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IoT-powered system for environmental conditions monitoring in poultry house: A case of Tanzania

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Poultry health is imperative for the continued growth of poultry and increased production. Environmental conditions such as temperature, humidity, and ammonia gas have an impact on poultry health. They affect the respiratory system and eventually cause death. In Tanzania, most smallholder farmers use charcoal and kerosene stoves to control the environmental parameters since they have limited access to low-cost, secure, and user-friendly poultry house monitoring systems. However, these traditional methods are unreliable, difficult to manage, not environmentally friendly, and inaccurate. Data were collected from 120 poultry farmers in Arusha and Kilimanjaro regions using convenience and snowball sampling techniques. Of the respondents, 43% revealed that smallholder farmers do not adopt automated systems despite being available because they are expensive. In this study, a system based on the Internet of Things (IoT) was developed for environmental conditions monitoring in poultry houses for low-resourced smallholder farmers in Tanzania. The system saves time (84%) and labour costs (66.7%) compared to the traditional system, as the farmer can monitor and control the conditions securely, reliably, and remotely. The study also proposes an algorithm for the system to work online and offline (i.e.,, synchronizing with the cloud server when internet access is available).

Keywords: conditions, environment, IoT, monitoring, multifactor authentication, poultry health

Introduction

The high demand for quality chicken products like meat and eggs has been growing globally in recent years. By the year 2050, it is estimated that the demand for poultry meat will be more than 40% higher than the current demand (Astill et al. 2020). The high demand for meat is because poultry products are affordable and a good source of nutrition. Poultry is also an income source for subsistence farmers. Poultry birds need to be raised in suitable environmental conditions to ensure their health and welfare (Edmond 2018; TLMP 2018).

Temperature, humidity, and ammonia are the primary environmental conditions that seriously affect poultry health (Ahmadi et al. 2019; Kocaman et al. 2006). The optimal temperature required in a poultry house is 20–26°C (Saeed et al. 2019). Above that range, the flock takes less food and suffers from heat stress, and when the temperature is below the range, the flock consumes more food than the required, that is costly to the farmer. The recommended amount for ammonia is less than ten (10) ppm, and humidity should be around 50–70% (Islam et al. 2019; Najafi et al. 2015; Oloyo 2018). Beyond the thresholds described above, it causes difficulty in breathing and vision due to lesions in the bird's airways and eyes (Hitimana et al. 2018; Mahale 2016).

In Tanzania, monitoring temperature, humidity, and ammonia gas in the poultry house is still challenging. Farmers use charcoal stoves and kerosene lamps to control temperature and humidity inside the poultry house (Edmond 2018; FAO SHFS 2015; TLMP 2018). They also use commonsense or devices such as thermometers and hygrometers to monitor conditions inside the poultry house. These methods are manual, inaccurate, and challenging to manage as the farmer has to visit the farm to monitor these parameters (Msami 2000; Phiri et al. 2018). In addition, charcoal promotes environmental pollution due to deforestation and the emission of carbon dioxide into the air (Edmond 2018).

Related work

Internet of Things

The Internet of Things (IoT) is a potential technological solution for smart remote monitoring of environmental conditions. IoT is the interconnection of devices that communicate and exchange data over the internet. The wide use of IoT in the automation and monitoring fields includes home automation, health, industrial, and environmental monitoring (Abdul-qawy et al. 2015; Miorandi et al. 2012; Pereira et al. 2020). This study uses IoT infrastructure to realize the remote monitoring system in the poultry house.

Multi-factor authentication

Multi-factor authentication (MFA) is a zero-trust security mechanism used to identify a user by requiring additional credentials (Mathew and Thomas 2013). For instance, instead of asking for only a username and password, the system may go further and require a code generated from the user's phone, facial recognition, voice recognition, retina or iris scanning, behavioural analysis, or requiring answers to specific questions. The appropriate use of the MFA features enhances protection from different attacks, for example, phishing, denial of service (DoS), eavesdropping, and many others (Griffin 2017; Mathew and Thomas 2013). Consequently, MFA has been integrated into our work to enhance security.

A low-cost IoT system for monitoring temperature, humidity, ammonia, and luminosity environmental parameters in poultry farms was proposed by Pereira et al. (Pereira et al. 2020). Sensors DHT 22, MQ 137, and LDR for measuring these parameters were connected to Wemos Mini D1. The system sent data to a cloud server where a client can access them through an Android mobile application. The model showed promising outcomes, demonstrating that its execution is feasible. However, the monitoring portal is not scalable and does not provide a mechanism to control temperature, and the author suggested the improvement of software engineering in the mobile application.

Another IoT solution to monitor temperature, humidity, and electricity in the cage with poultry under research was presented by Manshor et al. (2019). The authors used a Raspberry Pi (RPi) to connect to the DHT 11 sensor to read temperature and humidity values. The system used a Google firebase database for storing real-time data and status from the sensor devices. Moreover, a mobile application was developed to access the data and send alert notifications to users. However, the firebase database provides only a small storage capacity for data. Also, the system does not provide a mechanism to control them. Furthermore, a poultry house requires two or more nodes to monitor the conditions effectively; therefore, using RPi as a node by connecting directly to sensors costs more than using nodeMCU.

In addition, Phiri, Kunda, and Phiri (2018) proposed a low-cost model to monitor conditions in a broiler house's environment and send data to a client in real-time. In the proposed model, Arduino Uno boards are utilized for gateway and sensor hubs. Zig bee, GSM, and GPRS are used to provide connectivity. The proposed system monitors the temperature, humidity, and intruders using DHT11, PIR, and Ultrasonic sensors, respectively. However, one of the system's limitations is that it neither monitors ammonia gas nor works offline (i.e., when there is no internet connectivity). Also, little is known from the proposed model on incorporating security, scalability, and reliability issues.

Many studies describe poultry monitoring systems, but to the best of our knowledge, only a few have reported security, reliability, and scalability issues, as discussed by Farooq et al. (2020). Also, the monitoring platforms of many automated poultry systems are not centralized. For example, a farmer with three distributed coops needs three monitoring platforms that are both difficult to manage and cost-ineffective. Therefore, this study also proposes an IoT system that fills the previous studies' gaps while introducing new features such as a system to work in online and offline mode to accommodate the local context.

Specifically, the study seeks to answer the following research questions: *(i) What are the key factors that hinder the adoption of automated poultry monitoring systems among poultry farmers in Tanzania? (ii) How can the IoT-powered monitoring system be developed to suit the Tanzanian context?*

Methodology

Study area

This study was carried out in the Arusha and Kilimanjaro Regions, located in the northeastern part of Tanzania. Arusha region lies south of the equator between latitude 2°S and 6°S, while Kilimanjaro lies south of the equator between latitude 20° 25' and 40°15' S, and 36° 25' 30" and 38° 10' 45" E east of Greenwich. Kilimanjaro region borders Kenya in the north, Tanga region to the southeast and Arusha region to the southwest. Convenience and snowball non-probability sampling methods were used to reach 120 participants based on their availability and willingness to participate in the study. The same participant was used to refer the researcher to another individual within the population for participation in the study. A sample size of 120 participants was selected according to the Farm Level Applied Research for Eastern and Southern Africa (FARMESA) programme; the sample size of around 80–120 participants is satisfactory for most applied research studies in sub-Saharan Africa (Matata 2001).

System architecture

We developed our system using a design thinking approach. The design thinking approach is a paradigm that allows individuals to focus on people's needs when designing and implementing products (Kumar, Zindani, and Davim 2020). In realization of this concept, we created mock-ups, and poultry farmers from Arusha and Kilimanjaro regions in Tanzania were engaged to provide the requirements of the system. From these requirements, we developed a high-level system architecture diagram (Figure 1). The devices were based on a low-cost context, availability in the local market, and open-source.

A node (with sensor, fan, and heater) collects sensor data from the house and sends them to a local server (RPi gateway). The local server aggregates the data from different nodes, and forwards it to the cloud server using HTTP messaging protocol. The cloud server receives and processes data, sends back a response to the local server and ends the connection. A web portal platform facilitates farmers' monitoring and controlling the farm conditions in real-time. The system's design allows farmers to access the system online or offline.

Hardware components and communication protocols

NodeMCU

It is an open-source IoT development board for developing or prototyping IoT systems. The kit has a RAM of 128KB and 4MB of flash memory for data and programme storage. It also has Wi-Fi and Bluetooth microchips built-in and a deep sleep operating feature that is suitable for power optimization. The node uses 3.3 V power and can be driven directly from the adaptor or PC through a micro USB port or from an external power source through a Vin Pin. We used NodeMCU ESP8266 to collect and forward the sensed data to the local server/gateway. To achieve this, we developed a C ++ program using the Arduino IDE and uploaded it to NodeMCU.

Raspberry Pi

Raspberry Pi (RPi) is a small, low-cost system on chip (SOC) device with standard computer capabilities. Our

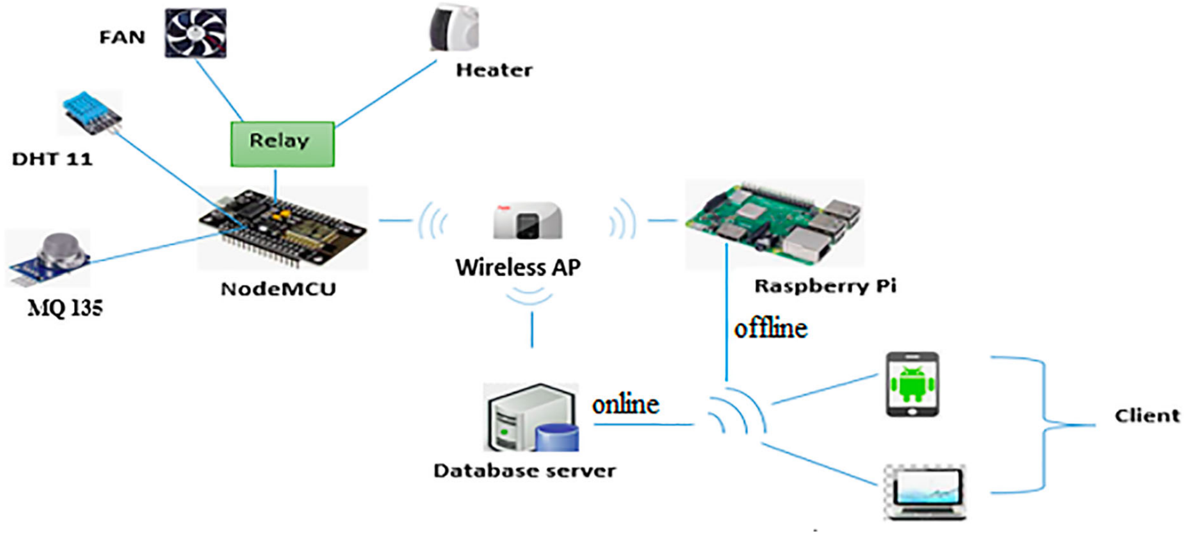


Figure 1: High-level system architecture for a reliable poultry monitoring system.

work uses the Raspberry Pi 3 Model B+ as a gateway and a local server to allow our system to work offline too. Raspberry Pi 3 Model B+ (Handigolkar, Kavya, and Veena 2018) is the latest version with 2.4/5 GHz 802.11b/g/n/ac Wi-Fi connectivity, 4 USB 2.0 ports, low energy Bluetooth 4.1 module, and 300 Base T ethernet port. Other features encompass ARM Cortex-A53 CPU of 1.4 GHz speed, a micro SD card, HDMI audio, and video output, and has 40 general purpose input output (GPIO) pins for digital input and output operating at 5 V/2.5A.

Sensors

These are devices capable of responding to external changes in the environment (Islam et al. 2019). In our work, we used the DHT11 sensor for reading temperature and humidity. The DHT11 sensor module is pre-calibrated by the manufacturer and hence does not need calibration. MQ135 was used to read ammonia gas in the poultry house. The detection range of MQ135 is 10 ppm–300PPM. The MQ135 sensor is highly sensitive to ammonia and other harmful gases such as benzene and carbon dioxide.

Wireless access point

The wireless access point (WAP) facilitates the connection of NodeMCU ESP8266 to the RPi gateway and the cloud server through the 2.4 GHz WI-Fi protocol.

Communication protocols

Various communication protocols exist for device-device, device-processor, or inter-processor communication. We use inter-integrated Circuit (I^2C) protocol to facilitate the communication between the NodeMCU processor and sensors. Unlike UART and SPI, I^2C uses two pins, which are CL and DAL, to communicate with the processor (Circuit Basics 2017; Leens 2009).

Wi-Fi protocol was also used to enable wireless communication between nodes and gateway and a cloud server. Wi-Fi is a good, reliable, and secure protocol for sending and receiving data between devices. Wi-Fi is now ubiquitous and the cheapest wireless network protocol after Bluetooth. Nearly all smart devices come with Wi-Fi embedded inside (Camps-Mur, Garcia-Saavedra, and Serrano 2013). Such smart devices include smartphones, laptops, smartwatches, et cetera.

Software development

Different software methodologies exist in developing software. In our work, we used agile development methodology to develop both web and mobile applications. In agile methodology (Figure 2), instead of the product being delivered as a whole, it was delivered incrementally (iterations). Each iteration follows the system development life cycles (SDLC), whereby a complete product increment is deployed for every iteration. Scrum is one of the agile development frameworks used in our work. In scrum, all requirements (user stories) are piled from time to time to form a product backlog. A few requirements (sprint backlog) are chopped from the product backlog based on the highest priority. All the sprint backlog requirements are then planned, designed, implemented, tested, and delivered as a shippable product increment in a given timebox (Vallon et al. 2018).

Our study identified two primary actors (Farmer and Admin), and their use case diagrams are shown in Figures 3 and 4, respectively. The core functions of the farmer are to monitor, control, and manage the farm conditions, while admin core functions are to perform the registration for a farmer, coop, and nodes, plus all activities a farmer performs. From the use-case diagrams, we developed a web portal for the farmer to interact with the system. We used PHP language and an open-source MySQL database management system for web portal development. We describe the results of our development in the result section of this paper.

System security implementation

Data/information could be tampered with during transmission or accessing (data at rest). During transmission,

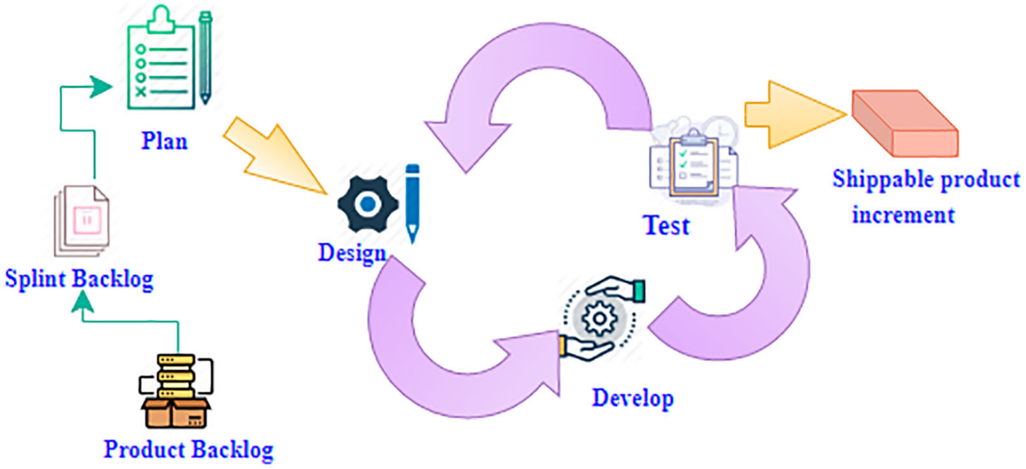


Figure 2: Agile (Scrum) software development model.

data could be vulnerable to man-in-middle attacks that could mislead the client's data. For example, an attacker could report a low temperature while in the field, the temperature is high. Tampering with the system can cause the death of flocks and result in a significant loss for the farmer. Also, while accessing data, a brute force attack could affect the confidentiality, availability, and integrity of the data. In our work, we used MFA and secure socket layer (SSL) to ensure data security when the system is accessed and during transmission, respectively.

In our study, we used codes generated from the user's smartphone to implement MFA. When the user logs in using a username and password, the system

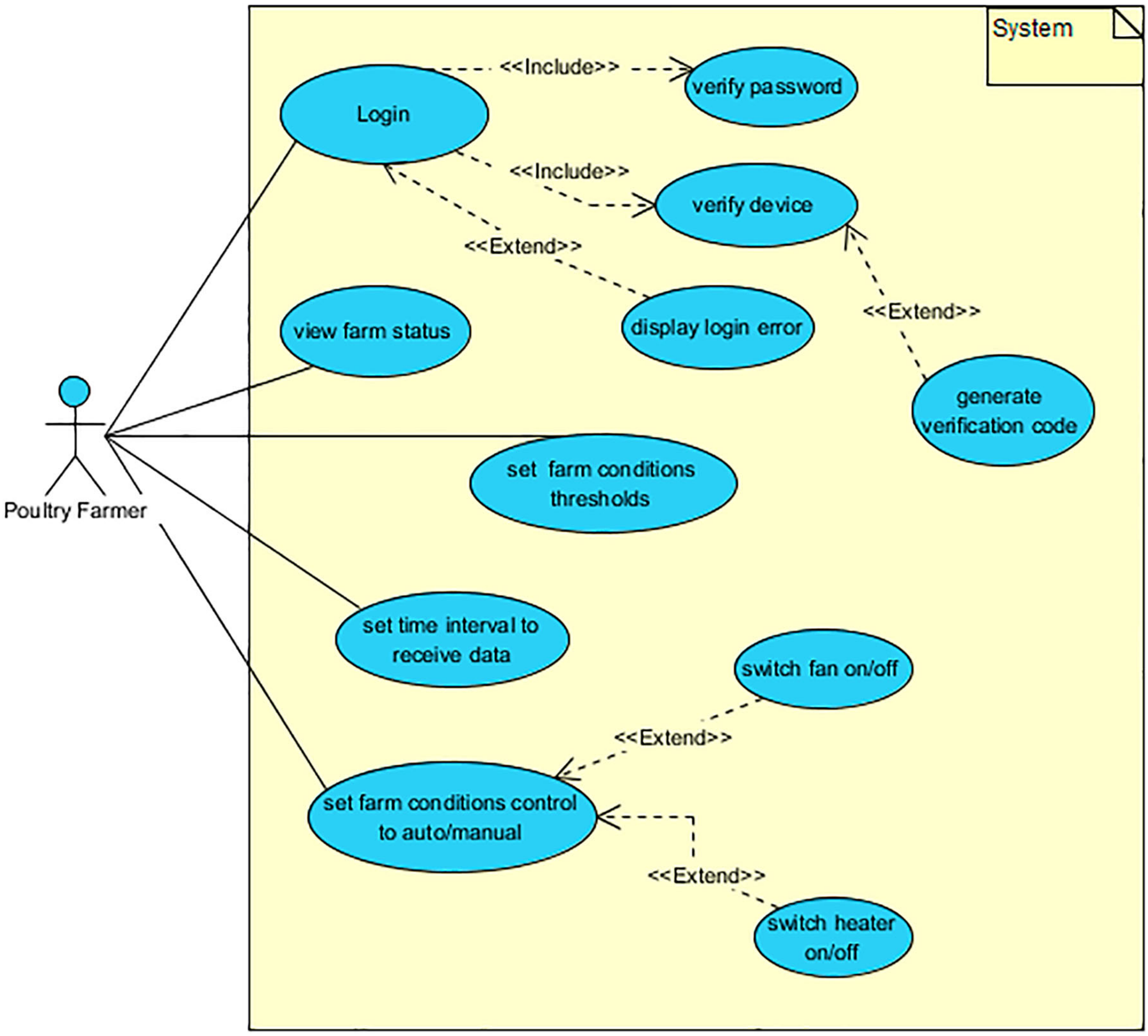


Figure 3: Poultry farmer's use case diagram.

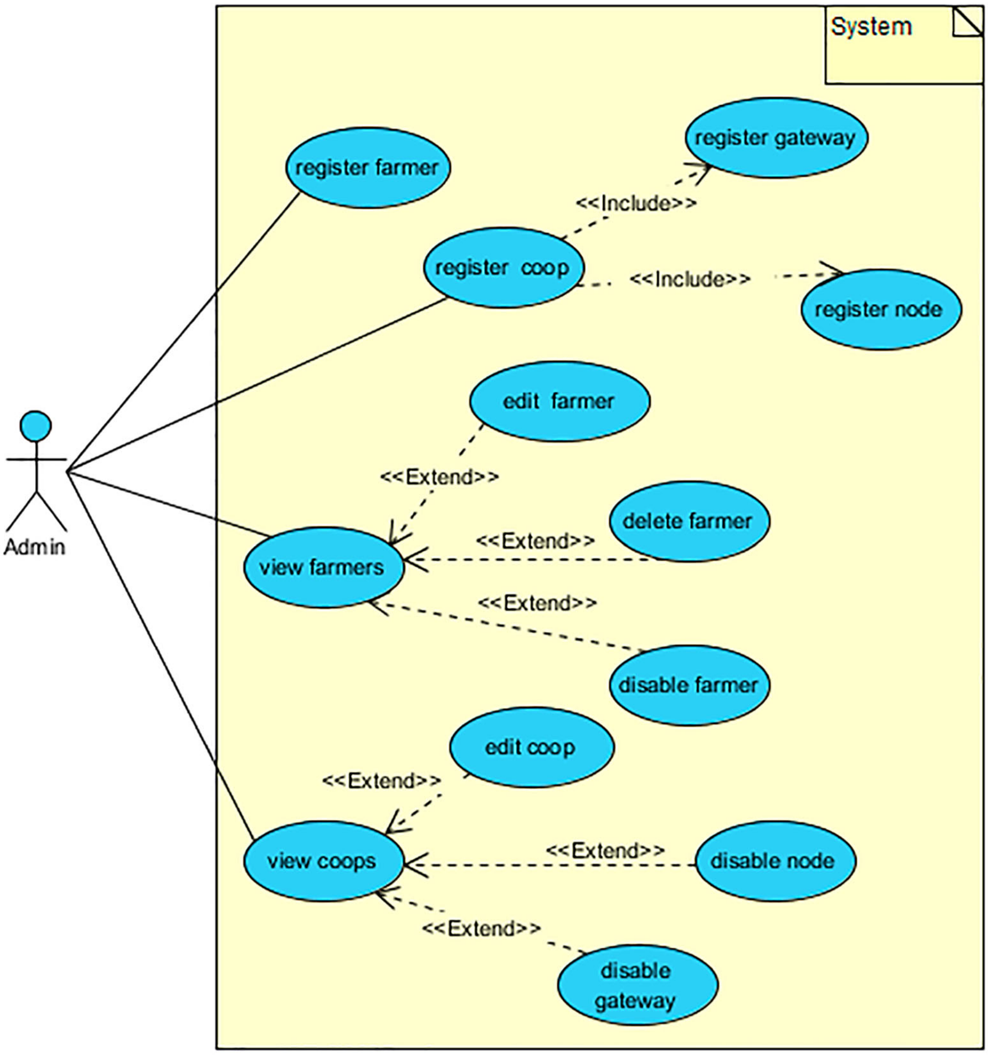


Figure 4: Admin's use case diagram.

simultaneously verifies the device, generates the code, requests the user to enter the code sent, and then grants the user access to the system upon meeting the predefined criteria.

We used an SSL security algorithm to secure data during transmission. SSL is widely used in cryptography for encrypting and decrypting messages because of its enhanced security. The SSL certificates contain data about the entity the certificate was delivered for, digital signature, and public key (PK) for encryption and digital signature proof. We installed SSL certificates in the webserver; the same keys are uploaded to the NodeMCU and Gateway when uploading the firmware software to these devices. The node and gateway use these certificates to encrypt and decrypt the message sent or received from the cloud server.

Reliability testing

Reliability is the statistical measure that defines the degree to which a system operates correctly over a given operation time (Menčík 2016). To determine and improve our proposed solution's reliability, we set up an experiment and recorded observed reliability and failure for seven days, as tabulated in Table 1. However, we made the following assumptions in the experiment:

- The system reliability is observed every two hours from 0800–0000 h a day for seven days. In this case, we have 16 h of operation per day.
- In every observation, the system is marked '1' if it performs all of the following core functionalities correctly: (i) monitor parameters, (ii) control parameters, and (iii) report sensor node failure. Otherwise, it is marked '0'. In summary, 1= reliable and 0 = failed.
- If the system is marked '0', then the failure plus fixing time is regarded as occuring within one hour.

Based on the data in Table 1, we used the following equations to estimate the system reliability:

$$\text{Total operating hours}\,(Nh) = 16hrs/day\,x\,7\,days$$
$$= 112\,hours \tag{1}$$

$$Down\ Time\,(Nf) = 9hrs \tag{2}$$

$$Reliability\ R(t) = 100{*}(Nh{-}Nf)/Nh \tag{3}$$

Table 1: System's operation for seven days.

Time (hrs.)	day 1	day 2	day 3	day 4	day 5	day 6	day 7
08:00	1	0	1	1	1	1	1
10:00	1	1	1	1	1	1	1
12:00	0	1	0	1	1	1	1
14:00	1	0	1	0	1	1	1
16:00	0	1	0	1	1	1	1
18:00	1	1	1	1	1	1	1
20:00	1	0	1	1	1	1	1
22:00	0	1	1	1	1	1	1
00:00	1	1	1	1	1	1	1

The computation of the system's reliability for seven (7) days operation using equation (1) to (3) reached 91.96%. However, we learned from the experiment that its reliability was mainly affected by its power source and the position of the nodes. We discuss these factors in the discussion section of this paper.

Time evaluation

We evaluated at what percentage our proposed system saves time in monitoring and controlling poultry farm conditions compared to the traditional system. To achieve this, we developed assumptions, mathematical equations, and data from the survey. Data from the survey indicated that a farmer uses an average time of eight minutes to visit the site (poultry house), five minutes to monitor the conditions and 12 minutes to control the parameters (e.g., opening/closing the curtains) as summarized in Table 2. In addition, we assumed the system setting up for both tradition and the proposed system is constant. Furthermore, we assumed that our proposed system uses two minutes to send data to the server for simplicity, although by default, unless configured by the farmer, it is 15 s.

Mathematical equations

$$T_o = V_s + M_c + C_c \tag{4}$$

$$T_1 = M_c + C_c \tag{5}$$

$$T_s = \left[\frac{T_o - T_1}{T_o}\right] * 100\% \tag{6}$$

where, T_o = total time used by the traditional system, T_1 = total time used by the proposed system, T_s = time in percentage saved by the proposed system compared to the traditional system, V_s = time to visit the site, M_c = time to monitor conditions, and C_c = time to control conditions.

By using equations (4), (5), and (6), it was found that the proposed system saves 84% of the time compared to the traditional system.

Labour cost evaluation

We evaluated at what percentage our proposed system saves labour costs compared to the traditional system. To achieve this, we developed mathematical equation (7) with the following assumptions: both systems require labour to operate, and a farmer owns three (3) distributed coops. Table 3 summarizes the task and number of labourers required in both the traditional and the proposed systems.

$$C_l = \left[\frac{N_t - N_p}{N_t}\right] * 100\% \tag{7}$$

where, C_l = percentage labour cost the proposed system saves, N_t = number of labourers in the traditional system, and N_p = number of Labourers in the proposed system.

Using equation (7), the proposed system saves 66.7% of labour costs compared to the traditional system. However, 66.7% labour cost saved depends on the number of coops the farmer owns. For instance, the proposed system would save up to 75% of the traditional system's labour cost for a farmer owning four (4) coops.

Algorithm for a system to work offline and online

By default, unless configured by the farmer, the node forwards data to the local server every 15 s. When there is no internet connectivity, the node still sends data to the local server (Raspberry Pi) since both devices are in the same LAN network. In this regard, a client will still access the information and control parameters locally provided that both are within the same LAN environment. Figure 5 shows a flow chart for a system operation modes, offline and online, with its equivalent algorithm in Table 4. In this algorithm, the local server forwards data to the cloud server provided that the online mode is enabled and there is internet connectivity; otherwise, the system stores data locally until processed by a synchronization subroutine shown in Table 5. The synchronization subroutine forwards data to the cloud portal provided that

Table 2: Average time required in traditional system and proposed system.

	Average time (minutes)	
Task	Tradition system	Proposed system
Visiting the site	8	0
Monitoring conditions	5	2
Controlling conditions	12	2

Table 3: Number of labourers required in traditional system and proposed system.

	Number of labourers	
Task	Tradition system	Proposed system
Monitoring and controlling conditions in three distributed coops	3	1

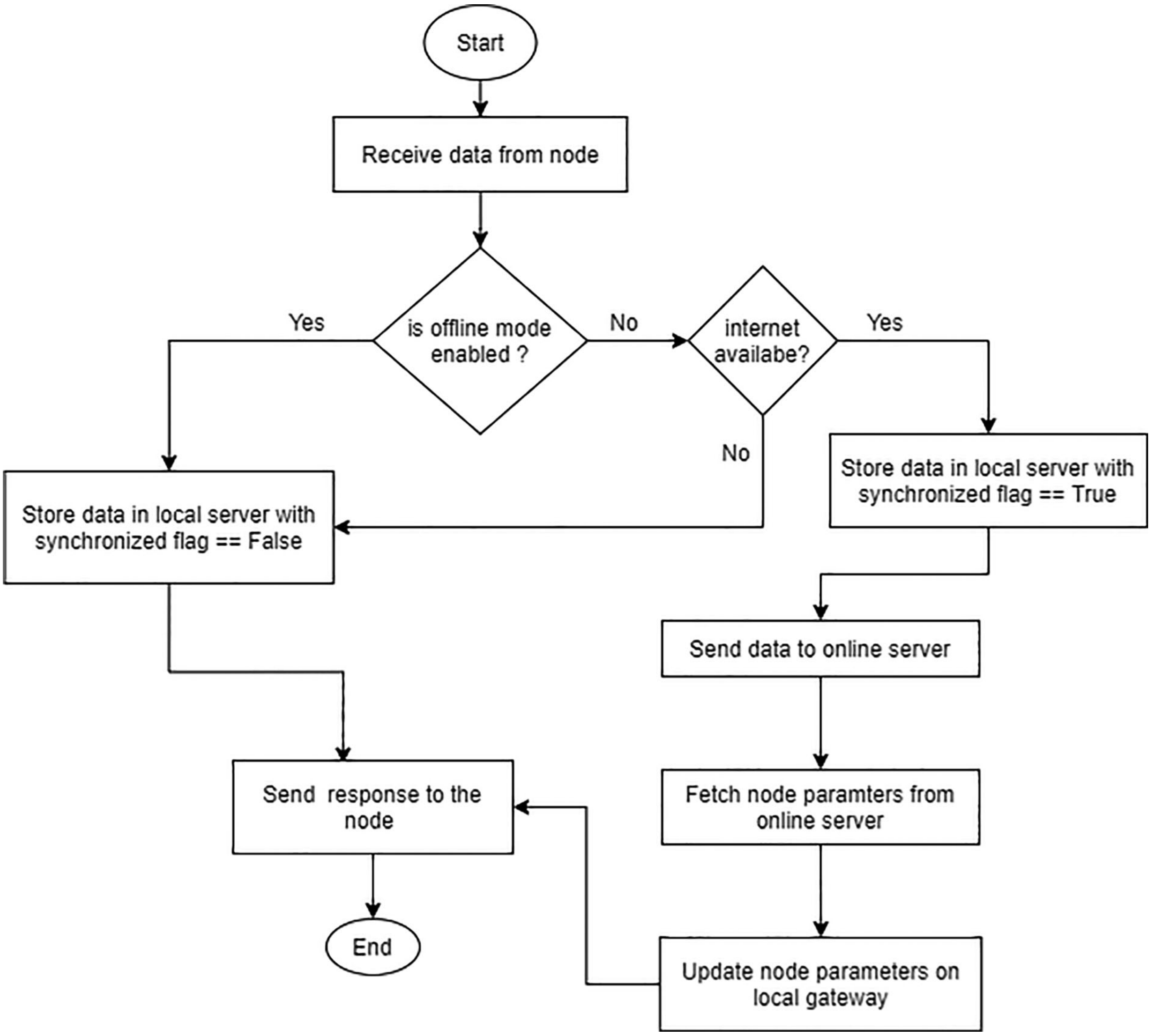


Figure 5: A flow chart for the system to work offline and online.

there is data to be synchronized, the online mode is enabled, and the internet is available. After two days, the data is deleted to prevent the local server from running out of memory. However, the system keeps monitoring the locally-stored data.

Scalability

We developed a scalable system that allows farmers to monitor as many coops as they own in real-time, switch a system to automatic or manual control, set threshold values based on the age of chickens, and set time intervals for the sensor to send data. For instance, when the user enables automatic mode, the device can spontaneously monitor and control the parameters. The system automatically checks if the temperature is out of the acceptable range and controls this by switching on a fan or heater. When manual mode is enabled, the tool monitors only the parameters and waits for the user to issue the command to control those parameters. Generally, the same software system can be utilized by the farmer to keep chickens of different ages and add new coops as they wish without affecting the software system.

Results

Poultry farmers' demographic characteristics

From Table 6, out of 120 respondents, 75 (62.5%) were male while 45 (37.5%) were female. The maximum age group was 60 years and above, while the minimum age group was 20–29 years. The majority of respondents were aged between 30–39 years, constituting 35% of the whole sample size. Also, the findings indicated that

Table 4: An algorithm for a system to work offline and online.

```
Algorithm 1-System to work offline and online
Receive data from a node – after every predefined time interval
If is_offline_mode == True || is_internet_available ==False Then
    Data_synchronized_flag ← False
    Store data in local DB server
    Send response to the Node
Else
    Data_synchronized_flag ← True
    Store data in local DB server
    Send data to online DB server
    Fetch node parameters from online server
    Update node parameters on local server
    Send response to the Node
End If
```

Table 5: A subroutine algorithm to synchronize data between the local and online server.

```
Algorithm 2 – A subroutine to synchronize data between the local and online server
1. Do While (is_data_available == False)
2.     μ ← Fetch data with data_synchronized_flag == False
3.     If μ! = Null Then
4.         is_data_available ←True
5.     Else
6.         is_data_available ← False
7.     End If
8. End While
9. If is_offline_mode==False && is_internet_available ==True Then
10.    Send data to online DB server
11.    Data_synchronized_flag ← True
12. End If
13. If is_data_over_two_days == True Then
14.    Delete the data in the local DB server
15.    Call step 1
16. Else
17.    Call step 1
18. End If
```

many poultry farmers have a primary education level (29.2%) followed by secondary level (25.8%) while certificate level was the lowest (10.8%).

There were no poultry farmers whose education was non-formal. This indicates that the two regions have a high literacy rate.

Methods used by farmers to maintain poultry house conditions

The study found that about 47.0% of farmers use curtains to maintain the temperature, humidity, and ammonia in the poultry house, while 34.8% use charcoal. Furthermore, the study found that 13.6% of the farmers use

Table 6: Poultry farmers' demographic characteristics.

Demographic characteristics		Respondents	Percentage (%)
Gender	Male	75	62.5
	Female	45	37.5
Age (in years)	Less than 20	0	0.0
	20–29	21	17.5
	30–39	42	35.0
	40–49	24	20.0
	50–59	21	17.5
	60 and above	12	10.0
Education	non-formal	0	0.0
	Primary	35	29.2
	Secondary	31	25.8
	Certificate	13	10.8
	Diploma	17	14.2
	University	24	20.0

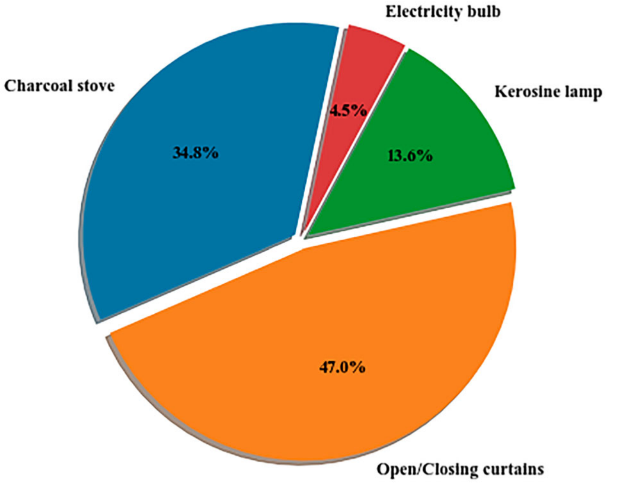


Figure 6: Methods employed by farmer to maintain poultry house conditions.

kerosene lamps while very few, about 4.5%, use electricity bulbs to maintain the poultry house's conditions. These findings are summarized in Figure 6 and reveal a need to develop a system that would provide farmers a potential alternative to using charcoal and kerosene lamps that are environmentally unfriendly.

Factors affecting adoption of smart poultry monitoring systems

The study revealed that, out of many factors, 43.0% of respondents reported cost as the leading factor which hinders the adoption of automated systems among poultry farmers, followed by lack of knowledge, 38.0%. In comparison, the fewest respondents (7.3%) reported that the systems lack some features to suit the local demand (Figure 7).

The developed system

We proposed, implemented, and evaluated an IoT-based system called ***Tanzakuku*** to monitor poultry house conditions. ***Tanzakuku*** comprises hardware and software. The hardware setup (Figure 8a) consists of nodes (with sensors, a heater, a fan), RPi gateway, and WAP. The setup was for testing purposes before deploying it to the field. Each node was then placed in a low-cost, waterproof container (Figure 8b), and then deployed in the field.

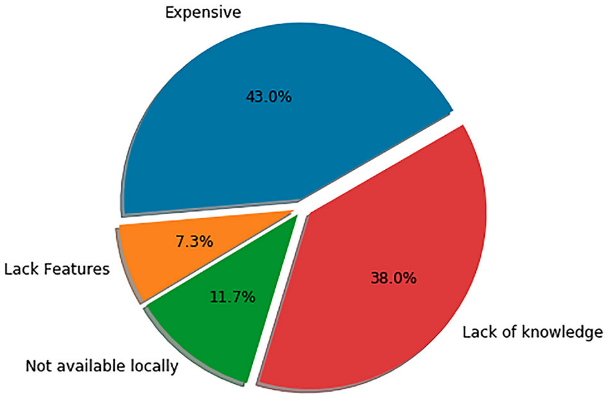


Figure 7: Factors affecting adoption of smart poultry monitoring systems in Tanzania.

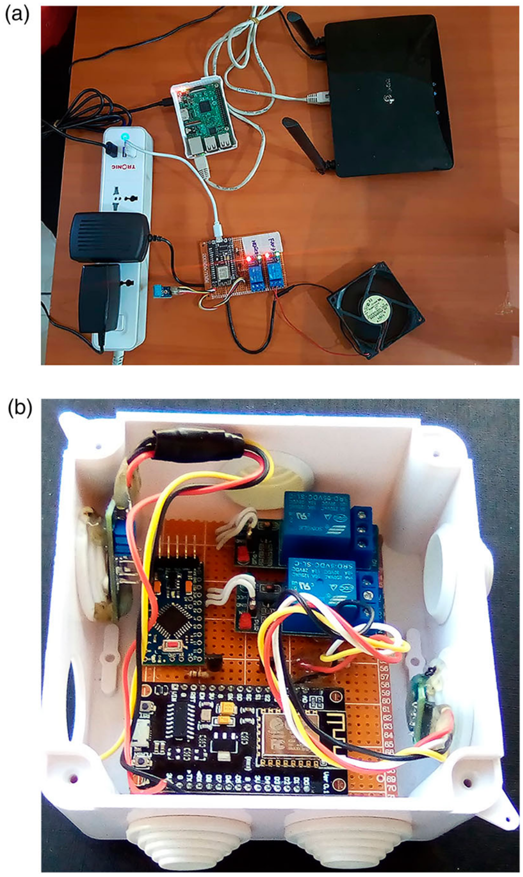


Figure 8. (a) Hardware setup for ***Tanzakuku*** before deploying to the field. (b) Sensor Node placed in a low cost water-proof container.

Authentication panel

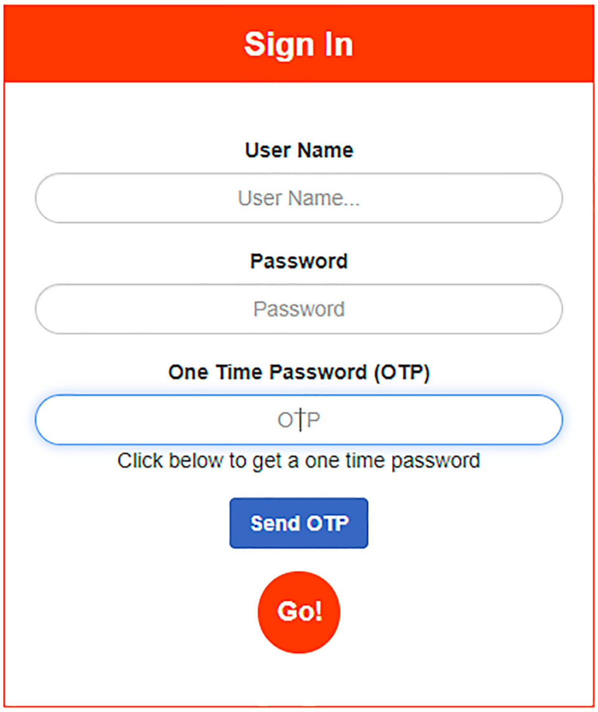
Figure 9 shows an authentication panel where the user supplies a username and password to login into the system. They then supply the code (One-Time Password) sent to their mobile phone for verification. The user is then presented with other pages like in Figure 10 upon successful login.

Discussion

A comparison standard error graph between the number of hours the system was operational against the downtime is shown in Figure 11. From the graph, the majority of data collected in 16 hours each day for seven days, about the number of hours the system was up, is significantly different from that of the same downtime. Uptime has, in fact, the highest number of hours, and it is conclusive. Table 7 summarizes statistical descriptions used to plot the standard error graph.

Also, the downtime decreased as the number of days increased. The reason for this decrease is because the factors identified as hindering reliability (listed below) were corrected as follows:

- ***Source of power:*** Some failures happened during the night because of a power cut-off. We used both micro-solar panels and LiFePO4 rechargeable batteries



Sign In

User Name

Password

One Time Password (OTP)

Click below to get a one time password

Figure 9: Login panel of the ***Tanzakuku***.

instead of depending only on micro-solar panels to rectify the power issue. We also implemented a deep sleep feature in NodeMCU to allow nodes to sleep in deep mode when waiting to send data. Furthermore, we opted for 2.4 GHz Wi-Fi technology, which uses low power compared to 5 GHz Wi-Fi technology.

- ***Position of the nodes:*** Initially, we put the sensor on the ground. However, they were disturbed by chickens. We, therefore, repositioned the nodes by hanging them from the roof using a reliable sword.

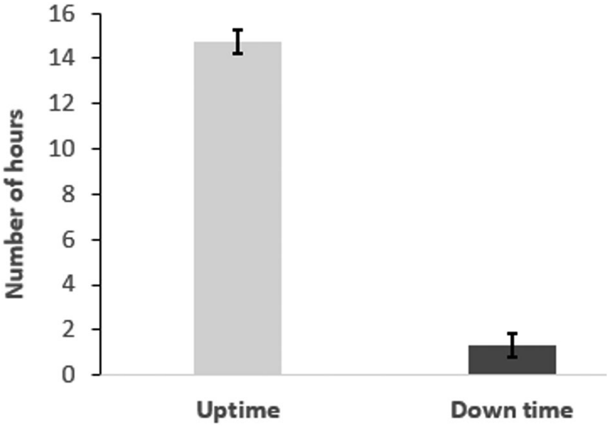


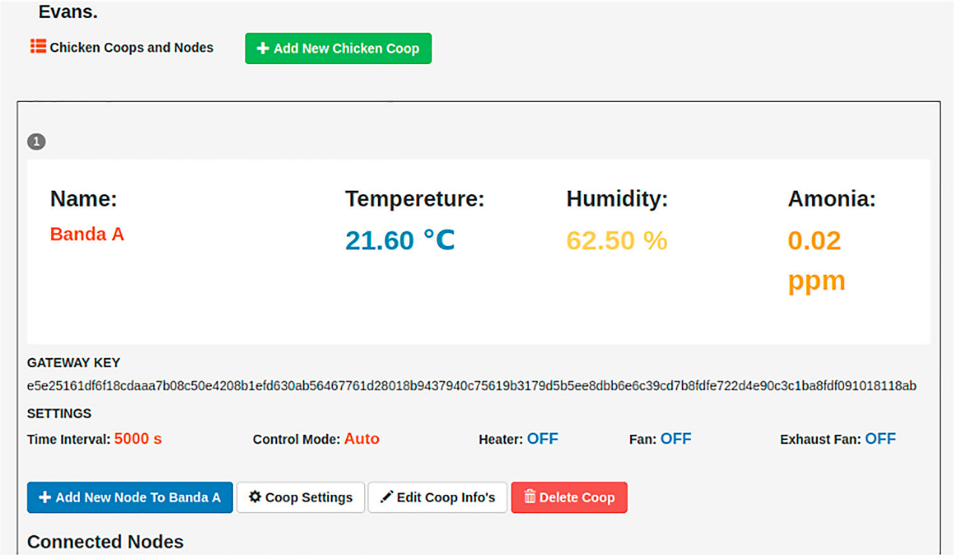
Figure 11: A comparison standard error bar graph for system's uptime and downtime.

Furthermore, there are two ways to access the system: online and offline mode. The online mode is used when a farmer is distant from the coop, where they are disconnected from Wi-Fi signals. The offline mode is used when the farmer is at home and does not have internet access. However, the LAN signal detection depends on the coop's distance from the farmer's house. The distance should be less than 100 m since 2.4 GHz Wi-Fi signals range up to 100 m. In this regard, the WAP should be positioned in a safe environment free from interference, diffraction, and attenuation.

The proposed system has not been evaluated for its efficiency in increasing poultry productivity against poultry farmers' traditional methods. Therefore, further experiments are needed to compare the extent to which the proposed system increases poultry productivity compared with traditional methods. This can be done by setting up two similar poultry houses running simultaneously, one with the proposed system and the other with the traditional methods at constant feed, number of chicken, and chicken age.

In summary, the significant contributions of this study are as follows:

- We have developed a tool to monitor environmental conditions remotely and securely through a web portal.



Evans.

Name: Banda A

Tempereture: 21.60 °C

Humidity: 62.50 %

Amonia: 0.02 ppm

GATEWAY KEY

e5e25161df6f18cdaaa7b08c50e4208b1efd630ab56467761d28018b9437940c75619b3179d5b5ee8dbb6e6c39cd7b8fdfe722d4e90c3c1ba8fdf091018118ab

SETTINGS

Time Interval: 5000 s

Control Mode: Auto

Heater: OFF

Fan: OFF

Exhaust Fan: OFF

Connected Nodes

Figure 10: Web portal interface for monitoring and control of parameters in the poultry house.

Table 7: Statistical descriptions for uptime and downtime.

Statistical description	Uptime	Downtime
Mean	14.71429	1.285714
Standard deviation	1.380131	1.38013112
Standard Error Mean (SEM)	0.521641	0.52164053

- We have developed a feature that allows farmers to monitor and control the farm in offline or online mode, when they are on-premise and off-premise, respectively. This feature supports both small-scale and large-scale farmers.
- We have developed a scalable system that allows farmers to monitor as many coops as they own in real-time, switch a system to automatic or manual control, set threshold values based on the chicken's age, and set time intervals for the sensor to send data.
- We have secured data during transmission from the sensor to the consumer (cloud server and mobile app) using an SSL algorithm.
- We have integrated MFA to secure access to the system.

Conclusion

This study indicated that the lack of awareness, lack of features to suit the local contexts, and the cost of automated systems are among the major factors that affect the adoption of smart poultry monitoring systems in Tanzania. Against this backdrop, we developed a secure, reliable, and scalable IoT poultry monitoring system that suits the Tanzania context by addressing the field survey and secondary literature's challenges. The system collects data from the field and sends them to the cloud database securely. We developed a centralized web-based portal to enable users to access the data securely. The proposed system saves both time and labour costs to farmers. We believe that the proposed system can be a solution to secure and reliable smart poultry monitoring systems. However, to improve our proposed system's security, incorporating emerging security technologies for distributed networks such as blockchain could be an exciting area for future works. Also, evaluating the proposed system's efficiency against the farmers' traditional methods is an open issue. Lastly, developing a mobile application with additional features such as a reminder scheduler for vaccination can also contribute significantly to the current work.

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