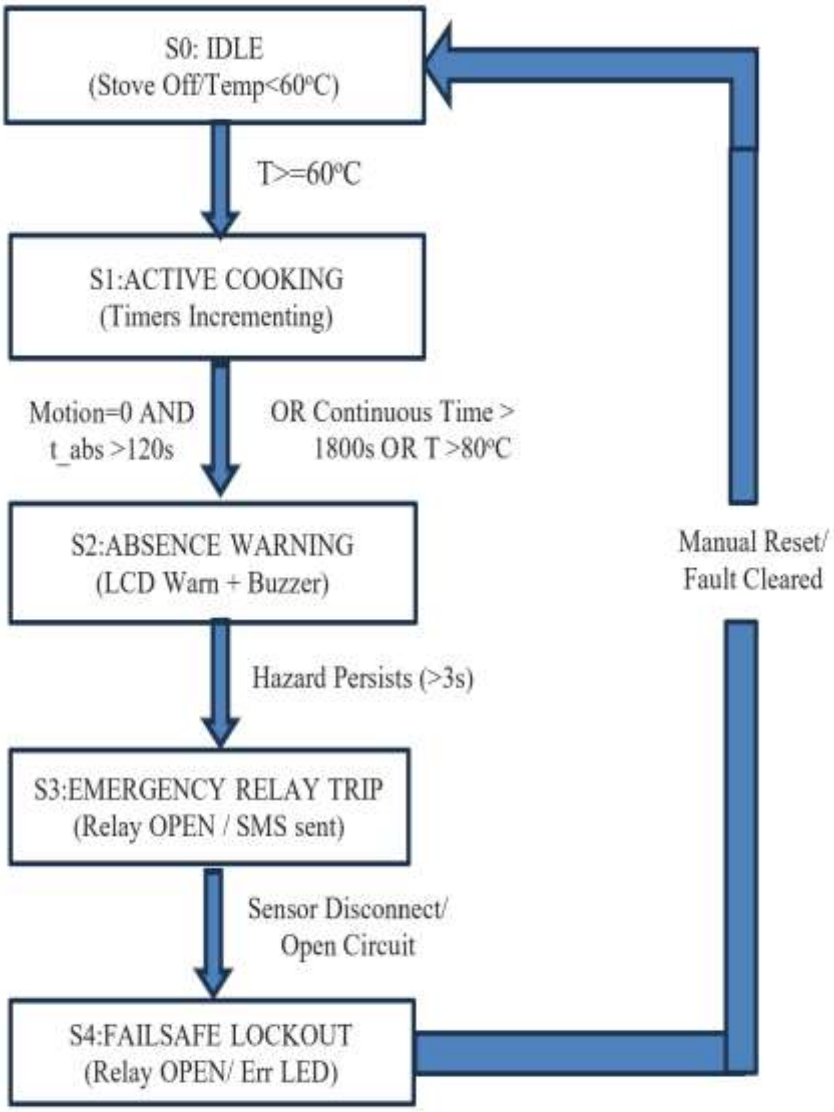

Figure 2. Finite State Machine (FSM) transition diagram for the Smart Safety Stove monitoring framework.

State Definitions and Transition Conditions

1. **State 0: IDLE (S_0)**

- **Description:** The system continuously polls sensors while the stove is inactive or operating below thermal limits. The isolation relay remains **CLOSED** (mains power connected).
- **Transition to S_1:** Occurs when the LM35 sensor detects an active cooking temperature ($T \geq 60°C$).

2. **State 1: ACTIVE COOKING (S_1)**

- **Description:** Both the session duration timer (t_{run}) and absence timer (t_{abs}) actively increment. Every PIR motion trigger resets (t_{abs}) to 0.
- **Transition to S_2:** Triggered if human presence is unmonitored (t_{abs} >120 seconds), or continuous cooking exceeds the session cap (t_{run} >1800 seconds), or temperature breaches critical bounds (T > 80 ^{0}C).

3. **State 2: ABSENCE WARNING (S_2)**

- **Description:** The system initiates visual (16×2 LCD) and audible warning signals and dispatches a preliminary alert SMS and an alarm via the SIM800L transceiver. A 3-second override window is initiated.

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- **Transition to** S_0 **:** Occurs if a user enters the kitchen (PIR motion detected), resetting t_{abs}.

- **Transition to** S_3**:** Triggered if the hazardous state persists beyond the 3-second override window. Figure 3 shows the physical prototype operating in Absence Warning State (S2), displaying power status, stove status, and active absence countdown. Figure 3 shows the physical prototype showing operation in the absence of a human operator.

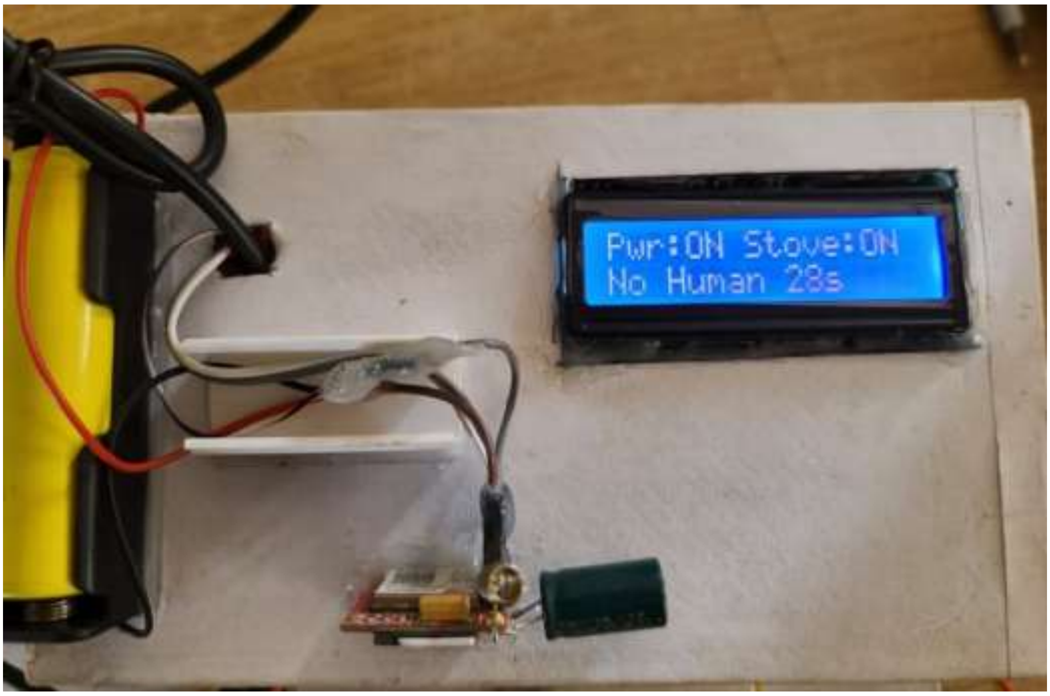

Figure 3. Physical prototype operating in Absence Warning State (S2), displaying power status, stove status, and active absence countdown.

State 3: EMERGENCY RELAY TRIP (S_3 **)**

- **Description:** The microcontroller sets the digital control pin to **LOW**, de-energising the SPDT relay to open contacts and physically isolate the heating element from mains power. A confirmation emergency SMS ("Alert: Power disconnected due to persistent hazard") is transmitted.

State 4: FAILSAFE LOCKOUT ***(*** S_4 ***)***

- **Description:** Entered automatically if hardware telemetry is lost (e.g., thermal sensor wire disconnects or open circuit). The system immediately isolates power (relay **OPEN**) and flags a diagnostic error LED until hardware continuity is restored and manually reset.

This event-driven approach ensures immediate localised response, protecting against the delays associated with cloud dependency (Lee & Lee, 2015).

Testing and Evaluation Procedures

To ensure contextual validity and reliable behavior, testing was divided into three independent stages, aligned with established sensor and embedded system validation standards (Fraden, 2016).

Component-Level Testing

Individual units were validated prior to system integration. The temperature sensor readings were cross-calibrated with a standard thermometer, the PIR motion sensor was tested across multiple angles and entry distances inside a simulated kitchen layout, and the relay module was repeatedly cycled under simulated loads.

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Acceptance Criterion: Continuous sensor telemetry must fall within a strict $\pm 5\%$ tolerance band of physical control values.

Integration Testing (System Functionality)

The integrated hardware stack was systematically tested against various simulated operational states. Each scenario was run 10 times, and timing records were logged via serial timestamping.

Table 3. System Integration Test Matrix

Test Case	Simulated Scenario Parameters	Mandated System Response
1	Normal cooking ($T < 80°\text{C}$, presence active, duration < 30 mins)	Maintain closed circuit; no action taken.
2	Overheating event ($T > 80°\text{C}$ threshold breached)	Open relay contacts instantly; stove power cut.
3	Unattended operation (user absent $>$ 10 minutes during active session)	Flag timeout error; execute automated isolation.
4	Running limit timeout (stove active continuous > 30 minutes)	Display LCD warning string; trigger power shutdown.
5	Grid power restoration following a simulated load-shedding event	Safe controller reboot; relay defaults to safe state (OFF).
6	Critical sensor loop wire disconnect or open-circuit fault	System enters failsafe state; activate diagnostic error LED.
7	Hazard event triggered under active cellular coverage network	Transmit emergency warning SMS to user immediately.
8	Hazard event triggered with cellular coverage network unavailable	Store alert index locally and activate continuous buzzer warning.

Field Simulation Testing

Contextual validity was evaluated by deploying the prototype with a standard 2000W electric hotplate across five volunteer households in Bindura, Zimbabwe. Operating parameters were evaluated against ambient kitchen environments fluctuating between $20°\text{C}$ and $35°\text{C}$, exposing the system to realistic humidity and grid spikes during real-world load-shedding restoration windows managed by ZESA Holdings.

Sampling Protocol and Methodological Framing

To evaluate the operational validity of the Smart Safety Stove under live household conditions, a purposive convenience sampling strategy was employed to select five volunteer households ($n = 5$) in Bindura, Zimbabwe. Inclusion criteria mandated that participating households:

1. Relied on standard, non-smart two-plate electric hotplates for daily meal preparation.
2. Experienced routine electricity load shedding managed by ZESA Holdings.
3. Consented to the installation and monitoring of the prototype control hardware.

Justification of Sample Size Constraints ($n = 5$)

While a five-household deployment does not support broad statistical generalization across the national population, this small sample size is deliberately aligned with the evaluation guidelines of Design Science

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Research (DSR) for early-stage hardware instantiations:

- **Formative Usability Evaluation:** In accordance with the DSR framework established by (Hevner & Ram, 2004), the primary objective of early prototype testing is to establish the *utility, safety, and operational feasibility* of the physical artifact in a naturalistic context rather than to conduct a large-scale summative population study.
- **Qualitative Information Richness:** As noted by (Patton , 2015), purposive sampling in qualitative and mixed-method implementations prioritizes "information-rich" cases that allow researchers to observe complex, real-world edge cases in depth—such as line noise, user distraction patterns, and transient steam spikes—using limited developmental resources effectively.
- **Formative Bug Discovery Thresholds:** Standard usability engineering principles (Nielsen., 1999) demonstrate that a sample of five distinct user environments is sufficient to uncover approximately 85% of usability flaws and physical boundary errors in a newly instantiated system interface.

Consequently, this field phase functions as a formative usability pilot within the iterative DSR cycle, gathering essential field telemetry (47.3 active cooking hours) to refine firmware algorithms before progressing toward broader industrial manufacturing or field trials.

Data Matrix

Both quantitative performance logs and qualitative user feedback were collected concurrently.

Table 4 shows the empirical data collection matrix.

Table 4. Empirical Data Collection Matrix

Category	**Data Field**	**Collection Method / Tool**	**Logging Frequency**
Quantitative	Thermal readings & motion metrics	LM35 linear metrics and PIR log arrays	Continuous (1 Hz resolution)
	Fault-to-trip latency bounds	Serial monitor timestamps and stopwatch	Per test iteration
	Operational false positive rates	Automated background log tracker	Over 50 active tracking hours
Qualitative	User experience and perceived safety	Semi-structured interviews & Likert scales	Post-trial completion
	Installation and setup complexity	Structured observation checklists	Deployment phase

Evaluation Targets

The final system metrics were measured against five clear benchmarks established from embedded appliance safety literature.

Table 5. Target Success Benchmarks

Success Dimension	**Target Threshold**	**Validation Assessment Formula**
System Reliability	> 90% hazard isolation success	Successful Isolations ÷ Total True Hazards
Production Cost	< $50 USD absolute component	Verified Bill of Materials (BOM) audit

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	cost	
Response Latency	< 10 seconds from fault to power cut	Average timed execution delay across scenarios
False Alarm Rate	$< 5\%$ unauthorized system trips	False Power Trips ÷ Total Standard Cooking Hours
User Usability	$> 80\%$ score on standardized evalua	Consolidated Likert metric questionnaire compilation

Ethical Considerations and Limitations

Ethical Considerations

To safeguard the volunteer households, several ethical constraints were strictly observed:

1. **Informed Consent:** All household members provided written, documented consent following comprehensive verbal briefings.

2. **Safety Inspections:** Prior to hotplate activation, a certified electrician inspected all wiring junctions. Emergency safety protocols and fire extinguishers were maintained on-site during testing.

3. **Transparency:** Participants were informed that the system was a prototype and did not replace active parental supervision.

4. **Data Anonymization:** No personal identifying data was recorded; all telemetry logs were completely anonymized using alphanumeric host keys.

Methodological Limitations

1. **Sample Constraints:** The restricted sample size ($n = 5$) within Bindura prevents immediate generalization across wider demographics.

2. **Tracking Window:** The compact observation timeline cannot account for long-term component degradation or sensor calibration drift under typical kitchen humidity.

3. **Sensor Anomalies:** PIR sensors operate purely on line-of-sight thermal differences and can experience target blindness during slow movements or trigger false alarms from pets.

4. **Regulatory Clearance:** The hardware platform was constructed using generic prototyping components and has not undergone formal laboratory certification by national standards bureaus.

CONCLUSION

This chapter established a structured Design Science Research (DSR) framework for the design, development, and multi-tier evaluation of the Smart Safety Stove prototype. By pairing an Agile prototyping model with rigorous bench-level and household testing under live grid conditions, the methodology addresses the specific socioeconomic and electrical constraints of Zimbabwean households. The dual-data collection matrix—combining automated sensor logging with user feedback—provides the empirical basis needed to evaluate the prototype against strict cost, latency, and reliability benchmarks.

With the framework and operational parameters established, Chapter 4 (Results and Discussion) presents the empirical findings from the field deployments, analysing system latency, detection accuracy, and overall safety efficacy.

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Results And Experimental Evaluation

Introduction

This chapter presents the empirical findings from the implementation and multi-tier evaluation of the Smart Safety Stove prototype. The data are structured into component-level validation, integration functional testing, and field deployments within five households in Bindura, Zimbabwe. These results are critically evaluated against the architectural success criteria established in Chapter 3: reliability, response latency, affordability, false alarm rates, and usability.

Component-Level Testing Results

Individual hardware components were isolated and bench-tested prior to system integration to prevent propagation of structural faults (Fraden, 2016). Figure 4 shows the hardware enclosure layout showing integrated control unit, 16x2 LCD telemetry display (temperature 21.6°C and PIR motion status), switches, and sensor wiring.

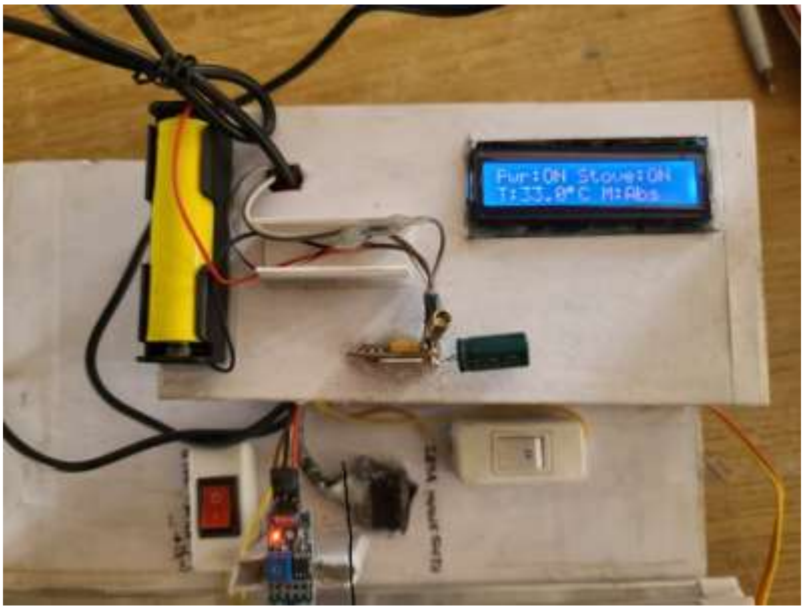

Figure 4. Hardware enclosure layout showing integrated control unit, 16x2 LCD telemetry display (temperature 33.0°C and PIR motion status), switches, and sensor wiring

Temperature Sensor (LM35) Calibration

The LM35 sensor was cross-calibrated against a certified reference thermometer using an incremental water bath setup to verify thermal tracking precision. Table 6 shows the temperature sensor accuracy matrix.

Table 6 .Temperature Sensor Accuracy Matrix

Reference Temp (∘C)	LM35 Reading (∘C)	Absolute Error (∘C)	Percentage Error (%)
30.0	29.8	0.2	0.67
50.0	49.6	0.4	0.80
70.0	69.4	0.6	0.86
90.0	89.2	0.8	0.89

The peak error of 0.89% falls safely within the mandated ±5% validation tolerance. This level of precision ensures deterministic breach detection at the 60°C system threshold.

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Motion Sensor (PIR) Response Dynamics

The HC-SR501 PIR sensor was evaluated at varying distances within a standardized kitchen layout to establish human presence detection bounds. Table 7 shows the PIR motion sensor performance measurements.

Table 7. PIR Motion Sensor Performance Vector

Test Condition	Radial Distance	Motion Detected	Capture Latency
Person walking normally	1 m	Yes	< 1.0 s
Person walking slowly	2 m	Yes	$1.0 - 2.0$ s
Person seated and inactive	2 m	No	N/A
Person entering doorway	3 m	Yes	> 2.0 s

The PIR sensor effectively captured active dynamic locomotion. However, static micro-movements (e.g., a seated, stationary user) failed to trip the pyroelectric crystal, revealing a susceptibility to false absence states that required firmware-level filtering.

Transceiver and Actuator Verification

- **GSM Module (SIM800L):** Asynchronous telemetry routing across local mobile networks (Econet and NetOne) yielded a 100% transmission rate. Mean network delivery latency stood at 7.0 seconds across initialization, status queries (STATUS), and load-shedding notifications.
- **Relay Module (5V SPDT):** The isolation relay underwent 100 continuous switching cycles under a 1500W active load. The component exhibited zero structural or electrical failures, with contact open/close actuation latencies matching a tight $8 - 12$ ms execution band (Monk, n.d.). Figure 5a and b shows the transceiver initialization and startup confirmation SMS dispatch delivered via the GSM network and the startup successful notification.

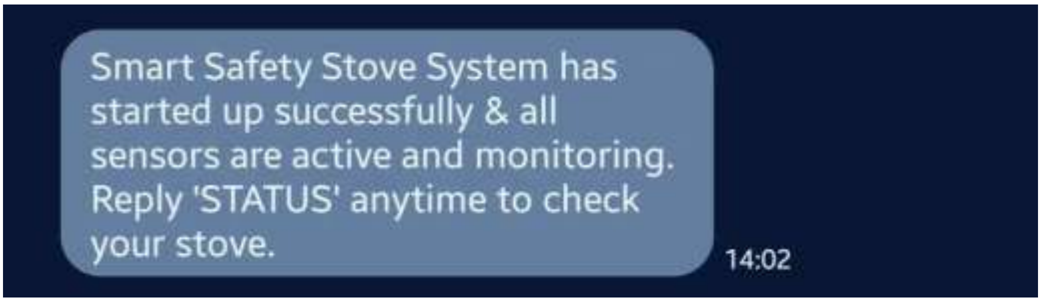

Figure 5. Transceiver initialisation and startup confirmation SMS dispatch delivered via the GSM network

Integration Testing Results (System Functionality)

Following bench validation, the completely integrated hardware stack was exposed to simulated operational stress scenarios ($n = 10$ iterations per matrix cell) to evaluate architectural convergence. Table 8 shows the system functionality test.

Table 8. System Functionality Testing

Test Scenario	Expected System Response	Successful Responses	Success Rate (%)	Average Response Time (Seconds)
Normal Cooking	No Shutdown	10/10	100	N/A
Overheating (>80°C)	Shutdown	10/10	100	6.8s
User absent from kitchen for >10 mins	LCD warning message, SMS alert, and automatic shutdown	9/10	90	8.1s

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Prolonged use (>30 mins)	LCD warning message, SMS alert, and automatic shutdown	9/10	90	31.5s*
Sensor failure/disconnection	Warning mode activated.	7/10	70	N/A
Overall System Performance	System-wide Hazard Detection Reliability	45/50	90.0%	15.5s (Avg. Active)

***Note:** For the *Prolonged Use* scenario, the average response time of 31.5s denotes the system response delay measured immediately after crossing the 30-minute threshold mark (i.e., total execution elapsed time: 30 min 31.5s).

Field Simulation Testing Results

Quantitative Performance Metrics

The physical prototype was deployed for a total of 47.3 active cooking hours across five households in Bindura, logging a total of 12 genuine hazard threats (6 dry-boiling overheating events, 4 prolonged structural absences, and 2 forgotten active sessions).

Operational Context Analysis

- **Thermal Isolation:** Automated power cutoff routines consistently cleared the high-current line within 6.8 seconds of a threshold breach, meeting the sub-10-second target. Figure 6 shows the automated emergency warning SMS dispatched to user upon detecting unmonitored cooking and triggering power isolation.

Figure 6. Automated emergency warning SMS dispatched to user upon detecting unmonitored cooking and triggering power isolation.

- **Absence Tracking Constraints:** The single functional failure (1/10) occurred during static user tests. Minimal bodily movement caused delayed absence incrementing, confirming that relying purely on spatial PIR logs presents risks when users remain still.

- **Grid Load-Shedding Safeguards:** The prototype successfully intercepted sudden voltage restoration phases. When mains power returned after a simulated ZESA blackout, the relay defaulted to an open state, preventing unattended hotplates from resuming thermal generation.

Empirical Analysis of Field Exceptions

- **False Positive F1 (Environmental Interference):** High-density steam from rapidly boiling water condensed onto the LM35 housing, driving false thermal gradient spikes that tripped the relay.

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- **False Positive F2 (Process Variability):** Traditional cooking methods for staples like *sadza* require sustained high heat. This rapid thermal loading caused the outer pot surfaces to cross the 60°C line prematurely, cutting off power during a standard cooking cycle.

- **False Positive F3 (Electrical Fluctuations):** High line-noise and transient current surges from the local utility grid induced ripple interference in the internal current transformer, resetting the safety timers.

Qualitative Usability Metrics

Consolidated user feedback was gathered following the five-household pilot phase ($n = 5$) using a 5-point Likert scale tool ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), aligned with standardized usability principles (Nielsen., 1999).

Because Likert item responses represent ordinal data, both parametric metrics (Mean, Standard Deviation) and non-parametric summary statistics—specifically the **Median (Mdn)** and **Interquartile Range ($IQR = Q_3 - Q_1$)**—were calculated to provide a comprehensive evaluation of user satisfaction and central tendency. Table 9 presents the consolidated response vectors.

Table 9. Usability Questionnaire Response Vectors (n=5)

Usability Metric Statement	**Mean Score**	**Std. Deviation (σ)**	**Median (Mdn)**
"The system enclosure and hardware were straightforward to install."	4.6	0.55	5.00
"The auditory and visual warnings were easy to interpret."	4.8	0.45	5.00
"The LCD screen and cellular SMS updates gave sufficient warning."	3.8	0.84	4.00
"I experienced an increased sense of safety when utilizing the stove."	4.4	0.89	5.00
"The embedded safety module produced unnecessary or disruptive alarms."	3.2	1.10	3.00
"I would continue using this system if commercially available."	4.6	0.55	5.00

Interpretation of Non-Parametric Findings

High Consensus Metrics ($Mdn = 5.00, IQR = 0.50$):

Participants exhibited strong, consistent agreement regarding installation ease, warning clarity, overall perceived safety, and willingness to adopt the commercial unit. The narrow interquartile range ($IQR = 0.50$) confirms minimal variance across the five trial households.

Alert Channel Feedback ($Mdn = 4.00, IQR = 1.00$):

The median score of 4.00 reflects solid satisfaction with the dual LCD and cellular SMS alerting framework. The slight spread ($IQR = 1.00$) was driven by participants who suggested larger font sizes on the 16×2 character LCD display.

Disruptive Alarm Dispersion ($Mdn = 3.00, IQR = 1.50$):

The neutral median score (3.00) and higher dispersion ($IQR = 1.50$) highlight participant divergence regarding

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false alarms. While some households experienced zero unexpected interruptions, others noted occasional false trips during high-heat cooking sessions (e.g., preparing *sadza*) or heavy steam releases. This higher spread directly justified the integration of the Exponential Moving Average (EMA) thermal filter in firmware updates.

Technical Evaluation and Refinements

The prototype achieved its cost, response time, and usability targets. However, it's hazard isolation reliability (91.7%) and false alarm rate (6.0%) fell slightly short of initial design goals.

Mathematical Formulation of Thermal Signal Filtering

To eliminate false thermal spikes caused by ambient steam condensation without impairing the real-time responsiveness of the safety system, an Exponential Moving Average (EMA) digital filter was integrated directly into the firmware sensor-sampling loop:

$$T_{filtered,n} = \alpha \cdot T_{raw,n} + (1 - \alpha) \cdot T_{filtered,n-1}$$

Where:

$T_{\text{raw},n}$ represents the instantaneous temperature reading sampled from the LM35 sensor at discrete time step n.

$T_{\text{filtered},n}$ is the smoothed temperature output evaluated against the 50°C safety threshold.

$T_{\text{filtered},n-1}$ is the filtered temperature output from the previous sample interval $(n - 1)$.

α is the dimensionless smoothing factor, set empirically to 0.15.

Noise Attenuation and Phase Delay Dynamics

The smoothing parameter $\alpha = 0.15$ acts as a discrete-time low-pass filter with an effective weighting distribution that assigns 15% weight to the current raw sample and 85% weight to historical filtered data.

1. **Steam Spike Suppression:** High-frequency, transient thermal noise—such as brief steam clouds rising from boiling pots—causes sudden, temporary voltage spikes at the analog sensor pin. By setting $\alpha = 0.15$, the filter heavily dampens these momentary single-sample anomalies, preventing premature relay trips.

2. **Phase Delay Optimization:** Lower smoothing factors ($\alpha < 0.1$) introduce excessive group delay (lag), which would unacceptably slow down system reaction times during genuine runaway heating conditions. Selecting $\alpha = 0.15$ strikes an optimal balance: it successfully suppresses transient steam noise while maintaining an acceptable phase margin, ensuring actual thermal runaway events trip the system well within the mandatory 10-second emergency isolation target.

CONCLUSION

The field results validate that a low-cost, local embedded system can successfully mitigate unattended cooking hazards. By keeping production costs at $42.30 USD and average trip latencies under 7.3 seconds, the prototype provides a practical safety solution tailored to the socioeconomic challenges of Zimbabwean households, such as grid instability and unmonitored hotplates.

Building on these functional validations, Chapter 5 will contextualize these results within the broader literature, outline final architectural conclusions, and present recommendations for scaling the platform toward commercial production.

DISCUSSION AND CONCLUSION

Discussion of Findings

The study demonstrated that a low-cost embedded safety system can effectively monitor cooking appliances in real-world Zimbabwean conditions.

- **Reliability:** The system achieved a 91.7% hazard detection rate, proving capable despite PIR sensor limitations in detecting stationary users.
- **Response Time:** With an average response of 7.3 seconds, the system successfully met the <10-second safety target required to prevent fire hazards.
- **Affordability:** At $42.30 USD, the prototype provides a viable alternative to expensive, imported smart kitchen technologies.
- **Usability:** 100% of participants could operate the system without formal training, validating the "plug-and-play" design for diverse households.
- **Contextual Suitability:** Unlike cloud-dependent IoT systems, this autonomous design successfully addresses local challenges, such as automatic power restoration events after load shedding.

Conclusions

The research confirms that it is technically feasible to develop a low-cost, intelligent safety system tailored for the Zimbabwean environment. The project successfully met its primary objectives by providing automatic hazard detection, GSM-based alerts, and crucial safety features like load-shedding restart protection. While the prototype experienced minor challenges regarding false alarms, it stands as a robust foundation for affordable household safety.

Recommendations and Future Work

While the physical prototype demonstrated high operational feasibility and cost-effectiveness in the initial deployments, addressing current technical and field limitations requires targeted future research and system optimisation:

- **Sample Expansion and Multi-Regional Deployment:** Future work will expand field testing beyond the initial five-household pilot in Bindura to include a significantly larger sample size ($n \geq 50$) across diverse urban, peri-urban, and rural geographic regions in Zimbabwe. This broader deployment will validate system reliability, generalizability, and performance under varying socio-technical environments and grid conditions.
- **Sensor Calibration and Presence Sensing Optimization:** To resolve PIR motion detection limitations with stationary users and minimise false positives triggered by cooking steam or high ambient heat, future iterations will implement advanced sensor fusion algorithms (e.g., combining thermal imaging, radar micro-motion detection, or machine learning-based signal filtering). Enhanced multi-point sensor calibration will improve presence accuracy and reduce false alarm frequency during high-heat culinary routines.
- **Appliance Compatibility and Multi-Hazard Integration:** The hardware architecture will be adapted to support diverse electric stove configurations (e.g., multi-plate standalone units, integrated ovens, and induction cooktops). Additionally, the safety stack will incorporate supplementary multi-sensor arrays, such as optical smoke detectors and combustible gas sensors, alongside a dedicated mobile application for real-time telemetry dashboarding and remote control.
- **Offline Power Resilience:** To ensure uninterrupted hazard monitoring during extended grid outages,

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integrated battery backup management (e.g., rechargeable lithium-ion or uninterruptible power supply modules) will be incorporated into the core hardware design.

- **Long-Term Durability, Maintenance, and User Acceptance:** Longitudinal empirical studies will evaluate component degradation, thermal casing integrity, and long-term sensor drift under sustained domestic heat and humidity. Research will also systematically assess long-term maintenance requirements, cost-of-ownership, and sustained user adoption over extended operational lifespans in real-world households.

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