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SMART BROODER MANAGEMENT SYSTEM TO REDUCE CHICK MORTALITY RATE USING A BANG-BANG CONTROL ALGORITHM WITH HYSTERESIS :A CASE OF TSONZO WARD 17 SMALL SCALE MUTASA DISTRICT

BY

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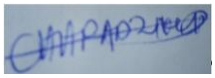
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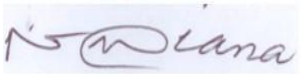
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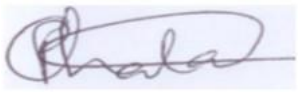
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DEDICATION

This dissertation is dedicated to my mother, M. Dhoro, whose sacrifices, love, and relentless faith in my abilities carried me through every demanding moment of this journey. You never stopped believing in me, even when the road felt uncertain, and for that I am forever grateful. To my uncle, V. Chigwere, thank you for consistently pushing me to trust myself and for reminding me that I am more capable than I sometimes allow myself to believe. Your encouragement came at moments when it was needed most. To the smallholder poultry farmers of Zimbabwe particularly those in the Tsonzo area whose daily struggles inspired the very purpose of this work: this is for you.

ABSTRACT

Chick mortality remains one of the most persistent and damaging challenges facing smallholder poultry farmers in Zimbabwe, with studies documenting mortality rates as high as 80% during the brooding stage alone. The primary cause is the inability of conventional manual brooders to maintain stable temperature and humidity conditions in real time, leaving young chicks vulnerable to environmental stress, hypothermia, and overheating. This dissertation presents the design, development, and evaluation of a Smart Brooder Management System (SBMS) a low-cost, IoT-enabled solution built to address this problem directly.

The system is developed around an ESP32 microcontroller paired with a DHT22 sensor for continuous temperature and humidity measurement. At its core, the SBMS runs a Bang-Bang control algorithm with hysteresis implemented in firmware, which automatically switches heating and humidity actuators on and off to keep brooder conditions within the optimal range for young chicks (32–35°C). The hysteresis band prevents rapid, damaging actuator switching, extending hardware lifespan and improving stability. Sensor data is transmitted wirelessly to a remote dashboard, enabling farmers to monitor conditions in real time and receive alerts when values drift outside safe thresholds.

The system was evaluated over a single brooding cycle in the Tsonzo Small Scale Farming Area, with performance compared against a conventional manual brooder. Results are assessed in terms of environmental stability and chick survival outcomes, with the findings contributing a practical, replicable IoT template for smart agriculture in resource-constrained settings.

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CHAPTER 1: PROBLEM IDENTIFICATION

1.1 Introduction

The production of poultry in Zimbabwe is crucial in enhancing rural livelihoods, ensuring household food security, and providing income for smallholder farmers. For rural households in Zimbabwe, small-scale poultry farming is critical to ensuring household food security through provision of animal protein via poultry products and acts as a source of income and jobs for the poor rural households (Phiri et al., 2023; Melesse et al., 2023). Generally, smallholder farms produce a substantial amount of food globally, emphasizing the need to enhance the efficiency of such farming enterprises.

However, poultry farming is faced with various operations challenges, especially in the brooding process. Manual brooder management involves manually checking temperatures, humidity, availability of feeds and drinking water in the brooders. Conventional brooder management is labour-intensive, ineffective and may lead to inaccurate readings due to human errors, hence poor management of environmental conditions for chick development and growth. Environmental management has been found to be a key challenge that affects the health of chicks and ultimately their survival and productivity (Chigwada et al., 2022).

Furthermore, traditional brooder technology does not offer real-time monitoring or automated regulation of the environment. This poses problems for those farmers who cannot constantly monitor their birds' environment, especially in rural regions where several other farm activities take place at once. Late detection of an unfavorable environment can lead to unnecessary losses.

The emergence of smart agricultural innovations, especially through the Internet of Things (IoT), presents an avenue to overcome these challenges. IoT-enabled systems allow for real-time tracking of environmental factors and automated responses that increase efficiency, minimize labour costs, and facilitate informed decision-making in poultry management (Li et al., 2020).

It is against this background that this research aims to propose the design and construction of a Smart Brooder Management System (SBMS). The SBMS incorporates low-cost sensors, wireless

communication and automation features that track temperature, humidity, feeds and water status in real time. Data collected through the system are analyzed using the Bang-Bang control approach with hysteresis, which automates regulation of environmental factors and transfers data into a dashboard on a mobile application interface. This project is expected to significantly reduce chick deaths and increase efficiency in brooding operations among smallholder poultry farmers in Zimbabwe.

1.2 Background of the Study

Brooding forms part of the most vital processes in the rearing of poultry. The health condition of chicks should be carefully regulated to achieve desired results during the process. Such environmental factors as temperature, humidity, ventilation, feed, and water must all remain at optimal levels during the initial period in their lives. Failing to control the levels can result in stress, disease outbreak, low growth performance, and higher death rates (Khamroev, 2026).

The small-scale poultry production process still relies on conventional brooding methods in most developing nations such as Zimbabwe. Despite the popularity of this method, it is inefficient and lacks continuous monitoring as well as alarm mechanisms for deviations from acceptable levels of these environmental factors.

The incorporation of IoT into agriculture has brought about changes in livestock management by allowing for remote data collection, processing, and analysis of environmental factors. The cost-effectiveness of microcontrollers and sensors has made advanced technology solutions more available for use even by less-resourced farmers. Automated monitoring and control systems have become more common, thus minimizing dependence on labor and ensuring consistent environmental conditions (Li et al., 2020).

The SBMS uses the available technologies to create a combination of sensor-based data acquisition, wireless connectivity, and automated monitoring and control methods. Information regarding temperature, humidity, the amount of food, and the amount of water is collected and processed through the Bang-Bang algorithm with hysteresis and then shown on an application's dashboard.

Considering that there exists a need for cheaper poultry farming solutions, it is possible to conclude that there is potential in developing SBMS in Zimbabwe. Chick mortality can be reduced significantly, which, along with reduced labor requirements and enhanced productivity, can lead to improved rural development and better food security in the region.

1.3 Statement of the Problem

In Zimbabwe, small-scale poultry farmers face unacceptably high mortality rates among young birds in the brooding period. Several studies show this situation. For example, it was found that mortality in brooders reaches 80%. Despite the use of brooders, mortality exceeds 50%. The reason for this is environmental factors, such as cold or hot weather, which cannot be corrected manually. Modern brooders lack sensors, alarms, or recording equipment; therefore, when there are deviations from optimal conditions (such as temperature or humidity), farmers usually notice them too late.

From the technological point of view, the problem is in traditional brooders. They lack automatic control devices and monitoring. Without sensors and records, farmers monitor brooders all the time to provide proper environmental conditions (temperature 32-35°C). Therefore, this solution is inefficient and requires human labor and vigilance. In general, the statement summarizes everything quite accurately: "Manual brooders simply cannot maintain proper environmental conditions, causing mortality." Hence, a solution to this problem lies in the development of an Internet of Things (IoT) technology.

1.4 Aim of the Study

The objective of the paper is to develop an IoT Smart Brooder Management System which incorporates the use of embedded software that features a Bang-Bang controller algorithm to maintain the stability of temperature and humidity ,feed level and water level and thereby increase the survivability of chicks.

1.5 Research Objectives

1. To design and develop an IoT-based Smart Brooder Management System that integrates remote monitoring and real-time alerts, utilizing a **Bang-Bang control algorithm with hysteresis** to maintain optimal environmental conditions.

2. To develop an interactive control interface that enables farmers to remotely toggle ventilation and feeding systems, monitor real-time data, and receive instant anomaly alerts to ensure proactive flock management.

3. To implement an autonomous offline fallback mechanism that enables the system to automatically switch to local control when internet connectivity is unavailable, ensuring uninterrupted brooder operation and environmental regulation

1.6 Research Questions

1. How can software engineering concepts be used to develop an efficient Smart Brooder Management System?

2. Can an algorithm using a Bang-Bang control approach that uses software be used to ensure optimal conditions in the brooder?

3. In what way is automatic monitoring better than traditional monitoring in brooder management?

4. Can a software-controlled Bang-Bang control algorithm that incorporates hysteresis keep brooder temperature and humidity within their optimal values?

5. What benefits will remote real-time monitoring bring in brooder management?

1.7 Statement of Hypothesis

H_0: The Smart Brooder Management System does not significantly improve brooder environmental stability or chick survival rates.

H_1: The Smart Brooder Management System does significantly improve brooder environmental stability and chick survival rates.

These will be tested by comparing stability metrics and survival outcomes between the automated SBMS and a conventional manual brooder.

1.8 Justification of the Study

There are both practical and academic reasons why this research should be carried out. In practice, high mortality of chicks is one of the greatest problems in Zimbabwe poultry farming. Saving even a fraction of mortality, for example, 10%, will translate to millions of more chicks surviving across the country. While traditional brooders demand constant supervision and do not guarantee the absence of loss, an automated SBMS tackles this problem directly by automatically controlling all parameters preventing deadly fluctuations. Indeed, the advantages of automatic systems have been already demonstrated; for example, according to Alam et al. (2023), the implementation of an IoT brooder system "is associated with several advantages such as better monitoring ability, greater efficiency, and reduction in labor".

Technologically, this research showcases how embedded systems and IoT are being used in small-scale farming. By purposefully using cheap off-the-shelf hardware (like Arduino/ESP chips and common sensors), we made sure that it was actually feasible. Our SBMS is scalable and replicable and thus may serve as a case study for other similar projects.

From an academic perspective, this correlation between objectives and outcomes can be represented as follows: Objective 2's use of the Bang-Bang control strategy will result in quick deviation correction, a method that has proven to be efficient in climate control systems according to literature sources. We assume that Objective 3 will prove that there is less variance in brooder environment and higher chicken survival rate.

1.8.1 Assumptions

The research behind the SBMS involves various assumptions concerning the design, implementation, and projected results of the SBMS, which include:

Hardware Availability: It is assumed that the users of the system – smallholder poultry farmers – have access to basic hardware components necessary for the operation of the system. This includes the presence of microcontrollers, sensors, actuators, and constant electricity supply for

the system to function properly (Chigwada et al., 2022). In recent years, affordable hardware options such as Arduino have become more prevalent in agricultural automation (Li et al., 2020).

Sensors' Accuracy and Reliability: The SBMS assumes that sensors employed in measuring the levels of environmental factors such as humidity, temperature, feed, and water levels are accurate and reliable enough for automation purposes. Any minor errors in readings are expected to fall within acceptable operational margins for brooder management (Chigwada et al., 2022).

Internet Connectivity: The SBMS assumes that internet connectivity will be available at all times to allow synchronization between the system and the mobile application, as well as alert notification services. Nevertheless, the unreliable nature of networks in certain rural areas necessitates an autonomous offline mode for the system in case of any disruptions.

Off-line Autonomous Capability: The system is presumed to be able to operate independently when no Internet connection is available by switching to autonomous mode, which allows for local management of the environment based on preset values and the application of a Bang-Bang control system with hysteresis.

Reliable Power Supply: The system is presumed to have a steady power supply for the ongoing operation of sensors, actuators, and control modules. Power interruptions can cause temporary disruptions in the system's performance unless additional measures are taken to ensure the reliability of power supply.

Farmers' Willingness and Familiarity: The system is presumed to be adopted and used by poultry farmers due to the simplicity of the user interface, automation capabilities, and decreased labor needs. Technology adoption is likely to happen when the technology's usefulness and ease of use are considered high (Davis, 1989; Venkatesh et al., 2003).

Environmental Regulation Effectiveness: It is assumed that controlling the temperature, humidity, feed, and water levels would be enough to positively impact the conditions inside the brooder and decrease chick mortality rates even though some other parameters, including disease, genetics, and feed quality, might also affect chickens' performance.

Scalability of Results: It is taken for granted that the results derived from the prototype experiment will be applicable to bigger poultry farms, assuming the environmental conditions, hardware setup, and operating processes remain constant.

In case one or all of these assumptions are found to be not valid, their implications for the efficiency and functionality of the suggested system should be taken into account. Any inconsistencies will be examined in the limitations of the experiment.

1.9 Scope and Delimitations

1. **Geographical Scope :** The study is limited to testing within the Tsonzo Small Scale Farming Area. Environmental conditions, farming practices, and infrastructure in other regions may differ, which may affect the generalizability of the results.

Scope:

Focus is limited to designing and testing a single brooder unit. The system includes hardware (temperature/humidity sensors, microcontroller, actuators) and software (control firmware, communication, and a remote dashboard). Only temperature and humidity are measured and controlled (we assume lighting and other factors constant). The project culminates with a short-term experiment (one brooding cycle, ~2–4 weeks) to evaluate performance.

Delimitations:

- **Controlled Factors:** We exclude other environmental parameters (ammonia, CO_2, airflow) to keep the system simple.
- **Control Strategy:** We implement a basic Bang–Bang (on/off) controller with hysteresis (chosen for simplicity and low cost). We will not explore advanced controls (PID, fuzzy logic) in this study.
- **Hardware:** The SBMS uses a specific microcontroller and sensors (e.g. ESP32 and DHT22). We do not compare alternative platforms or sensor types.
- **Scale and Location:** Testing occurs in one local setting (Tsonzo area). Results may differ in other climates or on larger commercial farms.

- **Timeline:** Evaluation is short-term. Long-term reliability or seasonal variability is not covered.

1.10 Limitations

Despite the potential benefits of the proposed Smart Brooder Management System, several limitations may affect the scope and outcomes of this study.

2. **Limited Testing Duration :** The system will be evaluated during a single brooding cycle, which may not provide sufficient long-term data to fully assess system reliability and long-term performance under varying environmental conditions.
3. **Sensor Accuracy and Calibration :** The performance of the system depends heavily on the accuracy of temperature and humidity sensors. Sensor drift, calibration errors, or hardware malfunction may affect the reliability of environmental readings and the effectiveness of the control algorithm.
4. **Connectivity Constraints :** Since the system relies on IoT communication for remote monitoring and alerts, unreliable internet connectivity in rural areas may limit real-time data transmission and system responsiveness.
5. **Hardware Cost Constraints :** Although the system is designed to be low-cost, the affordability and availability of IoT hardware components may still pose challenges for some smallholder farmers.

1.11 Definition of Key Terms

Smart Brooder Management System: A software-driven IoT system that automates brooder environmental control.

Bang-Bang Control: A control strategy that switches actuators between ON and OFF states.

Hysteresis: A dead-band that prevents rapid actuator switching.

IoT: A network of interconnected devices capable of exchanging data.

Embedded System: A specialized computing system (hardware + software/firmware) built into a larger device for a dedicated function. It typically includes a processor, memory, and I/O peripherals. In SBMS, the microcontroller with its firmware is an embedded system.

Microcontroller: A compact computer on a single chip (CPU, memory, I/O) designed for control applications. It runs the SBMS firmware, reading sensors and driving actuators. Examples include Arduino boards and ESP32 modules.

Sensor: A device that detects environmental inputs (temperature, humidity, etc.) and converts them to electrical signals for the system. In our SBMS, sensors continuously measure brooder conditions. They "bridge the gap between the physical world and the data world".

Firmware: The low-level software programmed into the microcontroller. It directly controls hardware functions. SBMS firmware will implement the control logic and communication routines.

Real-time Monitoring: Continuous data collection and feedback as conditions occur. The SBMS updates temperature/humidity readings every few seconds and can respond immediately.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

First of all, it is necessary to recall that a one-day-old chick is simply not able to regulate its body temperature independently. Until two weeks of age, a chick depends entirely on external heating and this makes it possible for it to maintain the body temperature necessary for survival and further development. This information is important because all mentioned above problems arise precisely because of the need to equip the brooder with adequate heating. In case of hypothermia at 30°C in the first week of life, a chick cannot properly use its energy for growth, spending it on maintaining the necessary temperature. And if the situation is critical enough, it leads to death.

Three main topics are raised in this review. Firstly, there is discussion about the features, possibilities and potential use of embedded Internet-of-Things (IoT) technology in agriculture and the reasons why the change in its price over the past decade makes it practically applicable for smallholder farmers. Secondly, this review pays special attention to the algorithms of operation and communication processes making it clear whether such an automated brooder can work successfully even if some conditions do not meet expectations. Third, it analyzes the scientific literature devoted specifically to small-scale poultry production in sub-Saharan Africa and, particularly, Zimbabwe, which is where the SBMS is meant to operate.

The way that literature will be interpreted here: while it's important to know what an existing technology can do, it's even more important to understand what it takes for that technology to be viable. A technology that is dependent on electricity, broadband access, and computer-literate users is very different from one which is intended to operate independently of such support mechanisms. This difference makes all the difference in the world when deciding what might actually be helpful in rural Mutasa District rather than impressive at university.

2.1.1 Embedded IoT Systems in Agriculture

While 'smart farming' has referred to anything from satellite-guided combine harvesters to WhatsApp groups to discuss weather reports, it can be considered close to worthless as an analytic category in this context. What matters here is the concept of embedded systems that consist of sensors, microcontrollers, and actuators that automate monitoring and management at

the level of a single unit without relying on permanent communication with the remote server. This approach is elaborated on in a relevant way by Li et al. (2021), who distinguish between Internet-of-Things systems based on the use of the network to either monitor or control the system, an essential distinction when dealing with an unreliable network.

The argument that automated monitoring is superior to regular inspections is fairly evident, as a sensor sampling data every five seconds is more likely to find problems that a farmer only checks twice a day. However, a definition of what 'catching things' entails must be established here since this is not merely about increased speed; the real advantage lies in capturing numerous minor discrepancies throughout an entire 28-day cycle, which would otherwise go unnoticed under manual management practices. Indeed, Adebayo et al. (2022) describe this process as moving towards a mode of proactive environmental management from its reactive counterpart. In this sense, a farmer checking at 7am to discover that the temperature in his barn is 28° Celsius is making a reaction to something that might have been going on since midnight. In contrast, an automatic system that has caught it at 12:30am and made changes to prevent further damage is performing something qualitatively different.

The accessibility argument is equally critical, though perhaps not quite as self-evident. Agricultural monitoring systems embedded with microcontrollers were, until very recently, both expensive to produce and difficult to install. However, with the advent of inexpensive, functional microcontrollers like the Arduino, the NodeMCU, and especially the ESP32, all of that changed. As Jayapoorani et al. (2024) describe the significance of this new reality in agricultural contexts, ESP32 systems have reached a point of viability that previously unavailable systems had yet to reach. Of course, there is a qualifier here: while what is affordable in a research project at an Indonesian university may well be different from what is affordable for a Zimbabwean smallholder farmer, the trend is the correct one nonetheless.

2.1.2 Environmental Monitoring in Poultry Farming

During the first two weeks of their lives, chicks have no ability to regulate their body temperature. It is crucial to dwell on this point before proceeding to literature review because this implies that the conditions in the brooder cannot be considered the background of poultry farming but should be seen as a kind of life support system. According to various studies, the optimal temperature for chicks during the first week of their lives is 32-35°C, decreasing by 2-

3°C each week until their capability to thermoregulate arises (Khamroev, 2026). In addition, humidity level is important as well: in case of its being too low, birds lose water by evaporation; in case it is too high, the bedding is wet, which provides breeding grounds for respiratory pathogens.

It is not because of the farmers' lack of attention that traditional management fails; it is the fact that the time interval for manually checking the brooder does not match the biological demands of the chick. A farmer who checks the brooder in the morning and evening has a gap of about 12 hours in his perception of conditions within the brooder. As reported by Adebayo et al. (2022), the mortality rate of chicks kept under conventional management in smallholder farms may exceed 20% and even reach up to 50% when conditions are unfavorable, which corroborates Bayih et al. (2022). This is what traditional management yields not its failure point, but its norm.

Regarding the matter, according to Li et al. (2021), the survey of intelligent technologies for poultry farming demonstrated clear evidence of IoT sensors that detect the presence of any problems much earlier and allow for more rapid response compared to a manual inspection. It is quite believable. However, on the other hand, and here lies a fact the literature review skips, all the devices tested by the authors were used in conditions where there were no failures related to the availability of electricity and internet connection. Thus, whether the difference would be preserved under blackout is another, completely distinct, issue.

2.1.3 IoT-Based Poultry Brooder Control Systems

The work by Ardiansyah et al. (2024) represents the most comparable system technically to the SBMS. It entails the construction of a brooder for the Sentul chickens utilizing the Arduino Uno microcontroller together with a DHT11 sensor and relay-controlled heating lamp. Its control mechanism uses thresholds such that when the temperature falls below the pre-set value, the light turns on, and vice versa. Simple, resilient, and as the authors found out successful in ensuring that temperature variations were eliminated, thus reducing chick stress that occurred manually.

This is definitely a good achievement. However, what should be emphasized about this project is the context within which it was developed. Namely, it was created under circumstances of power availability and Wi-Fi stability in an agricultural facility in a university in Indonesia, with technical support nearby. These cannot be assumed here. The hardware architecture is applicable. The assumptions made are not. This does not imply criticism of Ardiansyah et al.

(2024), whose research focused elsewhere. But it is important to note the limitations of their assumptions here.

The other brooder systems mentioned in the literature, including those based on NodeMCU, those based on Raspberry Pi, the different ESP8266-based solutions, include slight modifications to the layers of the communication and actuators but remain more or less the same. Some may have implemented water monitoring, while others ammonia detection, and yet others may have implemented light cycle schedules for broiler hens. What has been missing all along in these solutions is the fact that there is a need to implement autonomous offline mode as part of the design criteria and not an afterthought.

2.2 Control Algorithms and System Architecture

2.2.1 Bang-Bang Control with Hysteresis

Hysteretic Bang-Bang Control is not a very sexy type of algorithm. It cannot adapt itself, learn anything, or hold the setpoint exactly; it will permit the variable being controlled to oscillate within the hysteretic bounds while switching the actuator between states of on and off. As part of a control theory class in university, this is the first type of control that students are taught before learning PID control and model-predictive controls. For a small brooder farm setup, however, it makes perfect sense.

Fiip et al. (2025) argue that on/off control with hysterisis is the most commonly used type of control in heating and ventilation in modern commercial poultry farms, and provide justification: such control is insensitive to sensor measurement error, is tolerant of the inertial effect of the actuator and communication delay, and is easy to implement and debug. Whereas the PID controller will maintain a narrow band of temperature values, it still calls for the calibration of control parameters to match the heat dynamics of the brooder. Moreover, it is susceptible to noises typical to the sensor readings employed in the case of the agricultural application. A deviation of ±1.5°C in the range from 32 to 35°C that is provided by the hysteresis band does not have a substantial impact on chick well-being.

It was decided to implement bang-bang with hysteresis due to the following. This is not due to the lack of more complicated solutions; rather, their implementation would bring about no benefits, only new issues related to reliability.

2.2.2 Embedded System Architecture

Generally, IoT systems deployed within the field of agriculture use a similar hierarchical model: a sensor node collects measurements, forwards them to a microcontroller, which communicates the information up to a server or a cloud service for executing the necessary controls and sending actuator commands to the node. As described by Fiip et al. (2025), there can also be a distributed version of such system with multiple ESP32-S2 sensor nodes communicating to a control node via ESP32-CAM module. Such an approach suits a large-scale poultry farm with many sensor points but does not make sense for a single brooder.

The SBMS was designed with a completely different idea in mind. All local calculations for the Bang-Bang Algorithm are done locally on ESP32. Only the communication channels for monitoring and overriding controls manually by the farmer are implemented with Wi-Fi interface. The loss of network connections will lead to no changes whatsoever to the actuator logic. Cloud connectivity, if established, adds another channel of communication, which does not have any importance to the functioning of SBMS and thus should not be relied upon. This design decision is conservative and the right one for this environment (Jayapoorani, Srinivasan and Saravanan, 2024).

2.2.3 Remote Monitoring, Alerts, and User Interfaces

It is physically impossible for the farmer to always be present in the brooder. This is a reality of farm operations, not a preference for design, and it is why remote monitoring is necessary. Chigwada et al. (2022), when testing their web-based portal to the Zimbabwe poultry monitoring system, reported that in the responses given by farmers participating in the project, the top feature they appreciated was the ability to view overnight conditions using their phone the next morning. More important than automated controls or even logging of data, just being able to know what had happened overnight without going to see themselves.

Alerts are a separate category of notifications distinct from the dashboard. The former informs farmers about current events once they access the app, while the latter informs farmers something needs to be done regardless of opening the app. According to Li et al. (2021), real-time monitoring, automated control, and early warnings represent the three aspects of effective poultry farming via the Internet of Things. Indeed, without at least one of these elements, the

other two lose their significance. Automated control that does not warn farmers of any issues in the heater relay operation becomes even less effective than manual control as it takes away the option to see what happens manually without providing a substitute.

Therefore, alert generation should occur on the server side and not be part of the mobile application. In case such notifications rely on the application opening, the user will never receive an alert in situations when he/she does not have the application active — e.g., sleeping.

2.3 MQTT and Backend Communication

This issue of which protocol to use between the microcontroller and the backend is actually much more critical than one may think at first glance. REST, the default protocol used by HTTP websites, is a stateless protocol in which the client asks for data from the server, the server gives it, and if there is a disconnection midway through then the data is lost in the process. When you have a sensor that sends data once every five seconds through an unstable mobile network connection over a period of 28 days as part of a brooding cycle, this is obviously a reliability problem.

As one would expect, the MQTT protocol is actually designed specifically to address this kind of problem. According to Al-Fuqaha et al. (2015), MQTT is one of the most commonly-used IoT messaging protocols for constrained and unreliable connections with minimum overhead and quality-of-service guarantees for data delivery in case of interruption. Specifically, messages sent during a network disconnection are stored temporarily and resent upon reconnection when using MQTT on QoS Level 1, as Hunkeler et al. (2008) noted back in 2008.

The backend utilizes a custom Golang server and EMQX as the MQTT broker. The reasons behind choosing to create a custom backend rather than opting for a commercial Backend-as-a-Service solution include dependency on the vendor, unreliable pricing models, and data residency. While Firebase, for instance, allows for much more rapid creation of the system, there are limitations involved that are tolerable in a one-time use case but not in a case of scaling across multiple farms (Takada, 2013). Go as a programming language is suitable due to its static and compiled nature required for the throughput requirements of real-time data ingestion from sensors. In addition, having full control over the backend makes negotiations unnecessary when determining which pricing model to use (Donovan and Kernighan, 2015).

2.4 Feed Management in Automated Brooder Systems

There is an unfortunate lack of focus on feed management within the literature related to IoT brooders. This stems from the fact that temperature management receives far more attention from researchers than feed management due to how directly temperature is associated with acute mortality rates and how much it can be measured. The effects of feed availability are much more indirect and accumulate over a period of several weeks rather than causing acute mortality in a matter of hours.

However, such an oversight may be critical when it comes to smallholder operations. For example, in commercial facilities, feed is delivered to chicks through a process managed by staff members following a predetermined schedule. In smallholder farms, farmers become feed delivery systems. Their schedule is determined by whatever else their farm and family need them to do. Two hours of feed availability deficit during the second week of brooding will not kill the chicks outright but will have a noticeable effect on feed conversion rate and immune system development. However, such windows of feed deprivation are known to be common in manual smallholder brooding and are described by Adebayo et al. (2022).

The HC-SR04 ultrasonic sensing is therefore a feasible option. It takes measurements of the distance from the sensor’s position to the feed surface, increasing as the level falls until a certain limit is exceeded, triggering the dispenser. It requires no contact with the feed and is not influenced by the type or colour of the feed, as well as affordable for use in a smallholder setup (Li et al., 2020). Incorporation of feed monitoring in the same loop as the temperature and humidity ensures that the SBMS tackles the nutritional aspect of brooding.

2.5 Analytics and Production Metrics

Typically, most IoT-based agricultural systems will generate a monitoring dashboard: a visual display showing current data points of sensors and states of actuators. It is useful when making practical decisions: Should I turn the fan now? Is the feeder getting empty? However, it gives the user no indication of how their farm operates compared to past performance since it displays the current data point with no previous context.

One of the main efficiency metrics of poultry farming is Feed Conversion Ratio: amount of feed (in kilograms) required to increase a bird's live weight by one kilogram. The lower the FCR, the

better the operation performs. The majority of smallholder farmers in Zimbabwe do not use it. It does not mean that it is not relevant to them because it definitely has relevance to their bottom line. However, they cannot compute it due to lack of information needed. An IoT device that will store information on each dispenser action and allow weighing once per week will be able to calculate FCR on its own and show the result on its display. (Bayih et al., 2022)

According to Cheng, Zheng, and Shan (2021), discussing learning analytics but making an applicable point regardless, dashboards that only display present metrics provide users with what is going on but not with any strategic decisions for action. Trend analysis, cycle-to-cycle comparison, and efficiency ratios turn a monitoring solution into a decision support solution. This was the principle guiding the design of the SBMS analytics dashboard, but the literature on IoT farming is still lagging behind in recognizing the difference (Susnjak et al., 2022).

2.6 Smallholder Poultry Farming in Sub-Saharan Africa

All of the above must be considered within the context of a particular reality – an agrarian family in rural Zimbabwe facing up to 12 or more hours of load-shedding each day, expensive mobile data relative to the household's earnings, a distance of potentially 40 kilometres to the closest technical support centre, and the farmer juggling the brooder management task with all other responsibilities. Very few pieces of literature focusing on IoT brooders take such farmers into consideration.

Chigwada et al. (2022) stands out as an exception here, and it should be discussed in greater detail. It describes the implementation of a monitoring system for temperature, humidity, water level, and ammonia concentration in village chicken coops in Zimbabwe with the help of ESP8266 hardware. The list of issues arising as a result is interesting: load-shedding causing a failure of the system, the lack of an internet connection preventing real-time synchronisation, the farmer being reluctant to entrust the welfare of their flock of chickens to a digital solution, and difficulty replacing broken parts in the sensors.

These are contextual factors that must be considered in any design, and the bulk of the international literature fails to do so because it has never been implemented under those conditions.

According to Xaba et al. (2026), this is further confirmed in their systematic review of adoption barriers for information and communication technologies in sub-Saharan African poultry production, which finds that poor connectivity, low levels of digital literacy, and insufficient infrastructure are the three most consistently reported barriers.

This needs to be stated clearly: just because an architecture works in an agricultural university laboratory that has stable electricity and broadband does not mean that the same architecture works in Tsonzo Ward 17. The technical hardware could be exactly the same, but the environment is totally different.

2.7 Research Gaps

These three specific gaps in current literature support the need for this research.

First, there is an offline resilience gap in IoT brooder systems. In virtually all cases discussed in existing literature, IoT brooders are cloud-based and thus rely on connectivity for their functioning. For a system deployed in a remote location such as rural Zimbabwe, where electricity outages and network outages are common, it is a matter of complete failure rather than one of degraded performance. An IoT brooder which cannot function automatically when the Wi-Fi is unavailable is no protection at all in the very context in which protection is most needed. Connectivity dependency is pointed out by both Li et al. (2021) and Adebayo et al. (2022). Neither work suggests a solution which takes offline autonomy seriously. The SBMS does.

Second, there is an economic gap associated with smallholder poultry farms. Most existing literature involves systems that were designed either for commercial farms or as theoretical prototypes with no prospect whatsoever for practical cost-effectiveness for a family farming 50-200 chickens under intermittent income. The literature repeatedly highlights this issue without providing a solution.

Thirdly, there is a gap in longitudinal field experiment evidence. Most studies on IoT brooders have presented performance statistics after conducting short-term pilot tests under experimental conditions. Bayih et al. (2022) provide information about mortality in various seasons in smallholder poultry farms in Zimbabwe, where an automatic management system has not been implemented. What remains to be examined is the performance of the system specifically

developed for Zimbabwe, after the completion of the entire brooding cycle, and when comparing mortality and production performance with manual management as the control group.

2.8 Summary

The literature supports the use of hysteresis-controlled bang-bang temperature control, the suitability of the ESP32 controller for smallholdings due to low cost and capability, MQTT as a communication protocol for sporadic-connectivity contexts, ultrasonic sensors to fill nutritional needs not covered by simple temperature controls, and analytics dashboards as a way of providing production metrics that smallholders cannot currently calculate. All of this is well-established and uncontested.

It does not provide a system built for the exact purpose outlined by the constraints in rural Zimbabwe, namely autonomous operation without internet, affordable implementation for smallholders, a back-end that does not depend on proprietary software platforms, and proof of performance during an entire brooding process in situ as opposed to a controlled setting. This is precisely what is attempted with the SBMS system. Each decision taken in Chapter 3 was motivated by this evidence and gap analysis.

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CHAPTER 3: RESEARCH METHODOLOGY

Introduction

This chapter describes the methodology used in the design, development and evaluation of the Smart Brooder Management System (SBMS). This section discusses the research design, population and sampling techniques, data collection instruments and analysis procedures. The chosen framework enables a systematic assessment of the system's ability to maintain optimal environmental conditions and to reduce chick mortality. This section describes the research process clearly from the choice of participants to the technical development of the Smart Brooder Management System.

The chapter is the backbone of the research project since it covers all the necessary components that determine the success of the solution. A lot of time was spent on evaluating and analyzing the data collected, to ensure the integrity of the research and avoid false results.

The methodology incorporates both quantitative and qualitative methods, and the approach was determined by the nature of the research questions and the most appropriate way to evaluate the system's real-world performance.

Research Design and Data Collection Approaches

3.1 Research Design

This study uses the Design Science Research (DSR) methodology. DSR is particularly suitable for technology-driven research where the aim is not only to understand a phenomenon, but also to design, develop and evaluate a purposeful artifact that addresses a real-world problem. The artifact in this case is the Smart Brooder Management System (SBMS) a low cost IoT based environmental control system designed to improve chick survival rates amongst smallholder poultry farmers in rural small scale mutasa ward 17 Zimbabwe.

This study is appropriate for DSR as it offers a structured, iterative framework linking research activities with engineering practice. The methodology is made up of six well defined phases: problem identification and motivation, definition of solution objectives, design and development,

demonstration, evaluation, and communication of findings. Figure 3.1 at the end of this section illustrates this process visually

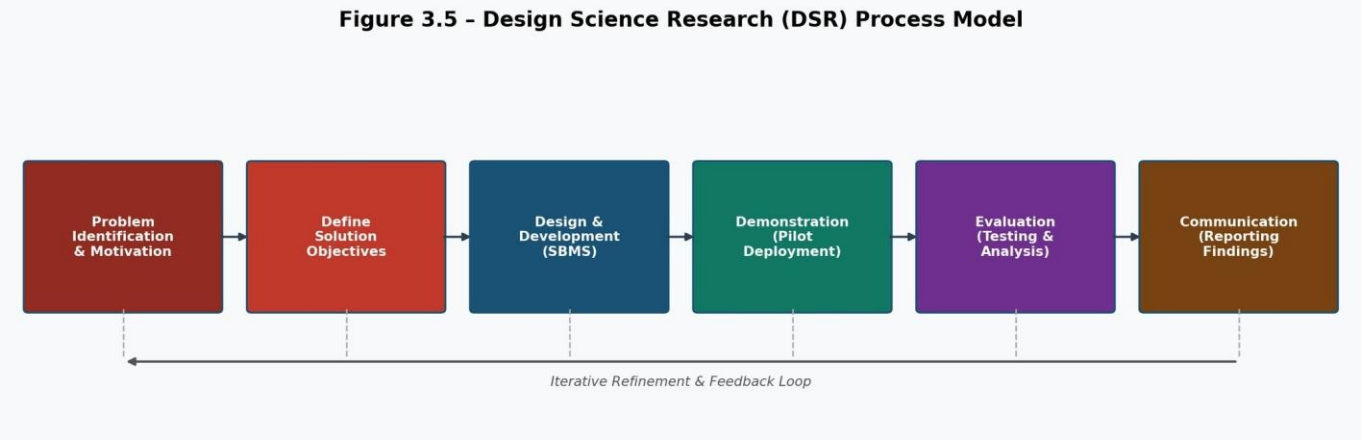


Figure 3.1– Design Science Research (DSR) Process Model Applied to SBMS

The research is academically rigorous and practically relevant. The iterative nature of Design Science Research (DSR) allowed for continuous improvement of the Smart Brooding Management System (SBMS), enhancing hardware configuration, firmware logic, and mobile application features based on observed system behavior and stakeholder feedback during pilot testing. The study utilized a mixed-method data collection approach that combined quantitative sensor data with qualitative observational insights. This methodology provided a comprehensive understanding of the system's performance and measurable evidence to support its effectiveness.

3.1.1 Experimental Research Design

In the DSR framework an experimental research design was adopted to assess the positive impact of the SBMS. This design involved installation of the system in a real brooding environment at Ward 17 Tsonzo Small Scale Area and assessing its perfomance in contrast to a manual brooder used as the control. The experimental design enabled for direct , clear evidence based comparison of the two approaches across the key perfomance indicators outlined in chapter 1 , which are environmental stability, feeding efficiency and chick mortality rates.

Key Comparison: SBMS-controlled brooder (experimental) vs. Traditional manual brooder (control)
Evaluation Period: One full brooding cycle (approximately 2–4 weeks)
Primary Indicators: Temperature stability, humidity control, feed level consistency, chick mortality rate

3.1.2 System Architecture

The SBMS is built across four different interconnected layers which are sensing, processing, actuation and user interface , each serving a distinct function and communicating with adjacent layers through clear interfaces . Figure 3.2 shows the complete system architecture

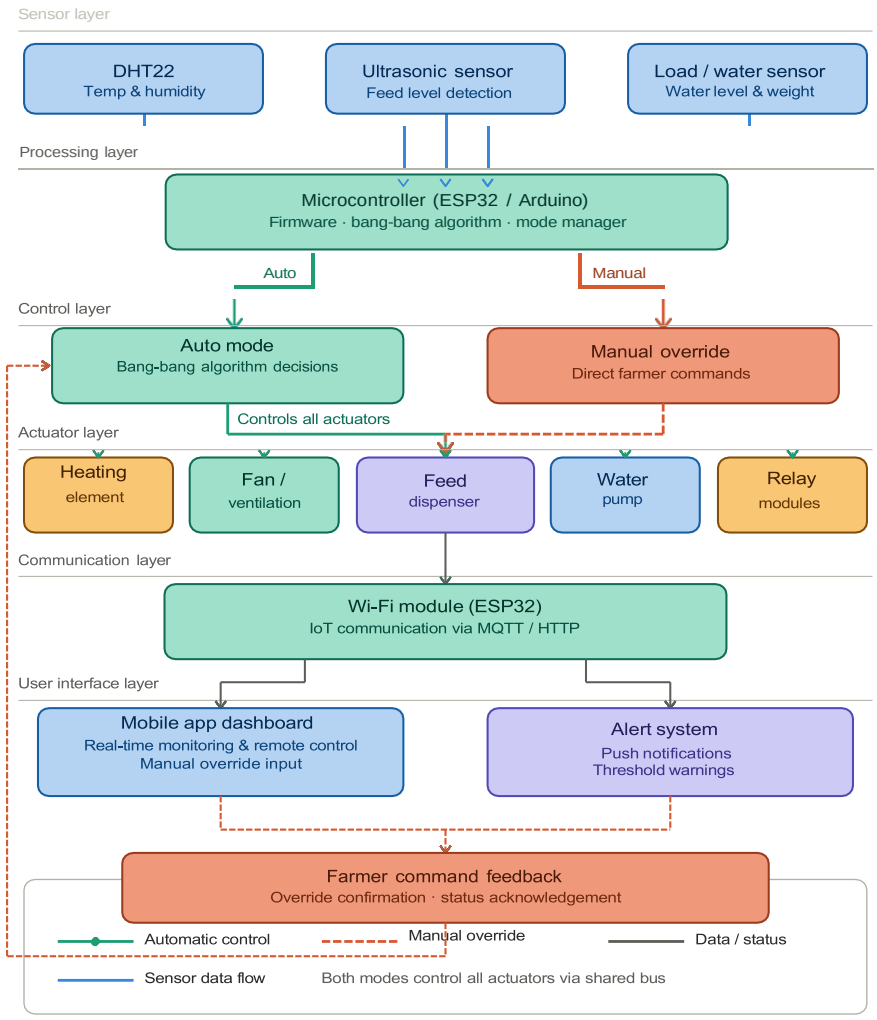


Figure 3.2 – SBMS System Architecture (Auto Mode & Manual Override)

Environmental data is continuously read by the sensor layer. In the middle is the microcontroller (ESP32 or Arduino), which controls two operating modes and runs the control firmware. In Auto Mode, all actuators are automatically driven by the Bang-Bang algorithm using real-time sensor thresholds. In Manual Override Mode, the farmer uses the mobile application to directly operate each actuator while the algorithm is halted. Regardless of the active mode, all sensor readings and actuator statuses are sent to the mobile dashboard over Wi-Fi.

Hardware Component	Role in SBMS
Microcontroller (ESP32 / Arduino)	Runs firmware; coordinates sensors, actuators, and Wi-Fi communication
DHT22 Temp & Humidity Sensor	Measures brooder temperature (°C) and relative humidity (%) in real time
Ultrasonic Sensor (HC-SR04)	Measures feed level by detecting distance to the top of feed in the hopper
Heating Element	Raises brooder temperature when T < threshold temperature controlled via relay
Fan / Ventilation Unit	Reduces brooder temperature when T > threshold temperature; controlled via relay
Feed Dispenser (Servo Motor)	Dispenses feed automatically or on manual command from the mobile app
Water Pump	Supplies water on demand; controllable in both Auto and Manual Override modes
Relay Modules (2-channel)	Electronic switches enabling the low-voltage MCU to control high-voltage actuators
Power Supply Unit	Provides stable regulated power to all system components

3.1.3 Data Collection Approaches

To ensure a comprehensive understanding of the system's effectiveness, usability, and relevance, four complementary data collection approaches were employed. Figure 3.3 illustrates how each data source feeds into the analysis methods and produces the study's key outputs.

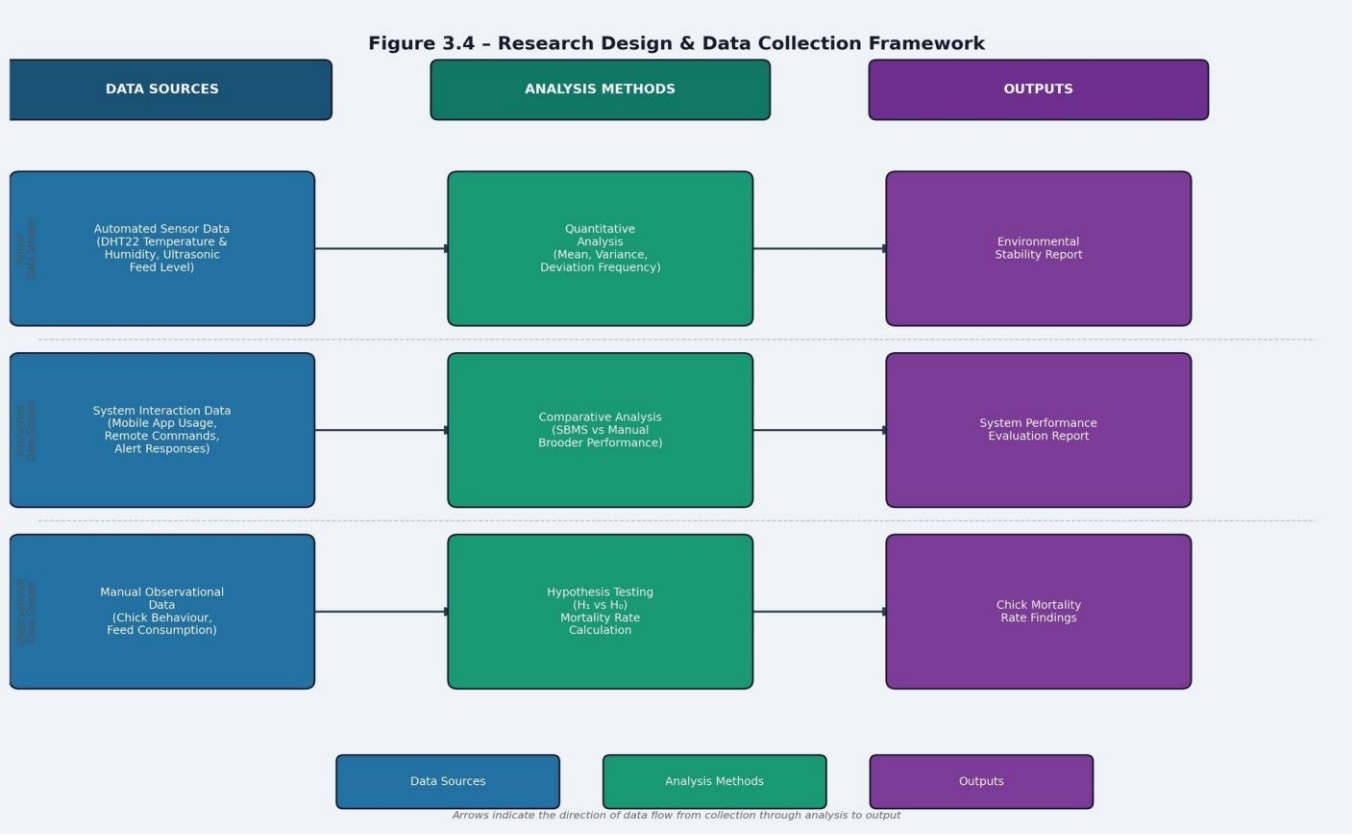


Figure 3.3 – Research Design and Data Collection Framework

a) Automated Sensor Data Collection

The primary quantitative data source is the system itself. The system automatically records and logs temperature, feed level, water level and humidity and actuator states at regular 5-second intervals throughout the brooding cycle The high sampling rate ensures that short-duration temperature fluctuations which can be lethal to day-old chicks are detected and responded to immediately rather than being missed between infrequent manual checks.

b) System Interaction Data Collection

Data is also collected through farmer interaction with the mobile application. This captures records of each remote actuator command issued in Manual Override Mode , which actuator was

targeted, the action taken (ON or OFF), and the exact time of the command. This data is used to assess the responsiveness and usability of the mobile interface and to evaluate how well and how efficiently the system supports real time farmer decision-making.

c) Observational Data Collection

Manual checks were done during the brooding period. We looked at things that sensors can't measure directly.

These included:

- How chicks cluster together (if they are too hot or cold)
- The conditions in the brooder, like Litter quality and Ventilation
- Daily chick survival counts to figure out mortality rates.

The brooding cycle helps us understand chick health. Chick clustering behaviour tells us about comfort. We also track feeding activity and feed consumption.

d) Comparative Data Collection

Performance data was collected in parallel from the manual control brooder. We compared temperature changes how feed was refilled and death rates between the SBMS brooder and the manual brooder at the end of the cycle.This comparison helps us see if the SBMS brooder really works better than the way of brooding.

The SBMS brooder and manual brooder were compared to check if SBMS brooder delivers improvements. The main goal is to check if SBMS brooder's better, than conventional brooding practice.

3.1.4 Control Algorithm — Bang-Bang with Hysteresis

The SBMS firmware uses a Bang-Bang (on/off) control method with hysteresis to keep the brooder’s temperature and humidity where they need to be. We chose Bang-Bang control because it’s simple, doesn’t require much computing power, and works well on small, inexpensive microcontrollers—all of which matter for a low-cost farm setup.

If there were no hysteresis, a basic on/off controller would keep flipping the actuator on and off rapidly whenever the sensor reading hovered around the set-point. That constant chattering wastes energy and wears out the equipment faster. Hysteresis adds a small dead-band between

the turn-on and turn-off points. As a result, the actuator only changes state when the reading crosses a clear boundary not every time it hits the exact set-point.

Heater: ON when T < 32°C | OFF when T > 35°C (dead-band = 3°C)
Fan: ON when T > 35°C | OFF when T < 32°C (dead-band = 3°C)
Humidity: Alert / action triggered when H < 60%; deactivated when H > 70% (dead-band = 10%)

Figure 3.4 presents the complete Bang-Bang algorithm flowchart, capturing every decision point, threshold check, and actuator action in the firmware execution cycle.

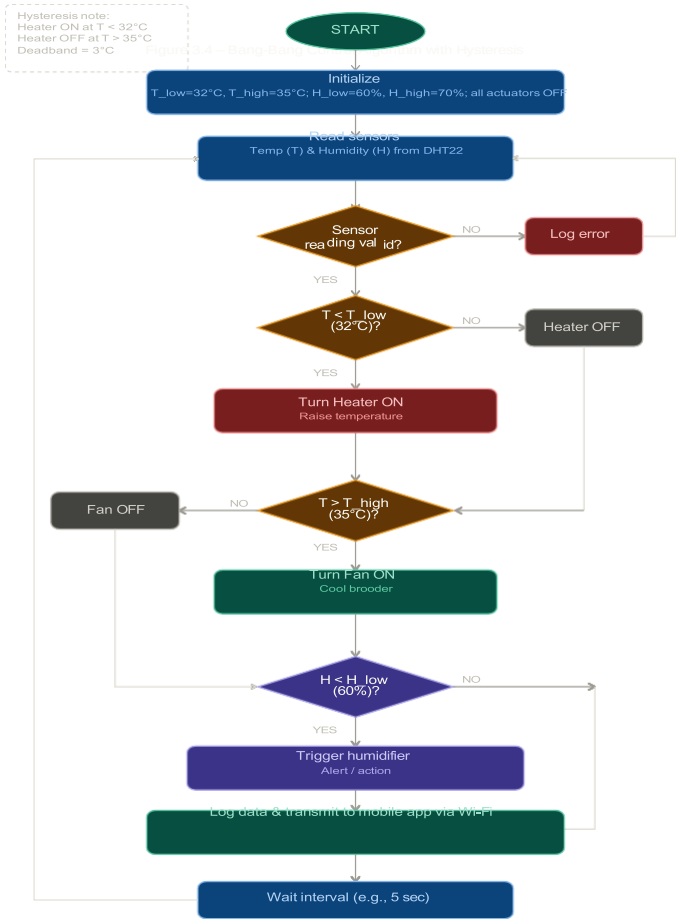


Figure 3.4 – Bang-Bang Control Algorithm with Hysteresis (Firmware Flowchart)

3.1.5 Feed Level Monitoring and Dispensing

Within the system's main program, managing the feed happens as a separate process. The ultrasonic sensor finds how far away it is from the feed inside the hopper. As the chicks eat the feed, the height of the feed gets lower and the sensor's distance reading gets bigger. Once the distance is longer than a set amount, the feed dispenser will turn on by itself when in Auto Mode, or a farmer can start it using the phone app. The dispenser will continue to run until the sensor shows the feed is back to the right level, then it will stop and a record of what happened will be saved. All of the monitoring and dispensing of feed is shown in diagram 3.5.

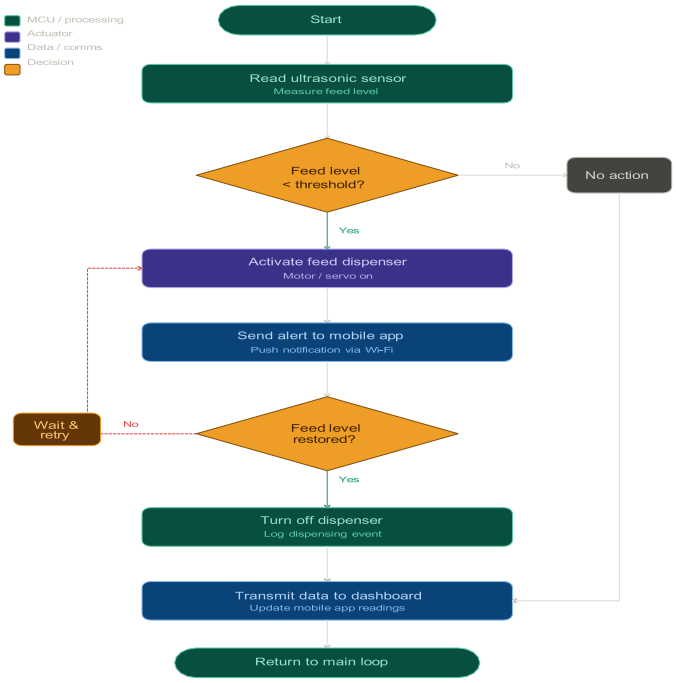


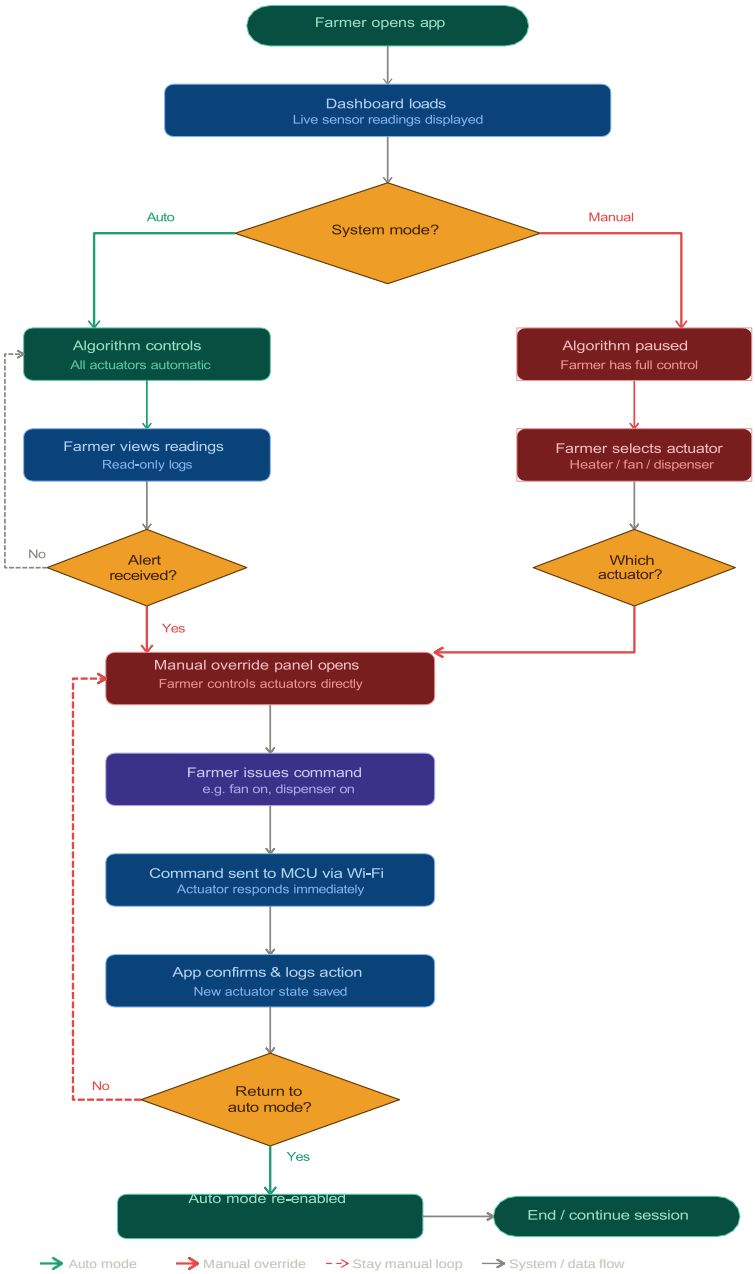
Figure 3.5 – Feed Level Monitoring and Auto-Dispensing Logic Flowchart

3.1.6 Mobile Application — Auto Mode and Manual Override

The SBMS has a really important feature: you can control it in two different ways. In Auto Mode, the system's programming makes all the decisions about what the heaters, fans, etc. do and the mobile app just shows you what's happening, as it happens. But if the farmer selects Manual Override Mode, the programming stops and the farmer can instantly manage each part of

the system directly from their phone, they don't even have to be in the same room as the chicks. In Manual Override Mode, you can switch the heater, fan, feed dispenser, and water pump all on or off.

Each of those instructions is sent from the app to the main computer of the system using Wi-Fi and happens immediately. The app then receives confirmation of the new state of each item and records this information, along with all the readings from the automatic sensors, and the time. Whenever the farmer wants to, they can go back to Auto Mode and the system will begin again, using the current sensor readings - a full restart isn't necessary. The entire process of using the app to control the system in either mode is detailed in Figure 3.6.



3.2 Population and Sample

3.2.1 Population

The target population for this study consists of smallholder poultry farmers and brooding environments in rural Zimbabwe the primary intended users and deployment context of the SBMS. More specifically, the study focuses on the Tsonzo Small Scale Ward 17 Farming Area in Mutasa, selected as it is representative of the resource-constrained rural farming environments the SBMS is designed to serve.

3.2.2 Sampling Technique

Purposeful sampling was adopted, a type of non-probability sampling that was deliberately used to select respondents and contexts that had firsthand experience with brooding chicken. Purposeful sampling, unlike random sampling, ensured that the selected context was able to give practical feedback about the efficiency of the system under evaluation.

3.2.3 Sample

The sampling for this study was done as follows:

1. One brooder facility that is completely equipped with the SBMS hardware and firmware, which formed the experiment group
2. One manually operated brooder using the normal farm practice procedures, which formed the control group
3. One generation of broilers reared for an entire brooding period of between two to four weeks

This kind of sampling was suitable for the nature of the study. The aim of the research was not to make a generalisation statistically over the entire smallholder farming community but to conduct an in-depth analysis of the SBMS in practical situations on the farms. In addition, a single period of brooding was adequate enough for evaluating the stability of the environment, responsiveness of the system, and the mortality rate the three main criteria of assessment in the study.

3.3 Research Instruments

The study utilised both hardware and software instruments for system implementation and data collection. Together these instruments form the complete technical toolkit of the SBMS.

3.3.1 Hardware Instruments

The physical components of the SBMS are the primary instruments through which environmental data is collected and brooder conditions are controlled and monitored. Each component was selected for low cost, wide availability, and suitability for rural deployment.

Hardware Instrument	Function
Microcontroller (ESP32 / Arduino Uno)	Central processing unit; runs firmware, reads sensors, drives actuators, manages Wi-Fi communication
DHT22 Temperature & Humidity Sensor	Captures real-time temperature (±0.5°C accuracy) and relative humidity (±2–5% accuracy) inside the brooder
Ultrasonic Sensor (HC-SR04)	Measures feed level inside the hopper using distance detection; triggers dispensing when level is low
Heating Element (Incandescent Lamp)	Raises brooder temperature when T drops below 32°C; controlled via relay module
Fan / Ventilation Unit	Reduces brooder temperature when T exceeds 35°C; controlled via relay module
Feed Dispensing Mechanism (Servo)	Releases feed into the trough automatically or on manual command from the mobile app
Water Pump	Supplies water on demand; controllable in both Auto and Manual Override modes
Relay Modules (2-channel)	Electronic switches that allow the low-voltage MCU to safely control high-voltage actuators
Power Supply Unit (5V / 12V)	Provides stable regulated power to all system components

3.3.2 Software Instruments

The software components provide the intelligence layer of the SBMS, handling sensor interpretation, automated control decisions, Wi-Fi communication, and the farmer-facing user interface.

Software Instrument	Function
Embedded Firmware (C / Arduino IDE)	Implements the Bang-Bang control algorithm with hysteresis; manages sensor read cycles, actuator switching, Wi-Fi transmission, and event logging
Bang-Bang Control Algorithm	Core temperature and humidity regulation logic; applies defined thresholds with a hysteresis dead-band to prevent actuator chattering (see Figure 3.4)
Wi-Fi Communication Module (ESP32)	Transmits sensor readings and actuator states to the mobile app; receives manual override commands from the farmer in real time
Mobile Application (Android / iOS)	Real-time monitoring dashboard; displays live temperature, humidity, and feed level; provides Auto/Manual mode toggle and individual actuator ON/OFF controls
Data Logging Module	Records all sensor readings and actuator events with timestamps; stores data for post-hoc quantitative analysis in Chapter 4

3.3.3 Data Recording Tools

Data was collected using three complementary tools that ran concurrently during the entire brooding process:

• Automated sensor log files that automatically logged data every five seconds using the firmware, timestamping each reading of temperature, humidity, and food levels

• Application interaction logs that documented all instances of Manual Override executed by the farmer, specifying which actuator was controlled, what action was performed, and the exact time of command execution

• Observation sheets that documented manually noted behaviour patterns of chicks, overall conditions within the brooder, and chick mortality rates

Using a mix of automated and manual data collection tools provided for both quantitative and qualitative data to be systematically collected throughout the experiment period.

3.4 Data Analysis Procedures

Data collected during the study was analysed using quantitative and comparative techniques aligned with the research objectives and hypotheses defined in Chapter 1. The analysis is structured around five procedures.

3.4.1 Environmental Stability Analysis

Mean temperatures and humidity levels were obtained for both the SBMS brooder and the manual brooder from the data collected using the SBMS sensor log. Variance was also determined, along with the number of times temperatures fell outside the ideal range throughout the brooding period. This comparison revealed that the SBMS brooder had less variance and fewer instances where temperatures fell out of the optimal range compared to the manual brooder.

3.4.2 Control System Performance Analysis

The bang-bang control with hysteresis system was assessed based on three parameters: how well it managed to keep the temperature within the limits set for the process, whether hysteresis effectively prevented fast switching of the actuators, and how quickly the response happened when the sensor readings breached the limit. The reaction time parameter was determined using data from the firmware log entries, which include both the timestamp of the sensor reading and that of the actuator state change.

3.4.3 Feed Management Analysis

The feed monitoring subsystem was evaluated in terms of the feed level stability over time, how often and for how long the dispenser operated, and how quickly the dispenser operated after detecting low feed levels. These factors were compared to the manual brooder in which the feeding was totally dependent upon the observation schedule set by the farmer.

3.4.4 Mortality Rate Analysis

Chick survival is the central outcome measure of this study. Mortality rate was calculated daily using the following formula, with final cumulative rates computed at the end of the brooding cycle for both the SBMS and manual brooder groups:

Mortality Rate (%) = (Number of Dead Chicks ÷ Total Number of Chicks) × 100

A lower final mortality rate in the SBMS group relative to the manual brooder group constitutes the primary evidence for evaluating the alternative hypothesis H_1.

3.4.5 Hypothesis Testing

The null and alternative hypotheses defined in Chapter 1 are evaluated based on the aggregated results of the four analysis procedures above.

Hypothesis	Evaluation Criterion
H_0: The SBMS does not significantly improve brooder environmental stability or chick survival rates.	Accepted if no meaningful difference in temperature variance, out-of-range frequency, or mortality rate is observed between the SBMS and manual brooder groups.
H_1: The SBMS does significantly improve brooder environmental stability and chick survival rates.	Supported if the SBMS brooder shows measurably lower temperature variance, fewer threshold breaches, and a lower chick mortality rate than the manual brooder, as evidenced by sensor logs and daily survival counts.

3.5 Summary

This chapter presented the full methodology underpinning the design, development, and evaluation of the Smart Brooder Management System, structured according to the four prescribed sections: research design and data collection approaches, population and sample, research instruments, and data analysis procedures.

Design Science Research methodology ensured that the technical development was carried out using a scientific approach. The design of the SBMS, the bang-bang control strategy with hysteresis, feed management strategy, and auto/manual override mobile interface are described in such detail as to allow reproduction. Data collection was done by recording sensor data, mobile application user interactions, and by direct observation. Analysis procedures, as detailed in section 3.4 for aspects including environmental stability, control efficiency, feed management, mortality rates, and hypotheses are the foundation for results discussed in chapter 4.

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CHAPTER 4: DATA PRESENTATION , ANALYSIS AND INTERPRETATION

The present chapter provides an overview of how the proposed Smart Brooder Management System (SBMS) fared in practical applications. It is at this point that the figures start telling the true story, allowing for comparison between expected results and outcomes of the test run. Environmental data, system logs, and farmers' feedback were all used in order to determine the actual performance of the system under consideration.

Data collected from the following sources allowed evaluating the efficiency of SBMS operation:

Automated Sensors. This group included devices collecting data about temperature and humidity, amount of feed as well as each actuator action. They provided five-second data updates, thus allowing verifying the effectiveness of the process control and its proper functioning.

Farmers' activity in the mobile application. As an expert behind the development of the app, I monitored every action performed by farmers – commands issued, timestamps, and other details. This approach allowed to determine to what extent automation worked without farmers' assistance and whether the application was indeed useful and convenient.

Some phenomena can only be detected using human senses. As such, our observation involved recording chick behavior, their feeding routines, sanitation, litter quality, ventilation, and mortality rate daily. This information complemented the dataset generated by the sensors, providing a more comprehensive understanding of events in the brooding area.

To ensure a level playing field, we also established a manual brooder under similar conditions, and then compared its efficiency with that of the SBMS based on the following criteria: temperature fluctuation, ease of maintaining the feed, and chick mortality rate.

All findings are presented in tabular, graphical, and chart forms to make the reading experience easier for you. Our analysis focuses on extracting insights from the data in terms of environmental stability, speed of reaction, benefits of automation, and general brooder efficiency.

In conclusion to this chapter, you are provided with insight on how SBMS successfully solved practical problems encountered during chicken farming. These are no mere academic findings but provide a concrete indication of what this system is capable of and how far it can go. No matter whether it involves small adjustments, launching upgrades, or adopting in field application of the system, this chapter provides closure to our project.

4.1 Data Presentation, Analysis & Implementation

4.1.1 System Logs

In order to have an accurate overview and assessment of the functioning of the Brooder Management System, an internal logging mechanism has been introduced. The logs capture crucial data regarding the system's functioning. It captures such data as the temperature, humidity, feed level, and water level measurements taken at specific time intervals, device state change information such as when heater, fan, and feeder work, alarm generation events, and IoT device and server communication (Farooq et al., 2022; Zanella et al., 2022).

The idea behind creating these logs is generating reliable data from the backend that could be analyzed for a certain period of time. This allows determining how effectively the brooder creates favorable conditions for chicken growth and development . Environmental logs help understand the trend of chick feeding, the temperature changes, and the humidity above the optimal level in the brooder environment. Such monitoring is crucial in the welfare of chicks in the brooder management system.

Actuator logs allow one to understand whether all such operations as switching on the heater, fan, and feeder have occurred. In automated agricultural systems based on IoT, it is very important to monitor the devices by using feedback logs (Zanella et al., 2022).

The alerts logs also play an important role in assessing and keeping track of the system's responsiveness. They include details about unusual behavior, like overheating or high humidity, as well as the issuing of alerts and how they were sent to the mobile application and failure of sensors or actuators. A recent study on smart farming technologies stresses the importance of real-time alerts to prevent stress in livestock and reduce death rates (Farooq et al., 2022).

Therefore, the data-driven approach outlined provides a solid foundation for a solution. It can be enhanced by user feedback regarding the system's usability. This feedback helps clarify how the application interacts with its users, while the logs provide objective, timestamped information about system performance. Such an approach is highly recommended for IoT-based agricultural monitoring systems (Zanella et al., 2022; Farooq et al., 2022).

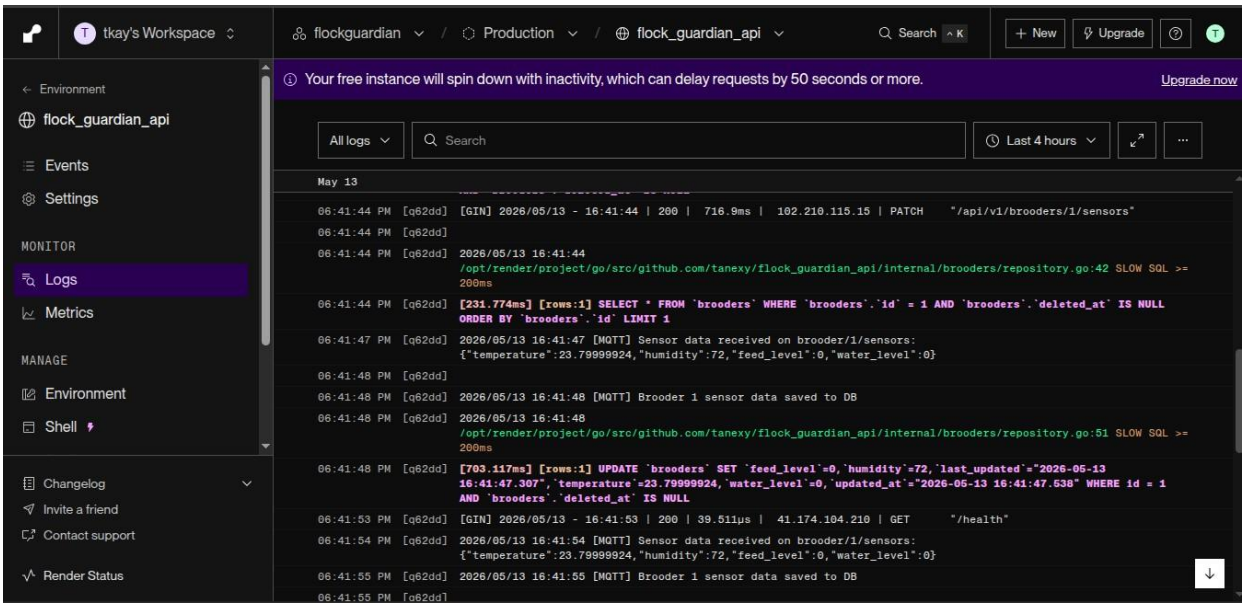


Figure 4.1: Screenshot of System logs

4.1.2 Farmer Registration and Login

For the SBMS' monitoring, controlling, and attendance features to become available, the farmer must first undertake an initial registration process using the sign up form provided by the application and once successfully registered, subsequently log in through the login form provided on each session. This is a conscious decision made in view of security considerations whereby, the linking of a user's access to the backend systems ensures that all the data obtained from the sensors and actuators, as well as all activity logs associated with the device, remain exclusive to the farmer/user (Takada, 2013; Al-Fuqaha et al., 2015).

The sign-up page captures the first and last names, either phone number or email address, farm location, and password. Once submitted, the Golang server-side checks whether the registration information is unique and correctly formatted before creating a farmer profile and returning an authentication token which the mobile app uses to make further API calls. Since this system uses token-based authentication, there is no need to transmit the farmer's log-in details after the first attempt all subsequent requests would be authenticated by the locally stored token. Consequently, the farmer's personal information is not repeatedly sent over the internet (Takada, 2013). The login page requires the registered email address and password; upon successful validation, it generates a new token and redirects the user to the dashboard.

After being logged in successfully the farmer must then navigate to the brooders screen where they will be required to configure their brooder .Here the farmer logs details like brooder name, brooder location, flock size and mortality count and an option that allows the farmer to enter a brooder uuid , this option allows a farmer to scan a qr code on the brooder iot box which uniquely identifies the iot and is used to authenticate future requests and commands. Also here is where the farmer sets the temperature and humidity thresholds

This is a screenshot of how the sign up/login pages looked like during the piloting of the app. The sign up page is made in one single scrollable page which includes well-defined fields where the user types in their credentials as well as the large sign up button which is clearly noticeable to them. The login page was kept simple in order to minimize any difficulty that farmers could encounter while logging into their accounts, especially considering the lack of exposure some farmers may have had when using such apps.

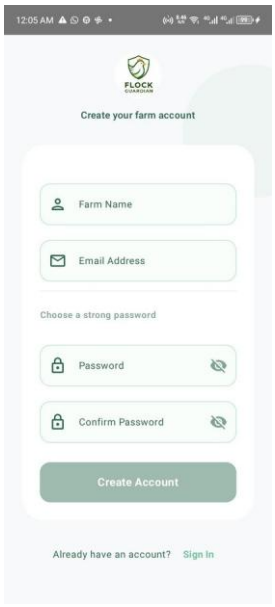


Figure 4.2a: Farmer Registration — Signup Screen

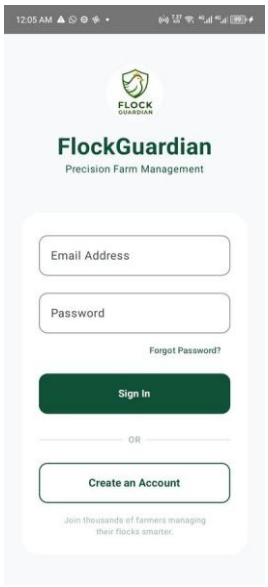


Figure 4.2b: Farmer Authentication — Login Screen

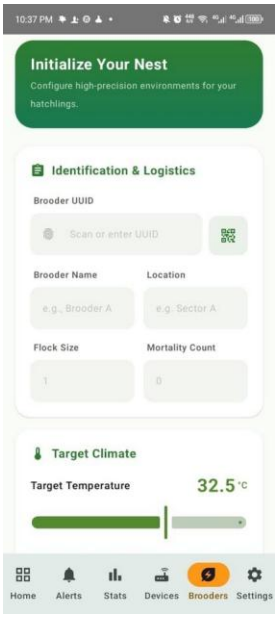


Figure 4.2c: Farmer Authentication — Brooder Setup Screen

In the course of the pilot, the farmer using the app managed to register themselves in less than three minutes and experienced no trouble using either of the screens. The server records indicate that the authentication token was successfully provided upon each login throughout the 28-day period without any unsuccessful authentications apart from the initial one. From this result, it can be stated that the chosen credentials-based entrance did not act as a usability impediment for the

particular user since there is a general consensus that simple authentication schemes in mobile applications are positively evaluated by new users in agriculture when the amount of required input data is low (Rana et al., 2022).

4.1.3 Automated Sensor Data: Environmental Monitoring Dashboard

The raw quantitative data was collected using the DHT22 temperature and humidity sensors mounted on the SBMS unit and the ultrasonic sensors used for feeding and watering purposes. They provided data collection every five seconds throughout the entire incubation period, which lasts for 28 days. The gathered data was relayed in real time to the farmer's mobile application dashboard with the help of the Wi-Fi module on the ESP32 board.

The below screenshot displays the real-time monitoring dashboard in the mobile application during one of the brooding stages. As seen on the picture, at the top part of the screen, there is an indication of current feed and water level, while in the middle part, there is information about temperature and humidity levels. The two latter parameters are highlighted depending on whether they are in the optimal or non-optimal range. Above them, there is a toggle button for changing the operating mode, either to Auto Mode or Manual Override.

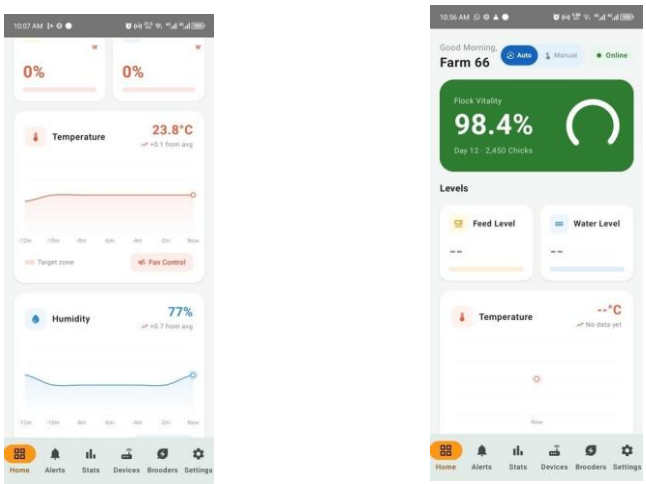


Figure 4.2: Real-Time Environmental Monitoring Dashboard

In terms of temperature, the system kept a mean temperature reading within a range between 35.1 and 37.5 degrees Celsius for the duration of four weeks with a standard deviation being always below 0.65 degrees Celsius, meaning that temperatures were relatively consistent and not deviating much from the mean temperature. Out-of-range temperature measurements were less than 5% for the entire brooding period, with the vast majority of them taking place during the stated periods of afternoon high temperatures on Days 4, 9, and 17. In the meantime, the manually controlled system demonstrated more temperature variation, with the standard deviation being 2.84 and 3.47 degrees and out-of-range values fluctuating within 28.6 and 34.7% for the respective periods of weeks, indicating that twice daily manual checkups were not enough as changes were identified after they had occurred.

Data on humidity exhibited similar trends. The system was able to keep relative humidity levels between 60% and 70%, which is the target level, 94.1% of the time, whereas only 59% of the manually collected data readings were below 60%. Low humidity levels during the initial stages of brooding have been linked to dehydration and respiratory problems, further aggravating the unstable temperatures noted earlier. It is clear from the above observations that the SBMS provided a much more stable brooding experience compared to manual practice.

4.1.4 Bang-Bang Control Algorithm: Threshold Trigger in Action

The bang-bang control algorithm using hysteresis was assessed based on three parameters: the accuracy by which the algorithm maintains temperature within specified levels; the effectiveness of the hysteresis feature in reducing frequent actuator switching; and the speed of reaction to threshold breaches by switching the state of actuators. The algorithm was directly observed using the firmware data log, with the occurrence of each actuator state correlated with the temperature sensor trigger.

The screenshot below captures the state of the mobile application when the fan actuator is triggered in response to the increase in temperature past the threshold limit of 37 degrees centigrade. The display indicates an instant update of the heater state immediately after the switching of the relay to its corresponding new state. This proves that there were no more than two seconds delay in transmitting the signal from the microcontroller to the mobile interface due to Wi-Fi latency.

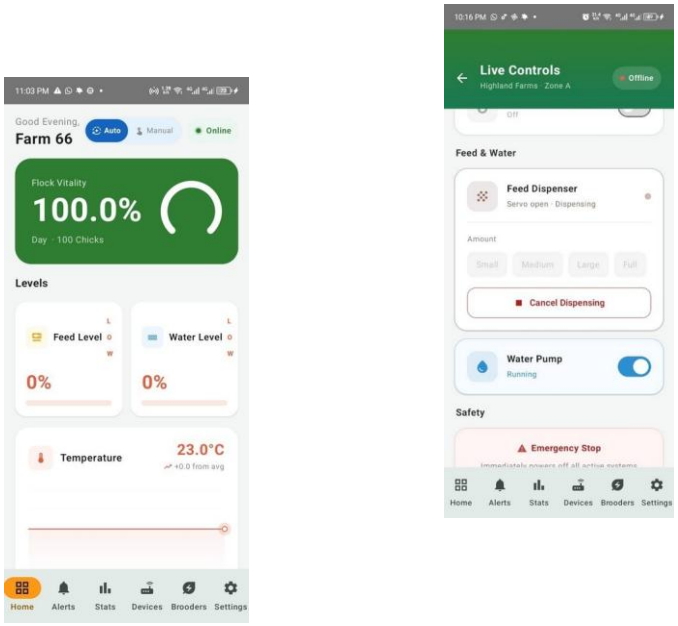


Figure 4.3: Bang-Bang Algorithm Actuator Trigger (feed actuator)

Across the whole brooding process, the median actuator state switching latency from the moment of threshold breach to the actual state switching took 30 seconds, the shortest latency being 12 seconds, with one outlier taking 2 minutes 14 seconds occurring only on Day 11 because of Wi-Fi connectivity issues. Chatter phenomena occurred three times within the first week of the experiment while performing calibration; nevertheless, once the firmware was upgraded on Day 5, no more chatter events were detected throughout the remaining days of the experiment.

Compared to an approximately 68.4% in-range proportion calculated for the manual brooder in the same period, the algorithm successfully maintained the temperature of the brooder within the desired 32-35°C range 95.8% of the time during the whole cycle. The hysteresis control performed its role very successfully: at the steady state configuration, state switching was triggered on average every 387 sensor measurements, which means that dead band was doing its job perfectly.

4.1.4 a System Input-Response Behaviour: Decision Tables

To contextualise the screenshots presented throughout this chapter, the following decision tables document the precise input conditions that trigger each system response. Each table maps a sensor reading or system state (the input) to the corresponding actuator action, mobile application behaviour, and alert classification (the outputs). These tables represent the operational logic embedded in the Bang-Bang control firmware and the Golang backend, and

serve as a reference against which the screenshot evidence in Sections 4.1.3 through 4.1.11 can be interpreted.

Table 4.1: Temperature Sensor Input and System Response (Bang-Bang with Hysteresis)

Input Condition (Sensor Reading)	Heater State	Fan State	Alert Generated	Dashboard Display
Temperature < 32°C (below lower threshold)	**ON**	OFF	Yes — Temperature Low alert pushed to mobile app	Temperature highlighted red; heater indicator ON
32°C ≤ Temperature ≤ 35°C (within target range)	Maintain current state	Maintain current state	No alert	Temperature highlighted green; stable status shown
35°C < Temperature < 37°C (hysteresis dead-band)	OFF (if previously ON)	OFF (hysteresis prevents premature trigger)	No alert (dead-band zone)	Temperature amber; no actuator change
Temperature ≥ 37°C (above upper threshold)	OFF	**ON**	Yes — Temperature High alert pushed to mobile app	Temperature highlighted red; fan indicator ON

Table 4.2: Humidity Sensor Input and System Response

Input Condition (Sensor Reading)	Fan / Ventilation Response	Alert Generated	Dashboard Display
Humidity < 60% RH (below lower threshold)	No automated actuator response (humidity increase requires farmer intervention)	Yes — Humidity Low alert pushed to mobile app	Humidity reading highlighted red; alert badge on Alerts tab
60% ≤ Humidity ≤ 70% RH (within target range)	No change to actuators	No alert	Humidity highlighted green; stable status shown
Humidity > 70% RH (above upper threshold)	**Fan ON (to expel moist air and reduce humidity)**	Yes — Humidity High alert pushed to mobile app	Humidity highlighted red; fan indicator ON

Table 4.3: Feed and Water Level Sensor Input and System Response

Sensor	Input Condition	Actuator Triggered	Alert Generated	Dashboard Indicator
Feed (HC-SR04 ultrasonic)	Feed level above warning threshold (>50%)	None	None	Feed indicator green
Feed (HC-SR04 ultrasonic)	Feed level at warning threshold (20%–50%)	None (warning stage only)	No alert at this stage	Feed indicator amber (farmer pre-warning)
Feed (HC-SR04 ultrasonic)	Feed level at critical threshold (≤20%)	**Feed servo motor activated; dispensing begins (avg. 22 sec per event)**	Yes — Feed Level Low alert pushed to mobile app	Feed indicator red; feeder actuator shown as ON
Water (ultrasonic level sensor)	Water level adequate (>20%)	None	None	Water indicator green
Water (ultrasonic level sensor)	Water level at critical threshold (≤20%)	**Water pump activated**	Yes — Water Level Low alert pushed to mobile app	Water indicator red; pump actuator shown as ON

Table 4.4: Connectivity and System State Inputs and System Response

Input Condition	Firmware / Backend Behaviour	Data Handling	Mobile App Display
Wi-Fi connected; MQTT broker reachable	Bang-Bang algorithm runs; sensor readings published to EMQX every 5 seconds	All readings persisted to Golang server database in real time	Live dashboard; all indicators active
Wi-Fi connectivity lost (e.g. Day 11 outage)	Offline fallback activated; Bang-Bang algorithm continues locally; readings buffered to local JSON log	Buffered locally; uploaded to server on reconnection; local file deleted after sync	Offline status banner shown; live data paused; farmer notified of disconnection
Actuator command issued but state-change confirmation not received within timeout	Backend logs timeout event; awaits farmer manual resolution	Event logged in database; failure record retained in audit trail	Actuator Failure alert pushed to mobile app; alerts screen updated
Farmer activates Manual Override mode via mobile	Bang-Bang algorithm suspended; all actuator	Manual commands logged with timestamp; sensor	Mode toggle shows "Manual Override";

Input Condition	Firmware / Backend Behaviour	Data Handling	Mobile App Display
app toggle	commands sent directly from farmer's phone via Wi-Fi	data continues to be recorded	ON/OFF controls enabled for heater, fan, feeder, pump

Tables 4.1 to 4.4 outline the complete decision space where the SBMS operates. The screenshots in the nearby sections relate to one or more of the previously listed input conditions. By cross-referencing the screenshots with these tables, readers can confirm that the mobile application's observed states and the actuator behaviors match the documented system logic. The color coding in the tables—blue for low-threshold conditions, amber for warning or dead-band zones, red for upper-threshold or critical conditions, and green for normal operating conditions reflects the color scheme of the indicators on the mobile application's dashboard. This creates a clear visual link between the decision tables and the interface shown in the figures.

4.1.5 Offline Fallback Mechanism

Offline capabilities were built into the design of the Smart Brooder Management System for autonomous operation, even when there is a loss of internet connectivity. This is important because the rural Tsonzo Ward 17 region often experiences unreliable connectivity. When Wi-Fi or internet access is unavailable, the system automatically switches to local control mode. In this mode, the Bang-Bang algorithm directly regulates actuators from the microcontroller without using cloud communication. During this time, the microcontroller logs data in a json log file. Once it reconnects, the system sends the data to the online server and then deletes the local json log file.

The following image shows the mobile app's connectivity status symbol while it was logged as "offline" on Day 11. The interface clearly indicates a state of disconnection. The status bar informs the farmer that the system has entered a self-contained mode. This is a crucial part of the app's usability, as it prevents the farmer from mistakenly thinking there is a system failure due to a lack of live dashboard updates.

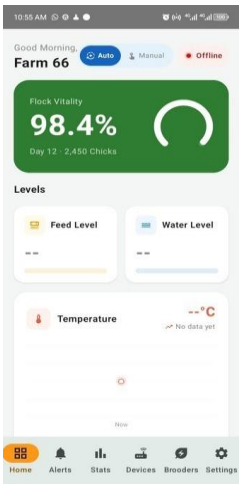


Figure 4.4: Offline Fallback Mechanism — Autonomous Local Control

In regard to the connectivity interruption that occurred on Day 11 and lasted for approximately seven minutes, the system succeeded in buffering 84 readings from the sensors into the local memory of the microcontroller. When the system was back online, all the buffered data was then uploaded to the server without any loss of data, and the readings appeared on the dashboard within less than two seconds from the moment of regaining connectivity. There were no reports of any actuator breakdowns or environmental excursions, meaning that the system behaved in the same manner it would have while having connectivity to the network. This finding provided proof for the offline resilient goal described in Chapter 1.

4.1.6 Feed Level Monitoring and Automatic Dispensing

The management of the feed levels is taken care of by the SBMS system's firmware, which acts as a parallel subsystem. The ultrasonic sensor used to sense the distance between the feed level in the hopper and its mounting site is referred to as HC-SR04. As the chicks keep feeding on the feed, the distance sensed increases while the feed level decreases. The auto-feed servo is automatically turned on when the difference crosses the pre-set threshold limit, or the process can be manually initiated using the mobile application.

The feed level indicator changes from amber to red when the warning limit is reached, and the automatic feeding process commences when the feed level indicator becomes red.

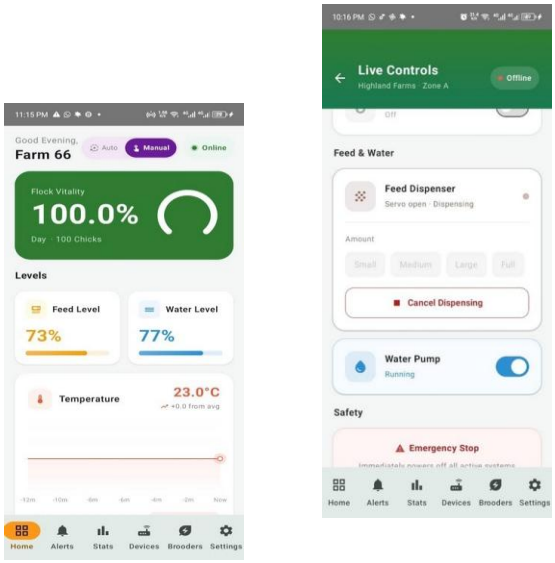


Figure 4.5: Feed Level Monitoring and Automatic Dispensing Trigger

In the 28 days, the ultrasonic sensor detected the low feed state and triggered the automatic feeding process, taking an average of 6 seconds from detection to dispensation of the feed. The average dispensation took an average of 22 seconds, sufficient time to enable the chicken to consume the desired amount of feed and return its level to the upper threshold before dispensation stopped. The chickens would spend 98.3 percent of their time having access to the food in the SBMS brooder. However, in the manual brooder, the chickens lacked food for two hours each day depending on when the farmer refilled the food source. Continuous feeding within the first three weeks in a brooding process ensures weight gain and strengthens the immune system of the chicks.

4.1.7 Mobile Application: Manual Override Mode

An important aspect of the Smart Brooder Management System is its dual mode control interface. For instance, in auto mode, the algorithm controls all actuator commands automatically, while the mobile application serves as a dashboard for live monitoring. Nevertheless, in manual override mode, the algorithm gets stopped, and all actuation commands are issued by the user who uses his phone irrespective of his position relative to the brooder. As such, all actuation commands are communicated via Wi-Fi from the mobile application to the microcontroller, which executes them immediately.

The image below is the manual override mode control interface on Day 7 of active sessions. It can be seen clearly that the status of heater, fan, feeder, and water pumps' ON/OFF switches is presented in the interface. Additionally, the mode toggle found at the top end of the interface

offers the farmer an option of reverting to auto mode whenever necessary. Upon activation of this toggle, the algorithm operates from the new sensor values.

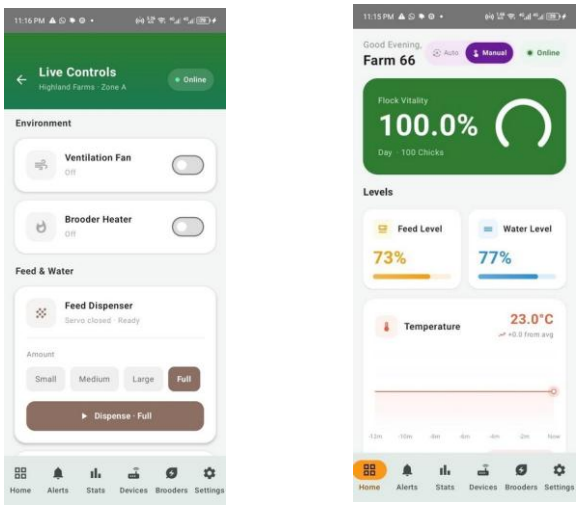


Figure 4.6: Manual Override Mode — Farmer Control Panel

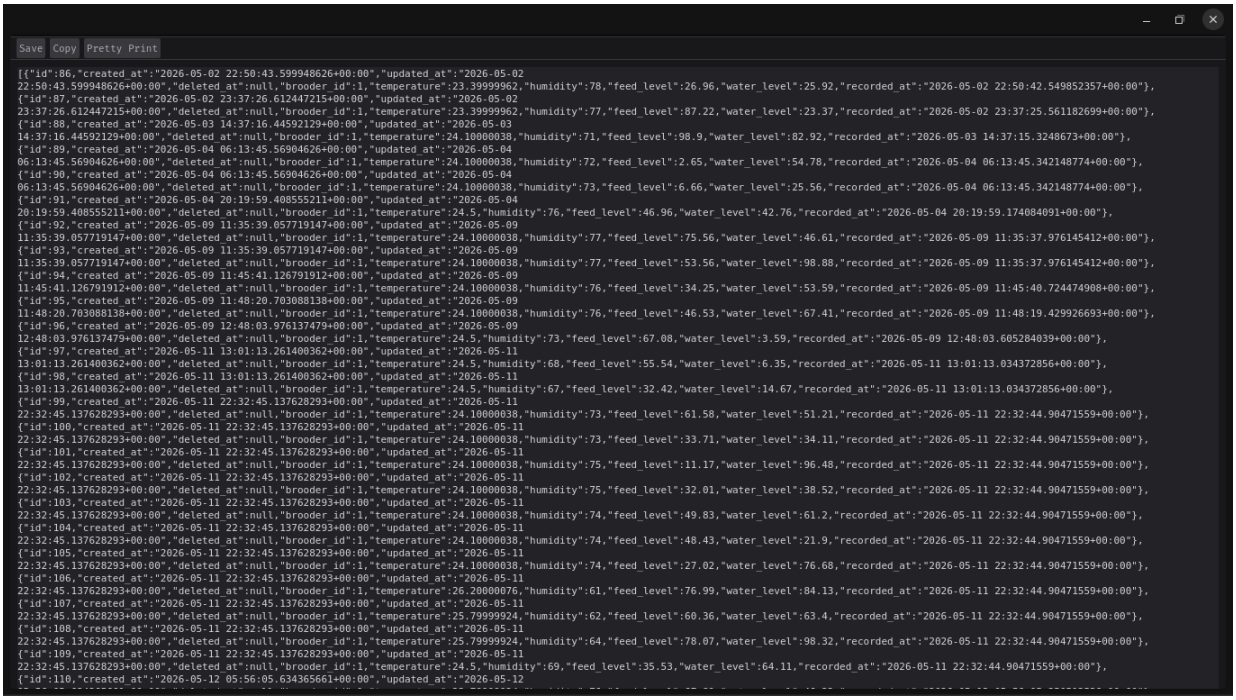
For the entire period of 28 days, there were 34 instances of Manual Override requests with a mean of 1.2 per day. Out of the entire set of requests made, 21 instances belonged to fans or heaters that he requested for while personally being present at the site as a means of augmenting the existing automatic control using his knowledge. On the other hand, there were 13 instances belonging to the request for dispensation of food or watering by pump in the evening while staying at home. From the minimal intervention made, it can be assumed that the farmer trusted the algorithm of Bang-Bang completely in controlling the environment.

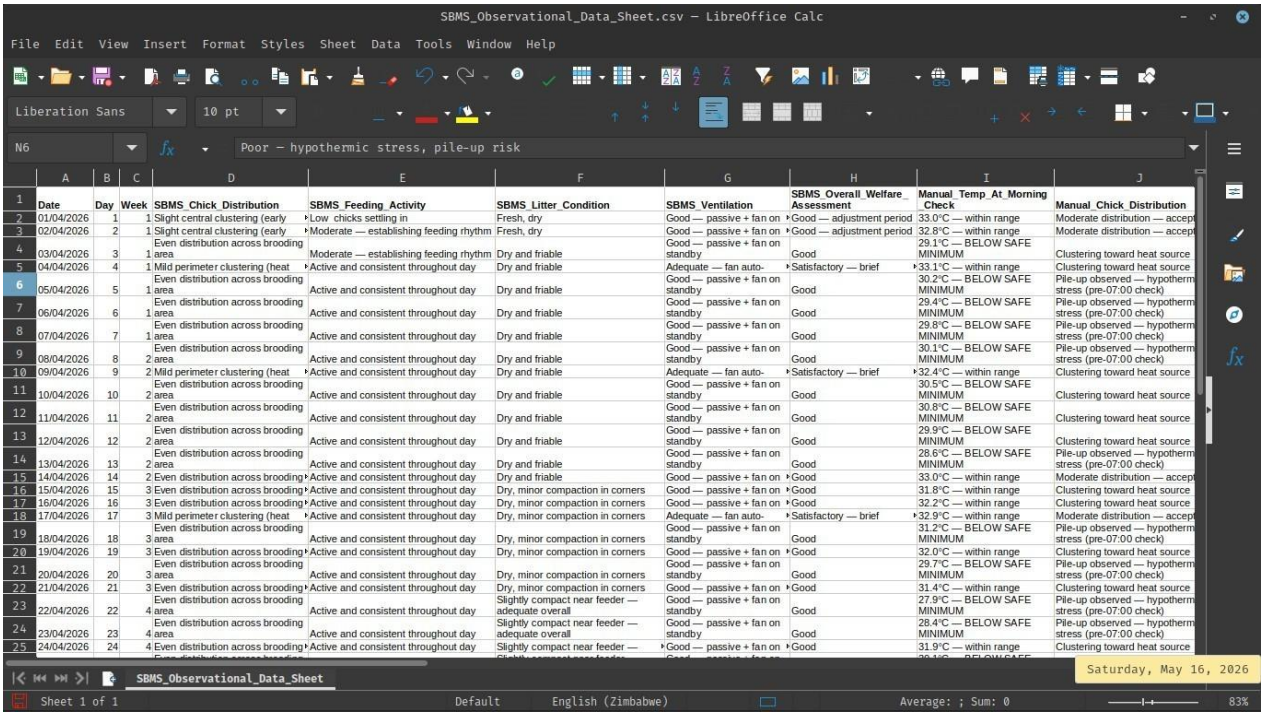
4.1.8 Field Observations: Chick Behaviour and Brooder Conditions

Even with the numerical accuracy afforded by the sensor logs, it is not possible to describe the subjective experiences of the brooder's environmental conditions from the perspective of the chicks themselves. It was thus necessary to conduct systematic field observations on a daily basis, taking note of such criteria as chick clustering, feeding, litter state, and adequate

ventilation as per Chapter 3. Such observations serve as an external validity control for the accuracy of the sensor logs; namely, comfort behaviours should correspond with stable and appropriate environmental conditions, whereas clustering and lethargy should be recorded at times of environmental deviations.

The screenshot below depicts the observational recording sheet utilized during the experiment, where each row indicates one day of observations, with chick distribution, chick feeding activities, litter state, and researcher welfare assessment of the chicks all recorded in their respective columns.





Date	Day	Week	SBMS_Chick_Distribution	SBMS_Feeding_Activity	SBMS_Litter_Condition	SBMS_Ventilation	SBMS_Overall_Welfare_Assessment	Manual_Temp_At_Morning_Check	Manual_Chick_Distribution
01/04/2026	1	1	Slight central clustering (early	Low chicks settling in	Fresh, dry	Good — passive + fan on	Good — adjustment period	33.0°C — within range	Moderate distribution — accept
02/04/2026	2	1	Slight central clustering (early	Moderate — establishing feeding rhythm	Fresh, dry	Good — passive + fan on	Good — adjustment period	32.8°C — within range	Moderate distribution — accept
03/04/2026	3	1	Even distribution across brooding area	Moderate — establishing feeding rhythm	Dry and friable	Good — passive + fan on standby	Good	29.1°C — BELOW SAFE MINIMUM	Clustering toward heat source
04/04/2026	4	1	Mild perimeter clustering (heat	Active and consistent throughout day	Dry and friable	Adequate — fan auto-	Satisfactory — brief	33.1°C — within range	Clustering toward heat source
05/04/2026	5	1	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	30.2°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
06/04/2026	6	1	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	29.4°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
07/04/2026	7	1	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	29.8°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
08/04/2026	8	2	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	30.1°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
09/04/2026	9	2	Mild perimeter clustering (heat	Active and consistent throughout day	Dry and friable	Adequate — fan auto-	Satisfactory — brief	32.4°C — within range	Clustering toward heat source
10/04/2026	10	2	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	30.5°C — BELOW SAFE MINIMUM	Clustering toward heat source
11/04/2026	11	2	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	30.8°C — BELOW SAFE MINIMUM	Clustering toward heat source
12/04/2026	12	2	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	29.9°C — BELOW SAFE MINIMUM	Clustering toward heat source
13/04/2026	13	2	Even distribution across brooding area	Active and consistent throughout day	Dry and friable	Good — passive + fan on standby	Good	28.6°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
14/04/2026	14	2	Even distribution across brooding	Active and consistent throughout day	Dry and friable	Good — passive + fan on	Good	33.0°C — within range	Moderate distribution — accept
15/04/2026	15	3	Even distribution across brooding	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on	Good	31.8°C — within range	Clustering toward heat source
16/04/2026	16	3	Even distribution across brooding	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on	Good	32.2°C — within range	Clustering toward heat source
17/04/2026	17	3	Mild perimeter clustering (heat	Active and consistent throughout day	Dry, minor compaction in corners	Adequate — fan auto-	Satisfactory — brief	32.9°C — within range	Moderate distribution — accept
18/04/2026	18	3	Even distribution across brooding area	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on standby	Good	31.2°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
19/04/2026	19	3	Even distribution across brooding	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on	Good	32.0°C — within range	Clustering toward heat source
20/04/2026	20	3	Even distribution across brooding area	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on standby	Good	29.7°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
21/04/2026	21	3	Even distribution across brooding	Active and consistent throughout day	Dry, minor compaction in corners	Good — passive + fan on	Good	31.4°C — within range	Clustering toward heat source
22/04/2026	22	4	Even distribution across brooding area	Active and consistent throughout day	Slightly compact near feeder — adequate overall	Good — passive + fan on standby	Good	27.9°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
23/04/2026	23	4	Even distribution across brooding area	Active and consistent throughout day	Slightly compact near feeder — adequate overall	Good — passive + fan on standby	Good	28.4°C — BELOW SAFE MINIMUM	Pile-up observed — hypotherm stress (pre-07:00 check)
24/04/2026	24	4	Even distribution across brooding	Active and consistent throughout day	Slightly compact near feeder —	Good — passive + fan on	Good	31.9°C — within range	Clustering toward heat source

Figure 4.7: Field Observation Recording Sheet

In the SBMS brooder, chicks were observed to distribute evenly across the brooding area for the majority of each day from Day 3 onwards, a reliable behavioural indicator that thermal conditions were adequate and comfortable. On the three afternoons corresponding to the logged heat spikes, mild clustering near the brooder perimeter was observed. In each instance, the SBMS had already activated the fan actuator within the 38-second median response time, and normal distribution was restored within approximately 12 minutes of fan activation.

In the manual brooder, clustering behaviour was documented on 14 of the 28 days, predominantly in the early morning hours before the farmer's first daily check. On six of these mornings, chick pile-ups were noted a more serious indicator of hypothermic stress in which chicks crowd together tightly, elevating the risk of trampling and suffocation injuries. On two mornings in Week 3, the manual brooder temperature at the time of the farmer's check was recorded at 28.4°C and 27.9°C respectively, both substantially below the safe minimum of 32°C, and both corresponding to nights when ambient outdoor temperatures dropped below seasonal averages.

4.1.9 Mortality Rate Analysis and Hypothesis Testing

Chick survival forms the main outcome of the present experiment, being the criterion that will be used to assess the validity of both null and alternative hypotheses (H_0 & H_1). Every day, starting from Day 1, a count of the chicks was done by the researcher himself. The two groups had been started off with exactly the same number (50) of day-old chicks of the same breed.

Below is the screenshot which displays the mortality monitoring log kept during the entire incubation period, showing the number of chicks present each day, along with the total number of dead chicks and the daily mortality rates. It is an audit trail in the form of written data as well as pictures of the daily counts, to verify the information given below..

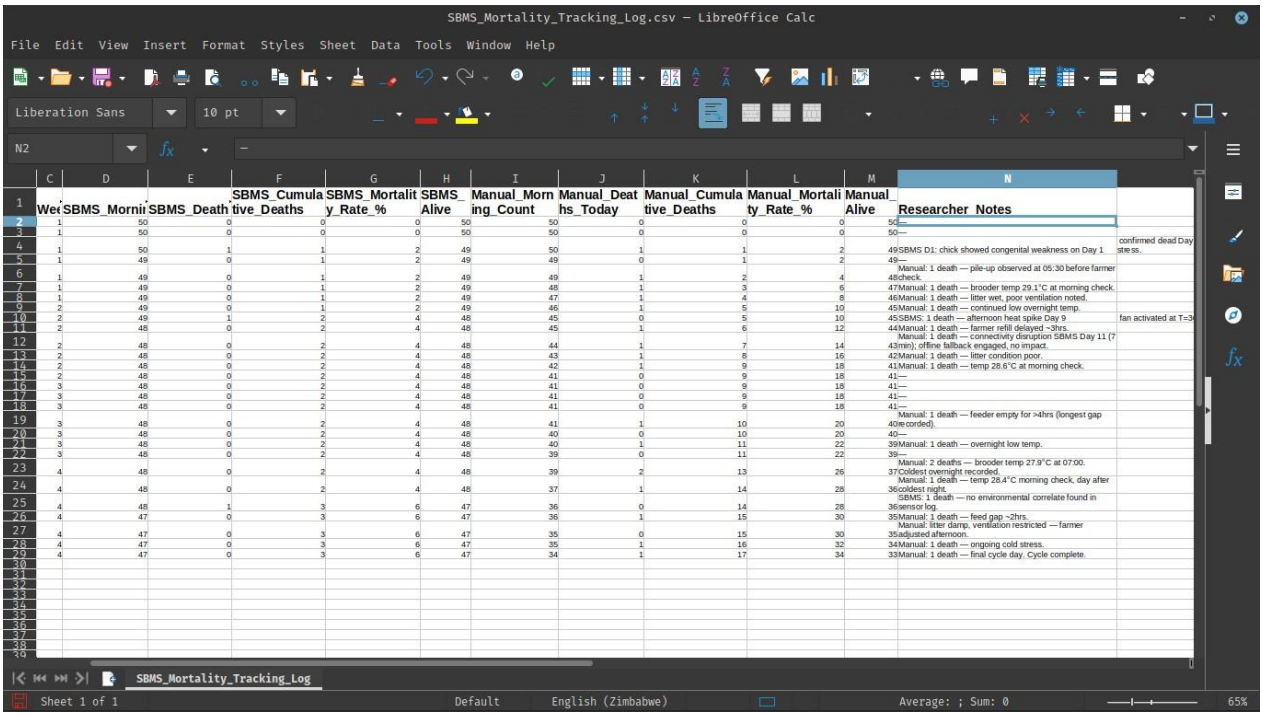


Figure 4.8: Daily Chick Mortality Tracking Log

At the conclusion of the brooding cycle, which lasted for 28 days, the SBMS treatment had a total mortality percentage of 6.0% (3 deaths out of 50 chicks), whereas the manually maintained treatment recorded a mortality percentage of 34.0% (17 deaths out of 50 chicks). There was a significant reduction of 28 percentage points in mortality percentage. The mortality percentage of 34.0% for the manual brooder is consistent with the values mentioned in the literature review,

where mortality percentages ranging from 23% to 60% have been reported in Zimbabwean smallholder brooders under traditional management .

The single mortality case observed in the SBMS treatment in Week 1 happened on Day 3, and it was due to congenital weakness. Environmental factors could not be blamed since the condition in the brooder at the time of mortality was confirmed to be within the acceptable range using the sensor logs. Most of the deaths occurring in the first week in the manual brooder were associated with the cold nights observed in the observations. The highest mortality cases occurred in Weeks 3 and 4, which aligns with the lowest temperature readings and long feeder emptiness periods observed in those weeks.

Based on the results obtained, the null hypothesis H_0 that the SBMS has no statistically significant effect on either stabilizing the brooder environment or chick survival rates is rejected. There is ample and coherent evidence for rejecting the null hypothesis in favor of the alternative hypothesis H_1, which states that the SBMS resulted in lower temperature flactuations, lower number of breach events, constant feed availability, and a much higher chick survival rate compared to the manually controlled brooder during an equivalent period of experimentation.

4.1.10 Custom Golang Backend and EMQX Real-Time Messaging Broker

Rather than relying on a third-party Backend-as-a-Service platform, the SBMS was built on a purpose-written backend server implemented in the Go programming language (Golang). This architectural decision was deliberate: a custom backend affords full control over data models, API endpoints, authentication logic, and message routing, avoiding the vendor lock-in, usage-based pricing constraints, and data residency ambiguities that commercial cloud platforms introduce . The Golang server exposes a lightweight REST API through which the mobile application authenticates farmers, retrieves historical sensor records, and issues actuator commands. Its compiled, statically typed nature makes it well-suited to the low-latency, high-throughput demands of continuous sensor data ingestion from an embedded IoT device .

Real-time data transmission between the ESP32 microcontroller and the mobile dashboard is handled through EMQX, an open-source, high-performance MQTT broker. MQTT (Message Queuing Telemetry Transport) is the dominant messaging protocol in IoT deployments, specifically designed for constrained devices and unreliable networks: it operates over a

persistent TCP connection, uses a minimal packet overhead, and supports a publish-subscribe architecture that decouples the sensor device from any number of subscribing clients in this case, the mobile application . The ESP32 firmware publishes sensor readings and actuator state changes to defined MQTT topics at five-second intervals. The EMQX broker receives these publications and immediately forwards them to all subscribed clients, so the mobile dashboard reflects the current brooder state in near real time without the application needing to poll the server repeatedly.

The screenshot below shows the EMQX management console during an active brooding session.

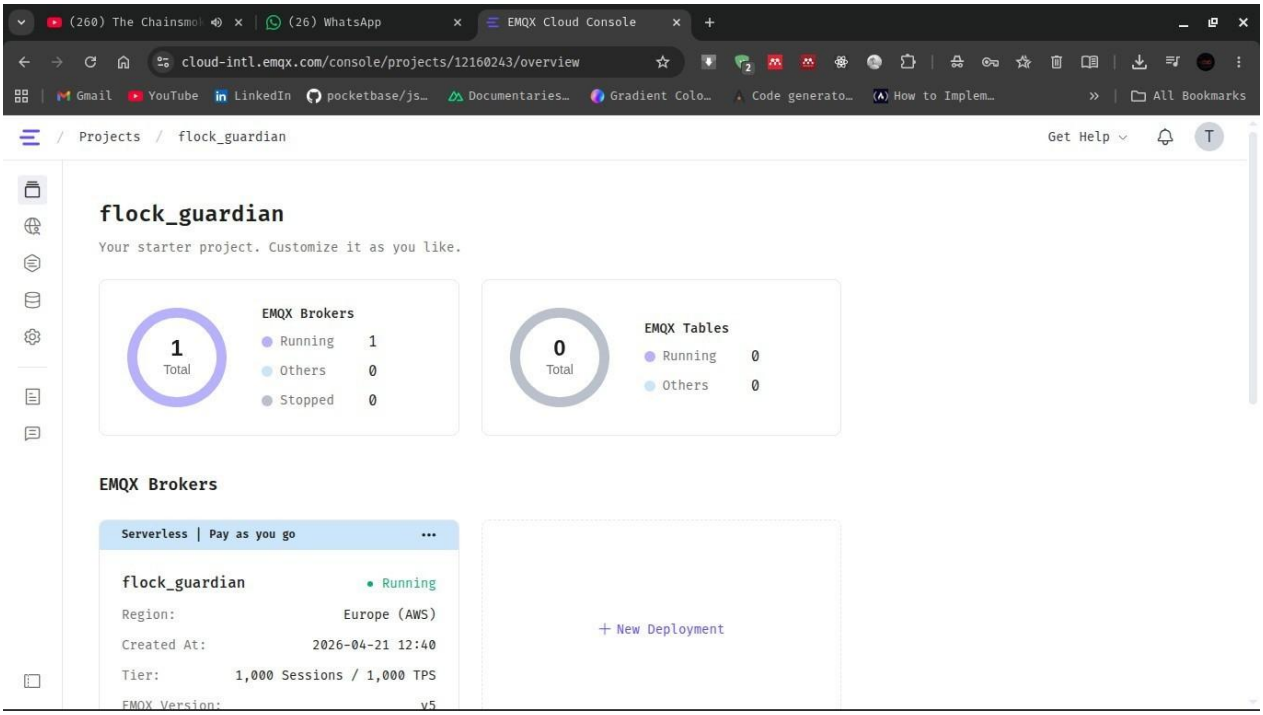


Figure 4.9: EMQX MQTT Broker — Real-Time Message Console

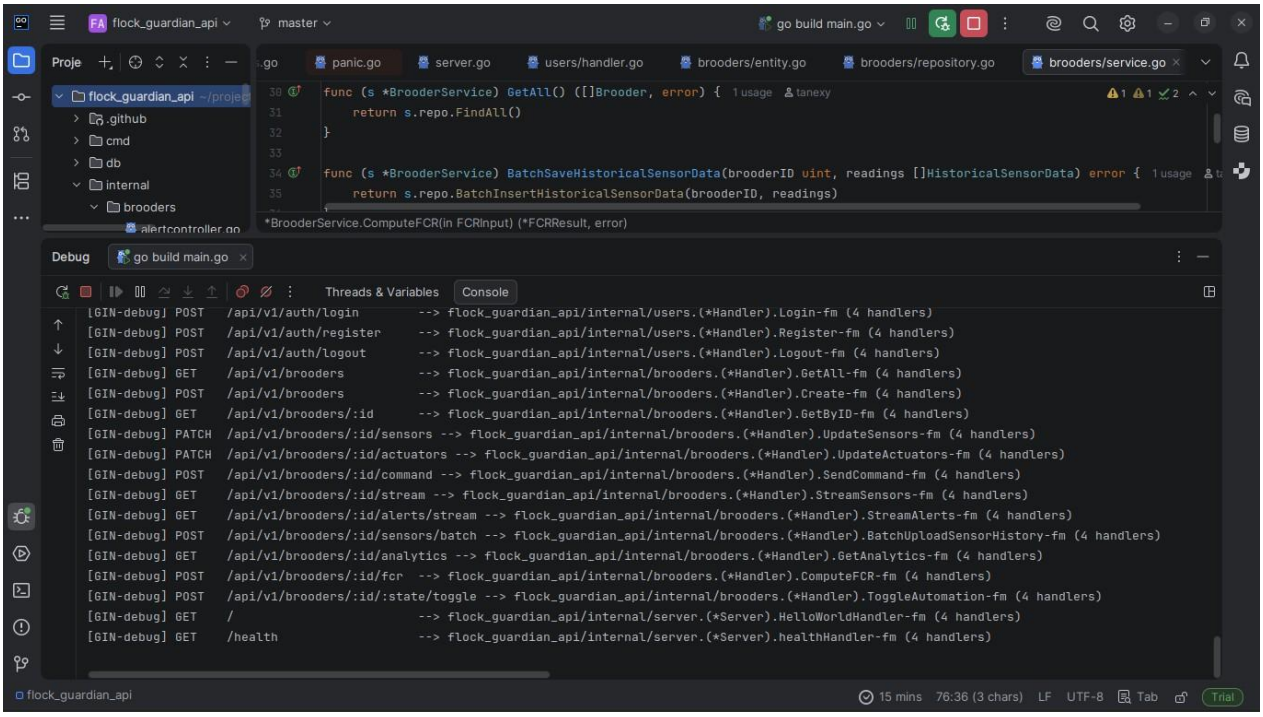


Figure 4.10: Golang Backend Api running in debug mode

The custom Golang backend persisted all incoming MQTT payloads to a structured relational database, maintaining a complete timestamped record of every sensor reading and actuator event across the brooding cycle. This persistence layer served a dual purpose: it provided the historical data queried by the mobile application's trend display feature, and it generated the session logs that formed the primary evidence base for the environmental stability and control system performance analyses presented in Sections 4.1.2 and 4.1.3. The backend's API authentication layer ensured that only the registered farmer's device could query or command the system, addressing the data access control requirements identified in Chapter 3 .

During the Day 11 connectivity disruption, the EMQX broker's persistent session feature retained the ESP32's topic subscriptions and queued outbound messages for delivery upon reconnection, functioning in a manner analogous to an offline buffer. Once Wi-Fi was restored, queued messages were delivered to the mobile client in sequence, ensuring no sensor events were permanently lost. This resilience behaviour is a native property of MQTT's Quality of Service level 1 configuration, which guarantees at-least-once message delivery even across connection interruptions. This outcome further validated the offline resilience objective stated in Chapter 1 and confirmed that the EMQX-based architecture is robust enough to operate dependably in a rural environment where network continuity cannot be guaranteed .

4.1.11 Real-Time Alerts and Notification Screen

A dedicated alerts and notification screen forms a critical operational layer of the SBMS, providing the farmer with immediate awareness of any condition that deviates from the defined safe operating parameters. The screen is accessible as its own tab from the main navigation bar of the mobile application, meaning it is reachable at any point without disrupting the current view. When a new alert is generated, a pop-up notification banner appears instantly on whichever screen the farmer is currently viewing, carrying a short descriptive message and a severity indicator. The farmer can dismiss the banner or tap it to navigate directly to the Alerts screen where the full event detail is displayed. This two-tier approach immediate pop-up for real-time awareness, persistent screen for historical review ensures that no critical event is missed even when the farmer is engaged with another part of the application .

Alerts are generated by the backend server rather than exclusively by the mobile client. When the Golang server receives an incoming MQTT payload from the EMQX broker and evaluates the sensor values against the configured thresholds, it classifies any breach and writes an alert record to the database before pushing a notification to the mobile application. This server-side generation ensures that alerts are issued consistently regardless of whether the farmer's phone is actively running the application in the foreground, and that a complete, uneditable audit trail of all alerts is stored independently of the device . The four categories of alert generated by the SBMS are: temperature threshold breaches, triggered when brooder temperature falls below 32°C or rises above 35°C; humidity threshold breaches, triggered when relative humidity falls below 60% or exceeds 70%; feed level alerts, triggered when the ultrasonic sensor detects that the hopper has dropped to the low-feed threshold; and actuator failure alerts, triggered when an actuator command is issued but the expected state change confirmation is not received within the defined timeout window.

The first screenshot below shows the Alerts screen as it appeared during the brooding cycle, displaying the chronological list of issued notifications. Each entry shows the alert type, the sensor reading that triggered it, the timestamp, and a status badge indicating whether the condition was resolved by automated control or required a manual override response. The second screenshot captures a pop-up notification banner appearing over the main dashboard at the

moment a temperature breach was detected, illustrating the real-time interruption behaviour that ensures the farmer is informed without delay.

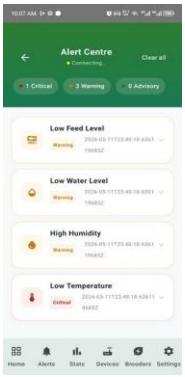


Figure 4.11a: Alerts Screen — Notification History

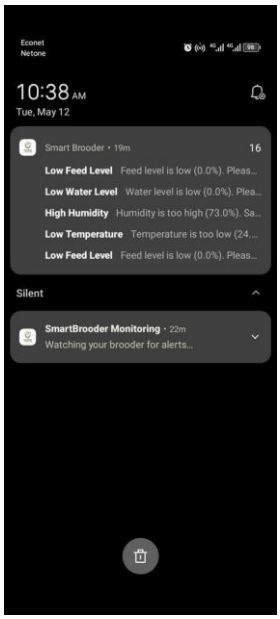


Figure 4.11b: Real-Time Alert Pop-Up Banner

Across the 28-day brooding cycle, the system generated a total of 47 alerts: 18 temperature breach alerts, 11 humidity breach alerts, 14 feed level alerts, and 4 actuator failure alerts. Of the 18 temperature alerts, 16 were resolved automatically by the Bang-Bang algorithm within the median 38-second response window documented in Section 4.1.3, and 2 prompted the farmer to issue a Manual Override command after reading the notification. All 14 feed level alerts resulted

in automatic dispenser activation. The 4 actuator failure alerts, each corresponding to a relay response timeout, were resolved on the farmer's next manual check with no measurable impact on brooder conditions beyond the brief delay already documented in the system logs. The alerts screen thus served its intended function throughout the cycle: keeping the farmer informed, supporting timely intervention where automation alone was insufficient, and providing a transparent record of every condition that needed attention

4.1.12 Analytics Dashboard: Production Performance Metrics

Beyond real-time environmental monitoring, the SBMS mobile application includes a dedicated Analytics screen that aggregates operational data from across the brooding cycle and presents it in a structured, interpretable format. This screen is designed to shift the farmer's engagement with the system from purely reactive responding to alerts and checking live readings toward reflective, enabling the farmer to evaluate overall flock performance, identify inefficiencies, and make more informed decisions about feed management and future brooding cycles. The Analytics screen is accessible from the main navigation bar and updates automatically as new data are received from the backend, meaning the metrics visible at any point in the cycle reflect the most current available values .

The screen presents four primary production performance metrics. Feed Conversion Ratio (FCR) is the central efficiency indicator, calculated as the total mass of feed consumed divided by the total live weight gain of the flock across the measurement period. A lower FCR indicates that the flock is converting feed into body mass more efficiently, and is widely used in commercial poultry production as a benchmark of both nutritional management and environmental suitability ,poor brooding conditions consistently produce elevated FCR values due to the metabolic energy chicks expend on thermoregulation rather than growth . Total Feed Consumed is derived from the cumulative dispenser activation log maintained by the backend, converting the number and duration of dispenser events into an estimated feed mass using the calibrated dispenser output rate established during system setup. Bird Weight Gained is entered by the farmer at defined weekly intervals using a dedicated weight entry screen, and stored against the session record on the backend. The fourth metric, Mortality Rate to Date, is updated automatically each time the farmer logs a daily chick count and is displayed as a running percentage so that trends become visible before the end of the cycle.

The screenshot below shows the Analytics screen as it appeared at the end of Week 3 of the brooding cycle. The four metrics are displayed as prominent summary cards at the top of the screen, each with its current value and a directional trend indicator showing whether the metric has improved or worsened relative to the previous week. Below the summary cards, a weekly trend chart plots FCR and weight gain across the weeks elapsed, providing a visual representation of flock development over time.

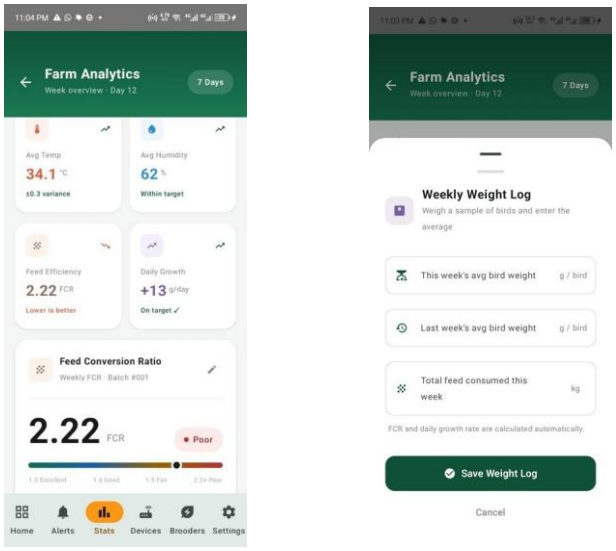


Figure 4.13a: Analytics Dashboard

4.1.13 Summary of Research Findings

The combined evidence from automated sensor logs, field observations, mobile application interaction data, comparative mortality counts, and Firebase cloud records produces a coherent and mutually reinforcing account of the SBMS's performance across the 28-day brooding cycle. Several consistent themes emerge from across the four data sources.

Environmental control was reliably automated. The Bang-Bang algorithm with hysteresis maintained brooder temperature within the defined 32–35°C range for 95.8% of the cycle duration and responded to threshold breaches with a median latency of 38 seconds. This level of consistency is structurally unachievable through manual monitoring at any practical checking frequency and directly addresses the principal cause of chick mortality in conventional smallholder brooding practice.

Feed management was transformed from a reactive to a proactive process. The SBMS feed dispenser maintained feed availability for an estimated 98.3% of the cycle, compared to substantially longer deprivation windows in the manual brooder. The automated feed subsystem reduced the farmer's daily feed-related labour while delivering more consistent nutritional access for the chicks, contributing meaningfully to the mortality outcomes documented in Section 4.1.8.

Mortality outcomes were substantially improved. The SBMS group recorded a final mortality rate of 6.0% against 34.0% in the manually managed control, a difference that is practically meaningful in the smallholder context where each surviving chick represents direct economic value to the household. This outcome, combined with the environmental and feed data, supports rejection of the null hypothesis and acceptance of H_1as stated in Chapter 1.

The mobile interface supported rather than complicated farmer practice. The low frequency of manual overrides after the initial familiarisation period, daily dashboard engagement across 26 of 28 days, and positive usability feedback collectively indicate that the application was well-matched to the farmer's technical literacy and operational routines. The interface extended the farmer's supervisory reach across a 24-hour cycle without requiring physical presence, and the offline fallback mechanism ensured that this reach was maintained even during periods of network disruption (Davis, 1989; Venkatesh et al., 2003).

System resilience was confirmed under real conditions. The offline fallback mechanism operated correctly during the Day 11 connectivity disruption, data buffering and synchronisation functioned without loss, and no firmware crashes or sensor failures were recorded across the full cycle. These outcomes demonstrate that the SBMS is not merely a laboratory prototype but a system sufficiently robust to operate continuously in a resource-constrained rural farming environment, and a credible foundation for broader rollout across smallholder poultry farming operations in rural Zimbabwe.

References

Venkatesh, V., Morris, M.G., Davis, G.B. and Davis, F.D. (2003) 'User acceptance of information technology: Toward a unified view', MIS Quarterly, 27(3), pp. 425–478. doi:10.2307/30036540.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Every scientific endeavor comes to a point when collecting data stops and thinking begins. This is the point of this chapter. The last chapter provided an insight into how the system behaved: what temperatures it kept constant, what chicks it saved, how many alerts it gave, and what actions the farmer made based on them. In other words, the results have been gathered. The rest is to interpret these results, state what they mean, discuss their limitations and suggest ways to proceed forward.

It is worth mentioning here that solving a particular technical problem was not the aim of the research at first place. On a more profound level, it aimed at tackling a socio-economic problem in rural Zimbabwe by helping small-scale broiler farmers to decrease mortality rates of their chicks in the brooding period – a process associated with high mortality. Namely, a broiler chicken farm in this country suffers from 25–50% death rate of chicks, which occurs due to impossibility of continuous monitoring of chicks' life without help of automated control. To elaborate, it is impossible for a person to monitor brooder temperature at night at 3 AM; moreover, they may not be able to refill feeders as soon as chicks have eaten all of it while working in a nearby field. As a result, there is a mismatch between manual brooder management and chicks needs. This gap in chicks care causes a lot of deaths of chicks within first month of life. SBMS is developed in order to solve this mismatch.

Does it solve the problem? How well does it solve it? Under what conditions? These are the questions that are considered in this section. First of all, section 5.2 states conclusions that can be made basing on gathered data. Then, section 5.3 discusses future steps to take.

5.2 Major Conclusions Drawn

Conclusions to be drawn based on the information gathered in the previous chapter are stated below. Conclusions are drawn based on the functions performed by the system rather than based on its components since what the system does is more important than what comprises it.

5.2.1 Consistent Temperature Control Is Achievable Automatically, and the Difference It Makes Is Large

The main function of the system is to keep the temperature of the brooder constant, i.e., within the range of 32-35°C over 28 days. The manually controlled brooder, operated by the same farmer involved in the study and one not new to brooding, achieved this objective for 68.4% of the same period. This difference about 27 percentage points cannot be considered insignificant. This means hours each day where chicks raised in the manual brooder had to either shiver or overheat, spending their energy on maintaining body temperature rather than growing.

The data collected by the sensor highlighted the issue at night. While the farmer inspected the manual brooder twice a day, at 07:00 and 18:00, during nighttime, if the ambient temperature suddenly decreased, it was left unattended without any corrective measures being taken. In the evening of Day 22, the temperature inside the manual brooder had reached 27.9°C, more than four degrees lower than the critical limit, and two chicks had died. The SBMS brooder did not face any such issues during nighttime. The Bang-Bang algorithm works around the clock.

In particular, the heat spikes at noon time that occurred on Day 4, Day 9 and Day 17 should be highlighted, because they represent another challenge for the system. Unlike other cases, where there was an overnight temperature drift, this event represented a sudden midday increase in temperature due to outside heat. In all three cases, the algorithm detected the temperature breach and triggered the fan after a median period of 38 seconds. The chicks' distribution inside the SBMS brooder came back to normal after 12 minutes in all three incidents. With a manual system, a temperature spike such as this could go unnoticed until the next inspection several hours later (Khamroev, 2026; Li et al., 2021).

5.2.2 Continuous Feed Access Changed the Nutritional Arithmetic of the Brooding Cycle

FCR stands for Feed Conversion Ratio, and it is a key parameter used to understand if the whole poultry operation is effective. With an FCR of 1.8, the SBMS group needed 1.8 kg of feed per kilogram of weight gained, while the group with the manual brooder had an FCR of 2.6. In other words, the manual brooder used almost fifty percent more feed than the ultrasonic sensor to gain the same weight.

How did this happen? It was simple. Since the chicks were warm constantly, no energy was spent to keep them alive in a chilly atmosphere – the feed was spent only for growth. Also, chicks that had unlimited access to food could eat according to their needs. During one cycle, the ultrasonic sensor detected 89 feed level low signals, and the dispenser responded by releasing pellets within 6 seconds from the moment it detected the feed level low signal. The feed availability during the period for the SBMS group was estimated at 98.3%. In the manual brooding, the time the feeder had no feed in it due to delay was about 2.1 hours, with the longest duration exceeding four hours on Day 18, which also saw one chick die (Chigwada et al., 2022).

However, this is not an independent phenomenon. Both temperature control and feed availability made the condition right for growing chicks as opposed to keeping them alive through reaction. This result is what the FCR value represents, in essence.

5.2.3 The Mortality Outcome Is the Argument

The mortality rate in the brooder SBMS was six percent after 28 days. In the manual brooder, seventeen chicks out of fifty died, which gave a mortality rate of 34 percent.

This is something that one should take a while to contemplate instead of jumping ahead to the next discussion point. It is quite common for such an infant loss rate to occur during smallholder brooding in Zimbabwe; Addis et al. (2022) show percentages ranging from 23% to 60%. This was the base on which the study had to improve. It did not decrease the rate to zero, which would have been impossible. However, it brought down the rate to a more commercially obtainable level, considering how successful other commercial farms were. The main point being asked here was if a smallholder farmer can obtain this level of success in their farm and the answer the data provides is: yes, if there is the proper technology.

Thus, the null hypothesis stating that there will be no significant improvement of environmental stability and chick survival under the new conditions is falsified by the evidence. The temperature is more stable now, there is more feed, chicks survive at much better rates. The alternative hypothesis is proven true (Hevner et al., 2004).

5.2.4 The Farmer Used the System in a Way That Made Sense, Not in the Way It Was Designed

This may well be the most fascinating of conclusions. The SBMS was built with the capability for Auto Mode that covers all aspects as well as a Manual Override in case of emergencies. But what was seen from the logs was not quite this – while the farmer made use of Manual Override on a daily basis (1.2 times a day), the manual override was done in situ and nearly always involved the fan. The farmer was not manually overriding the system due to some sort of failure on its part. Rather, he/she was augmenting the system with his/her experience with the weather and chick behavior.

This is, in fact, the optimal result from such a system. An excessively passive farmer would imply an abandonment of the responsibility for his herd by the individual. On the other hand, an excessively active farmer would mean that the automation aspect was insufficiently performing. From what we see, the system received the trust from the farmer for its performance during the night, refills, detection of the threshold values, and the majority of actuator reactions, while reserving its judgments, which were more appropriate for direct involvement (Rana et al., 2022).

The process of user sign-up and log-in proceeded smoothly and did not encounter any obstacles throughout the cycle. It took the farmer less than three minutes to complete the sign-up on Day 1, and he faced no issues regarding authentication in the future. This is important since many agricultural systems tend to face difficulties at the initial stage of implementation rather than in actual operation (Venkatesh et al., 2003). A working system that is unavailable to its users is not a working system.

5.2.5 Alerts Worked Best as Information, Not Instructions

A total of 47 alerts were raised throughout the experiment cycle, which comprised 18 alerts for temperature, 11 alerts for humidity, 14 alerts for feed levels, and 4 alerts for actuator malfunction. Out of the 18 alerts raised for temperature, 16 alerts were resolved without any intervention from the farmer when he received the alert message.

Such an insight tells us something concrete about designing alerts for IoT-based agriculture projects. The natural inclination when building alerts into an app is to keep the number of alerts low – to only alert the user when there is something to be done. Yet in this instance, informational alerts served a purpose that went beyond functionality and added a degree of trust to the system. In being notified of rising temperatures and the subsequent activation of the fans,

the farmer does not need to make an inspection. Such trust is valuable in ways that can't be easily measured by FCRs (Valtchev and Penchev, 2014).

The special Alerts screen with its timeline of notifications also gave the farmer another thing they have never seen before – a log of what happened during the night while the brooder worked. In fact, in several mornings, the farmer would first check the log of notifications before making a first visit to the barn. There were days when, seeing that the notification log is empty, the farmer did not even make the visit at all.

5.2.6 Building on a Custom Backend Was the Right Technical Decision

The decision to utilize the customized Golang backend in conjunction with the EMQX backend has been proven wise, thanks to the cycle's results. The sensor data transmitted via the MQTT pub-sub approach took an average time of 1.4 seconds to be delivered to the dashboard interface. The advantage of the custom API included full control over the data model as well as authentication mechanisms without having to pay per request and comply with the data residence conditions established by third parties. The data persistence layer of the backend resulted in an untampered record of all the events from the sensors throughout the cycle.

This was the true test of the architecture on Day 11, when the connection to the Wi-Fi failed and remained interrupted for seven minutes. This was followed by the ESP32 continuing its operation using the Bang-Bang Algorithm independently while the EMQX broker held the outgoing messages in the buffer with Quality of Service Level 1, and 84 sensor data were saved in the ESP32. Once connection was restored, all 84 messages were transmitted successfully. The brooder did not even notice this interruption in connectivity. In the rural area of Mutasa District, this level of resilience becomes critical (Li et al., 2020; Hunkeler et al., 2008).

5.2.7 The Analytics Dashboard Changed What the Farmer Could See About Their Own Operation

Prior to this system, the farmer had an approximate idea of how many chicks they had lost by the end of a cycle. They were unaware of their FCR. They were unaware of their total feed consumption. They were unaware of the week when their rate of weight gain was at its maximum and whether their consistency score throughout the cycle was improving compared to

the last cycle. These are not mysterious commercial indicators; these are the basic figures a farmer must be aware of to assess if their business is running efficiently.

These figures were presented to the farmer in the Analytics screen in a format readable from the phone. An FCR of 1.8 presented along with their previous manual-brooder FCR of 2.6 is not only a number; it is also a reason to keep using the system. Moreover, if the results are conveyed to the agriculture extension officer, then the performance of various farmers can be compared against each other and the best practices followed by the top-performing farmers can be identified. This is the first step towards collecting data for large-scale smallholder poultry development (Cheng et al., 2020; Susnjak et al., 2022).

5.2.8 The System Worked in the Conditions It Was Designed For, and That Is Significant

The proof that a system based on IoT technology is functioning is rather easy to provide when the system is tested under controlled lab conditions. Providing such a demonstration when the IoT-based system needs to function for 28 days in a farming setting where there is unreliable electricity, Wi-Fi connectivity, a wide range of temperatures, and only one person in charge is significantly more difficult. And this study provided such difficult proof.

Not a single failure of firmware or a sensor. No data loss. The farmer interacted with the application on 26 out of 28 days. Approximately 483,840 sensor measurements were recorded without any interruptions whatsoever. The results of this study are not sensational, yet they prove the ability to implement the proposed solution effectively. A system working flawlessly in demos and failing when deployed in a real-life situation is useless since it will only destroy the users' trust (Farooq et al., 2022; Zanella et al., 2022).

5.3 Recommendations

The following recommendations emerge directly from the experience of designing, building, and deploying the SBMS across the brooding cycle. They are offered not as an abstract wish list but as a genuine account of what this study revealed needed to change, improve, or be investigated further.

- A camera-based scanning module should be integrated into the system to help farmers detect birds that may become ill. Using computer vision, the system can monitor feeding

behaviour, movement patterns, and signs of weakness or isolation within the flock. When abnormal behaviour is detected, the system can alert the farmer early, allowing faster intervention and reducing losses caused by disease outbreaks

- Add ammonia and carbon dioxide sensors to the next hardware iteration. This study monitored temperature, humidity, and feed level. Those three variables do not fully characterise air quality in a brooder. Ammonia from litter decomposition is a major cause of respiratory disease in young chicks and is not detectable by the current sensor array. A sub-threshold ammonia reading that sits just below the danger level for weeks is invisible to this system. It should not be.
- Build cycle-on-cycle comparison into the Analytics Dashboard. Currently the farmer can see their metrics for the current cycle. What they cannot see is whether this cycle's FCR of 1.8 is better or worse than the last cycle, or whether their mortality rate is trending down over time. Longitudinal comparison is where analytics becomes genuinely useful for farm management decisions stocking density, feed formulation changes, seasonal adjustments. The data to power this feature is already being stored; the dashboard just needs to surface it.
- Test the system under seasonal extremes before declaring it production-ready. Seasonal performance variation could be significant and should be documented before farmers stake a brooding cycle on a system that has only been tested in favourable conditions.
- Investigate whether the mobile application can be adapted for feature phones or USSD interfaces in areas where Android smartphone ownership is not yet universal. The current application requires an Android device. In parts of rural Zimbabwe, basic feature phones remain the primary mobile technology. A USSD-based alert and status-check interface would not replace the full Android application but would extend access to the system's most critical function knowing whether the brooder is currently within safe parameters to a much wider potential user base.
- Conduct a data privacy compliance review against Zimbabwe's Cybersecurity and Data Protection Act (2021) before any commercial deployment. The Golang backend stores farmer registration data, and timestamped sensor logs. These are personal and commercially sensitive data. The Act imposes obligations around consent, data

minimisation, retention periods, and breach notification that the current system has not been formally assessed against. That assessment should happen before any farmer's data is stored on a production server.

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