BULGARIAN ACADEMY OF SCIENCES
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A V T O R E F E R A T

ON THE DISSERTATION

for awarding the educational and scientific degree "doctor"

CYBER-PHYSICAL SYSTEMS FOR INTELLIGENT MANAGEMENT OF ANIMAL HUSBANDRY COMPLEXES

Scientific field: 5. Technical sciences

Professional area: 5.2 Electrical engineering, electronics and automatics.

PhD program: 2.21.07: Automated information processing and control systems.

Scientific supervisor: **Prof. Dr. Nayden Shivarov**

Bulgarian Academy of Sciences – Sofia, 2025

The dissertation was discussed and admitted to defense at an extended meeting of the Department of Cyber-Physical Systems of IICT-BAS, held on 16.09.2025.

The dissertation contains 178 pages, including 92 figures, 18 tables and 11 pages.
Literature includes 134 titles and 33 websites.

The defense of the dissertation will take place on .0.20… г. от ..:.. hours in Hall ..... of Unit 2 of IICT-BAS at an open meeting of a scientific jury consisting of: :

1. Prof.

2. Prof.

3. Prof.

4. Prof.

5. Prof.

The materials for the protection are available to those interested in room ….. of IICTBAS, ul. "Acad. G. Bonchev", bl. 25A.

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Title: CYBER-PHYSICAL SYSTEMS FOR INTELLIGENT MANAGEMENT OF ANIMAL HUSBANDRY COMPLEXES

General characteristics of the dissertation work

Relevance of the dissertation topic

Nowadays, microclimate management in livestock farms is becoming increasingly important. This is due not only to the growing demands for energy efficiency, increased productivity and sustainability, but also to the humane attitude towards animals. Microclimate is a set of parameters such as temperature, humidity, air speed, lighting and concentration of harmful gases, etc. which have a direct and indirect impact on the health, productivity and well-being of animals. Inappropriate conditions can lead to slowed growth, reduced productivity of meat, milk, eggs, increased morbidity and mortality.

The topic is especially relevant in the context of climate change and the introduction of increasingly strict environmental regulations. Automated systems can help to more efficiently use resources such as electricity, water and time for farm management. In addition, digitalization and the use of "smart" technologies fit into the trend towards building sustainable and precision agriculture.

The introduction of automated climate control systems is key to the modernization of farms. They allow precise control of the internal environment through sensors and algorithms that can manage the parameters of the environment in real time. Considering the cost of existing climate control systems in livestock farms, it is necessary to develop new systems that are accessible to a wider range of users.

Purpose and tasks of the dissertation

The aim of this work is to develop a Cyber-Physical System (CPS) for microclimate management in animal husbandry complexes and for environmental management in fish farming based on openHAB.

The object of the research is not only the study of the possibility of implementing the CPS with the selected software, but also the analysis of the influence of the environment on the productivity and health status of animals.

The subject of the study includes the need to consider the various parameters of the microclimate in livestock farms and the impact they have on the given species of animals directly and indirectly. The influence of the parameters and quality of water when raising fish or other aquatic animals in a closed ecosystem or so-called aquaponic system is also considered. Different methods for controlling these parameters are considered, because the environment affects both the health of the animals and their productivity and, last but not least, the humane attitude towards them. Therefore, it is very important to develop systems that can reliably control the environment, using minimal resources for this purpose.

Approbation of the results

Various parts of the results obtained have been reported at the following forums, conferences and workshops:

- ✓ „Third Interdisciplinary Doctoral Forum June 6-7, 2022. Park-Hotel "Kyustendil", Kyustendil", "Cyber-Physical System for Intelligent Management of a Cow Farm“
- ✓ IFAC Workshop on Control for Smart Cities., June 27-30, 2022, Sozopol, Bulgaria, “Algorithms for Cost Oriented Cyber Physical System (COCPS) for intelligent control of animal husbandry farms “
- ✓ IFAC International Conference on Technology, Culture and International Stability - 21st TECIS 2022, October 26-28, Prishtina (Kosovo) - Online „Cost Oriented Cyber-Physical System algorithm for pig farm microclimate and air quality control”
- ✓ 4th Interdisciplinary PhD Forum with International Participation, 16 – 19 May 2023, Sandanski, Bulgaria „Cyber-Physical System algorithm for pig farm microclimate “
- ✓ 5th Interdisciplinary PhD Forum with International Participation 16 – 19 April 2024 Kyustendil, Bulgaria “Poultry farm microclimate management by calculating felt temperature”
- ✓ XXXIII International Scientific and Technical Conference AUTOMATION OF DISCRETE PRODUCTION ENGINEERING “ADP – 2024” 27 - 30 2024” June 27 - 30, 2024, Sozopol Base of TU-Sofia “Cyber-physical system for microclimate management in livestock farms “
  Scientific seminar of IICT - BAS in the section "Cyber-Physical Systems", on 06.12.2024. 15:00 in hall 228 in block 2. Presentation on the topic: "Concept for a CFC for controlling a self-cleaning aquaponic module".

Publications on the dissertation topic

Scientific publications in referred journals and indexed in world-renowned databases (Web of Science, Scopus).

- ✓ „ Algorithms for Cost Oriented Cyber Physical System (COCPS) for intelligent control of animal husbandry farms“, Stefan Chivarov, Kristian Dimitrov, Nayden Chivarov; IFAC-PapersOnLine Volume 55, Issue 11, 2022, Pages 31-36, https://doi.org/10.1016/j.ifacol.2022.08.044

- ✓ „Cost Oriented Cyber-Physical System algorithm for pig farm microclimate and air quality control “, Kristian Dimitrov, Stefan Chivarov, Nayden Chivarov; IFAC-PapersOnLine Volume 55, Issue 39, 2022, Pages 336-341, https://doi.org/10.1016/j.ifacol.2022.12.047

- ✓ „Algorithm for Autonomous Management of a Poultry Farm by a Cyber-Physical System“ Special Issue Intelligent Animal Husbandry; Nayden Chivarov, Stefan Chivarov, Kristian

Dimitrov; Animals 2023, 13, 3252. https://doi.org/10.3390/ani13203252 CiteScore-4.9, Impact factor 2.7, Quartile Rank Q1 – Animal Science and Zoology

- ✓ “Concept of a Cyber–Physical System for Control of a Self-Cleaning Aquaponic Unit” Kristiyan Dimitrov, Nayden Chivarov, Stefan Chivarov, Tsvetelina Paunova-Krasteva, Emil Filipov and Albena Daskalova, AgriEngineering 2024, 6(4), 3843-3874; https://doi.org/10.3390/agriengineering6040219 CiteScore-4.7, Impact factor 3.0, Quartile Rank Q1 – Horticulture

Scientific publication in non-refereed journals with scientific review.

- ✓ „"Cyber-Physical System for Microclimate Management in Livestock Farms" Kristiyan Dimitrov, Automation of Discrete Production, Issue 6 July 2024, TU-Sofia Publishing House, ISSN: 2682-9584, https://mf.tu-sofia.bg/mntkadp/includes/archive/2024.pdf

Citations.

- ✓ Vatn, K.J.D., Kavallieratos, G., Katsikas, S. (2024). Threat Analysis in Dairy Farming 4.0. In: Katsikas, S., et al. Computer Security. ESORICS 2023 International Workshops. ESORICS 2023. Lecture Notes in Computer Science, vol 14398. Springer, Cham. https://doi.org/10.1007/978-3-031-54204-6_3

- ✓ Ibrahimov, B.; Stapleton, L.; Technology, International Stability and Culture (TECIS) – TC9-5 Exploring the Alignment of Control and Automation Systems with the United Nations Sustainable Development Goals (UN SDGs). IFAC-PapersOnLine Volume 58, Issue 3, 2024, Pages 176-181, https://doi.org/10.1016/j.ifacol.2024.07.146

- ✓ Tan, C.; Yu, Z. A Low-Carbon Emission Production Scheduling Algorithm of Intelligent Manufacturing based on Energy and Environmental Efficiency. Procedia Computer Science 2024, 247, 1215. https://doi.org/10.1016/j.procs.2024.10.146

- ✓ Kistanova, E.; Yotov, S.; Zaimova, D. Intelligent Animal Husbandry: Present and Future. Animals 2024, 14, 1645. https://doi.org/10.3390/ani14111645

- ✓ Montalvo, A.; Camacho, O.; Chavez, D. Cyber-Physical Systems for Smart Farming: A Systematic Review. Sustainability 2025, 17, 6393. https://doi.org/10.3390/su17146393

Dissertation content

This dissertation consists of an introduction, seven chapters, a conclusion, contributions and a list of cited literature. It consists of 178 pages, with the main content being placed on 156 pages, plus 11 pages of used literature including 134 titles and 33 websites.

CHAPTER 1. Introduction, analysis and systematization of existing research and practices on the topic

1.1 Introduction

The main purpose of the first two chapters is to demonstrate the need for this research and to define the problem area. Here, motivation is discussed, the goals, methodology and the tasks of the dissertation are presented.

1.1.1 Defining the problem

The first and second chapters examine the main problems that are on the agenda in modern animal husbandry and methods and practices for its improvement and development. In particular, attention is paid to the methods and means for improving the microclimate in closed livestock farms for raising dairy cows, pigs and broilers. Some basic problems in improving the environment for growing fish and plants in aquaponic systems are also discussed. The direct and indirect influence of the microclimate on the economic indicators of animal farms is examined. Existing microclimate automation systems with their main subsystems of leading companies worldwide are shown, as well as some scientific developments from the last few years are examined, in order to get a general idea of how far the development in the given area has come.

1.2 Influence of the environment on productivity in livestock farms

1.2.1 Influence of microclimate on milk production in a cow farm

Microclimate affects productivity both directly and indirectly. Temperature is the main factor that must be controlled to maintain the thermoneutral zone TNZ. At temperatures above 28 °C, even at low relative humidity, cows show a state of hypertension and heat stress [1,2] in which feed intake, milk yield, milk fat and protein production, as well as fertility rates are reduced [3]. The effect that temperature has on animals is directly related to the relative humidity RH. This is determined by the so-called temperature-humidity index (THI) [4]. High values of THI have the greatest impact on milk yield after two days [5]. At THI values around 68 we have the highest milk yield, and increasing THI values from 68 to 78 reduce DMI by 9.6% and milk production by 21% [6] feed intake starts to decrease the day after the onset of heat stress HS, while milk yield decreases on the second day after HS [7]. According to other studies [8], THI has no effect on milk yield at values between 35 and 72. Heat stress also affects the health of cows.

1.2.2 Impact of microclimate on meat production in pig and poultry farms

The microclimate seriously affects the health status and production of all age categories of pigs [9,10]. The increase in temperature above the comfort zone leads to a decrease in feed intake and, consequently, a progressive decrease in pig productivity [11]. It affects reproductive abilities, growth and development of the body, quality and quantity of production, the development of new diseases and mortality [12]. Deviation from the nominal parameters of the microclimate in the room leads to a decrease in the average daily weight gain and affects the safety of birds, especially in the autumn-winter period, as well as on productivity [13]. The optimal microclimate in poultry farms reduces the cost of poultry products by 15-20%. In cold, humid and poorly ventilated poultry farms, birds are up to 4 times more susceptible to disease, and their productivity decreases by 10-50%, although feed consumption increases by 10-30% [14]. Heat stress has a negative impact on feed intake, feed efficiency, body mass index, meat quality and mortality [15]. Despite advances in technology and modernization of the sector, poultry farming worldwide is significantly affected in terms of productivity, health and overall welfare of chickens by heat stress [16]. In poultry exposed to heat stress, abnormalities in the immune system, hormonal irregularities, respiratory difficulties and electrolyte imbalance are observed [17,18]. Ventilation has a serious impact on all parameters of the microclimate in the building, as well as controlling the presence of harmful gases in the premises.

1.3 Influence of the environment on aquaculture production in an aquaponic system

In connection with the increased consumption of food products in recent years, aquaculture has also developed significantly. Over the past 20 years, aquaculture in the EU has had a sustainable growth rate, with the share of fish obtained through aquaculture in the total harvest increasing from around 15% in 2000 to around 20% in 2021 [19]. Attention is also being paid to the recirculation of wastewater, which has a major impact on reducing pollution in aquaculture [20].

In high-density aquaculture, water pollution from waste products such as excrement, food scraps, etc. is converted into harmful substances such as ammonia NH3, nitrite NO2 and hydrogen sulfide H2S. These can be extremely dangerous in high concentrations for aquaculture. This can lead to large economic losses as well as negative environmental impacts on a global scale [21,22]. One of the advantages of aquaponics is the closed loop, in which fish waste released through the gills and as urine, which is mainly ammonia, is converted through the processes of nitrification [23] and mineralization [24]. Solid waste is also separated, some of which is converted to ammonia by microbial activity [23]. This reduces biological pollution of wastewater. Aquaponic systems can be located outdoors or indoors. There are many examples of combining aquaponics and greenhouses, and this approach is constantly evolving [25,26,27].

1.4 Summary

After careful review and analysis of the above facts regarding the influence of the environment and microclimate on farmed animals, we can conclude that the implementation of control over certain environmental parameters is of utmost importance for their welfare. Environmental management helps both to increase productivity and to improve the health of animals and, last but not least, ensures humane treatment of them.

We can summarize that in closed livestock farms it is necessary to control the temperature, humidity and air velocity, the presence of pollutants in the air such as harmful gases, dust particles and microbial contamination, as well as the lighting and ambient noise. In the second case, in an aquaponic system it is necessary to control not only the quality of the water, but also other parameters of the environment. These are the temperature and pH of the water, dissolved oxygen and carbon dioxide, ammonia, nitrites, nitrates and other parameters, as well as exposure to direct sunlight.

Therefore, it is necessary to review and compare the existing methods and means of environmental and microclimate control in animal farms and aquaponic systems. This comparison would allow analyzing some gaps and weaknesses, proposing new methods or more accessible ways of management.

CHAPTER 2. Research of existing methods and means

2.1 Existing methods for maintaining microclimate in livestock farms

As examples of leaders in the production of automation and control systems for livestock farms, we can consider companies such as Big Dutchman, Fancom, SKOV, etc.

2.1.1 Executive mechanisms

They offer a variety of equipment for maintaining the microclimate. They have different types of fresh air inlets, blinds, fresh air or circulation chimneys, fans, heating systems, sprayers for evaporative cooling, etc. Some basic components for microclimate management on livestock farms are discussed below.

Fresh air inlets for wall [28,29,30] or for ceiling [28,29] allow easy control by servomotors [28,29], being equipped with a spring that keeps them tightly closed, and the servomotor pulls them out. The fresh air chimney for fresh air [28.29] has the advantage over other ceiling flaps because they are not affected by wind speed.

Blinds are used when it is necessary to make the ventilation openings larger. For example, in warmer climates, in natural ventilation, in tunnel ventilation. Their control is like that of fresh air inlets, but some blinds are not equipped with a closing spring [28,30].

For tunnel ventilation, in addition to blinds, vertically opening flaps [29] or large panel flaps [28] can also be used. Both have less air resistance than louvers [28,29]. In many cases, it is more convenient and cheaper to use blinds [28] instead of flaps or louvers.

Fans used in livestock farms can be divided into several groups according to their purpose. These are fresh or exhaust air fans (inlet or outlet), circulation fans or mixed-type fans [28,29,30]. According to the design of the blades, fans can be divided into axial or radial (centrifugal). There are fans with or without flaps to close the opening. They can be without the ability to adjust the speed, with step regulation or with the possibility of stepless regulation. In recent years, etc. smart fans have appeared [29].

Various heating systems are available on the market. In addition to conventional steam heating with radiators or pipes, there are various methods of gas heating [28]. In recent years, heating systems with heat exchangers [28] have been used more and more often in livestock farms. With this, heating costs can be reduced by more than 50% [28].

Sprinkler systems [30,31] are used for air cooling and humidity control in premises, for directly wetting animals to cool them, for loosening dried dirt on walls and floors, and for disinfecting premises [30,31]. They can be used in poultry houses, pig farms, and cattle barns, and their main advantage over other cooling systems is lower cost. They are most effective in dry climates and at high temperatures. Evaporative cooling pads [28,30] are widely used in various types of livestock operations, particularly with tunnel ventilation. They are installed at tunnel inlets and work as follows. Water is poured over the top edge of the pads, wetting them. As air passes through the pads, the water evaporates, cooling the air without leaving water droplets that could wet bedding and worsen conditions inside the facility.

2.1.2 Sensors

Common sensors used to control microclimate in livestock farms monitor only some environmental parameters. These include temperature and relative humidity RH, which is usually a combined sensor, a sensor for ammonia NH_3, carbon dioxide CO_2, pressure, air velocity and illumination. Even global leaders in automation do not use sensors for continuous monitoring of carbon monoxide CO, methane CH_4, hydrogen sulfide H_2S, or fine particulate matter [28,29,30].

2.1.3 Climate-control computers in livestock facilities

On the market, there are various solutions for managing microclimate in livestock farms. At one end are control systems for a single room with support for several temperature sensors—these can turn heating and cooling on or off based on temperature, and ventilation power is adjusted manually, not based on measured temperature. At the other end are multi-zone systems with support for numerous sensors that can control every environmental component [28,29].

2.2 Existing methods for maintaining environment and controlling aquaponics systems

When it comes to automation in existing and commercially available aquaponics systems, it's still in its infancy. Aquaponics systems have been thoroughly researched, yielding enough information to create systems for controlling basic environmental parameters, but practically few such systems exist. Commercial aquaponics solutions from reputable global brands with long-standing experience offer minimal automation: they only monitor and regulate water temperature in tanks, air temperature in rooms, and pH. Other environmental parameters—water hardness, dissolved oxygen, carbon dioxide CO_2, ammonia NH_3, ammonium NH_4-, nitrites NO_2- and nitrates NO_3- are measured manually using reagent test kits and litmus strips.

2.2.1 Actuators

Choosing the right air pumps is crucial to provide the necessary dissolved oxygen DO. Pumps are mainly divided into two types based on their construction. The first are piston pumps and the second are turbine pumps [32]. Diffusers are needed to transfer more oxygen from air bubbles to water [23]. Diffusers [32,33] may be made from porous materials like volcanic rock or from various types of plastic, ceramic, or metal. Those with smaller pores are more effective but require higher air pressure, clog more easily, and need more frequent maintenance [23]. Electric heaters are mainly used to maintain temperature in aquaponic systems [32,33,34]. Often made of titanium due to its high corrosion resistance, heaters can come equipped with temperature sensors and in some cases, controllers. They can be installed submerged in tanks or in-line with circulating water [32,33,34]. In colder climates, using heat-pump installations is more cost-effective for water heating, significantly reducing heating costs, though initial investment is higher. Heat pumps can also cool water, which is critical for rearing cold-water fish that cannot thrive above 18 °C [23]. Automatic feeders are used for fish feeding and can dispense food very precisely [32,33]. Existing systems typically use timers to schedule feeding times and durations. Vibrating feeders are suitable for all types of food, and even oily foods pass through without clogging the feeder. Rotary roller feeders have a very accurate feed amount, and spreader feeders are suitable for larger areas because they do not pour the food in one place.

2.2.2 Sensors

Flow meters (for air and water) are used to monitor the operation of air pumps and water circulation pumps [32]. Generally, these include a normally open or changeover contact that activates when air or water passes through them. pH sensors [35] are available that can trigger alarms if the value exceeds or falls below predefined thresholds.

2.2.3 Aquaponics system controllers

Feeders in these systems are time-controlled [32]. Timers range from simple units with settings for on-time and duration to specialized timers capable of managing one or more feeders [32].

Many aquaponics equipment suppliers use the Sensaphone 800 controller [32,33] for monitoring and remote access, as it can monitor several temperatures and has inputs for various alarms. If a threshold is exceeded or an alarm is triggered by a sensor or flow meter, the controller can call preset phone numbers and play different recorded voice messages depending on the alarm triggered.

In recent years, with IoT and affordable electronic sensors, various scientific developments have emerged for continuous monitoring and remote access in aquaponics systems, often including partial control, though temperature is the only parameter usually controlled automatically. Below are some examples of existing systems and research, mainly concerning DWC systems.

2.2.4 Examples of existing research on monitoring and control systems in aquaponics

With the development of the Internet of Things (IoT) and the emergence of affordable electronic sensors, many developments have emerged for continuous monitoring and remote access to information, which also include partial control over aquaponic systems.

A monitoring system for an aquaponic system has been developed [36] in which it was found that the metabolism of fish is directly related to the amount of oxygen they consume. Active movement of fish is peaked for the period before, during and after feeding, for about 15 to 30 minutes [36]. Taking this into account, it is necessary to monitor the DO change during active movement, and not only when the fish are at rest.

Another system measures pH, water level, temperature, electrical conductivity EC, total dissolved solids TDS, ammonium NH_4+, nitrite $NO_2−$ and nitrate $NO_3−$. It also measures air temperature, relative humidity RH, carbon dioxide CO_2, and light intensity. It uses a NodeMCU controller that controls water circulation pumps, EC levels, and ammonia concentration; however, its mechanism for achieving control is not explained. The system also claims to control air temperature, RH, CO_2, and lighting in the room [37].

Some NodeMCU-based systems monitor only pH, water temperature, dissolved oxygen DO, and ammonia NH_3. The first three parameters are measured directly by sensors, while ammonia is assessed using a test strip submerged in water and read by a color sensor [38].

Another system for monitoring and control not only manages the water pump and lighting but also has autonomous fish feeding capability. It measures temperature, pH, and water level, with data viewable via a Raspberry Pi–hosted web interface [39].

2.3 Summary

A comprehensive review of microclimate control devices and actuators in livestock farms shows a wide variety of offerings: different wall, ceiling, or chimney ventilation flaps and their controllers; fans; heating and cooling systems; disinfection equipment, etc. A broad range of sensors is also available, though those specialized for livestock use come at relatively high prices. On the other hand, climate-controlled computers are offered by various manufacturers, but selecting them requires predefining all necessary sensors and actuator channels. Most systems lack future expandability, and high-channel-count systems are too expensive for the small and medium farms.

In the realm of aquaponics, commercial systems do not offer full environmental control. Only some parameters are monitored and controlled; others are manually measured, typically with litmus strips. Although research prototypes exist for partial control, they fall short of achieving fully balanced, expert-free management.

Therefore, it would be beneficial to develop more modular environmental control systems, easily expandable in terms of both the number and type of controlled parameters, and capable of flexible control logic. This would make them accessible on a wider user base. To achieve this goal, the first step is to create a concept outlining the necessary requirements for such a system.

CHAPTER 3. Developing a requirements-based concept for a CPS for intelligent management of animal husbandry facilities

3.1 Definitions of a Cyber–Physical System

The overall architecture of a Cyber–Physical System (CPS) includes models of physical processes, software models, computational platforms, and networks. The feedback loop between physical processes and computation encompasses sensors, actuators, physical dynamics, computation, software scheduling, and networks with contention and communication delays. [40]. CPS are integrations of computational and physical processes: embedded computers and networks monitor and control these physical processes, typically with feedback where the physical world influences computation and vice versa [41]. There are many definitions of a CPS. It comprises multiple components and layers, intertwining physical and virtual elements - from sensors, hardware components, actuators, to corresponding software. Different types of telecommunications are used between the networks through which the components are connected. Approaches from cybernetics, mechatronics, and embedded systems are involved. Unlike them, a CPS is generally a network of interlinked interacting elements with physical inputs and outputs.

3.2 CPS requirements

To implement a CPS suitable for managing animal farming complexes, one must consider required components and their specific requirements. These components can be physical or virtual, necessitating careful analysis of all external and internal influencing factors. The following steps outline the required process to realize a CPS tailored to the specific livestock facility.

3.2.1 Define which environmental parameters can be controlled

3.2.2 Define which parameters need to be controlled automatically

3.2.3 Identify whose environmental parameter values must be known

3.2.4 Specify which parameters are measured directly via sensors

3.2.5 Determine the types of sensors

3.2.6 Determine sensor quantity per measured parameter

3.2.7 Determine sensor locations

3.2.8 Choose sensor connectivity type to the system

3.2.9 Select relays for controlling actuators and end devices

3.2.10 Choose actuator types

3.2.11 Choose end devices

3.2.12 Choose a control computer

3.2.13 Choose an operating system

3.2.14 Select specialized software

3.3 Summary

Creating a concept for implementing a CPS in animal husbandry facilities provides clear steps to build the system. Once component requirements are defined, one only needs to select suitable elements and test them for compatibility.

After outlining core requirements and guidelines for CPS implementation, it's necessary to choose and test both an operating system and compatible software. Additionally, initial installation and configuration software with remote-access capability must be selected.

CHAPTER 4. Research and analysis of software and systems for CPS management. Concept development for CPS management software in animal husbandry facilities

4.1 OS and software requirements

We'll detail software requirements prior to selection. The operating system, along with additional software, libraries, and drivers, must work in harmony, this must be thoroughly evaluated before deploying the system into production.

Firstly, the OS must support real-time operation (Real-Time Operating System – RTOS), synchronization protocols like NTP or PTP, and a wide range of communication protocols (e.g., TCP, HTTP/HTTPS, FTP/SFTP, SSH, EtherNet/IP, WebSocket, MQTT, Modbus). It must also support wireless networking protocols like IEEE 802.11, Zigbee, BT/BLE, Z-Wave, 6LoWPAN, LPWAN, LoRa, SigFox. The goal is to support a large volume of ultra-low-rate, ultra-low-power wireless sensors and devices.

4.2 Operating system selection

For this research, the Linux-based system OpenHABian was chosen, which includes the independent, Java-based platform OpenHAB.

4.2.1 OpenHAB

OpenHAB (Open Home Automation Bus) is an open-source smart-home automation platform. It enables management and integration of various IoT devices, such as sensors, thermostats, cameras, smart bulbs, alarm systems, controllers, and more [42]. It supports multiple communication protocols, including Z-Wave, Zigbee, Wi-Fi, Bluetooth/BLE, Modbus, RS232, RS485, HTTP/HTTPS, MQTT, WebSocket Thread, KNX, DMX, REST, IFTTT, HomeKit, Hue, LIFX, Nest, Sonos, EnOcean, Xiaomi Mi Home, OpenWeatherMap, SolarEdge, SMA, Fronius, Kodi, MySensors, DLNA/UPnP, and others [42].

4.2.2 OpenHABian

OpenHABian is a Linux distribution based on Raspberry Pi OS Lite (a lightweight Debian variant), optimized for various Raspberry Pi models. It's tailored to simplify setup and optimization for OpenHAB. Although designed for Raspberry Pi, it can also run on other Linux-based systems, including x86 computers.

4.3 Additional software selection

The following open-source software products were chosen. While some have paid versions, all have free, open-source variants.

4.3.1 Eclipse Mosquitto MQTT Broker

Eclipse Mosquitto is an open-source MQTT message broker supporting MQTT versions 5.0, 3.1.1, and 3.1 [43]. In this CPS, it's installed on the server to provide wired or wireless communication between sensors, controllers, actuators, and the CPS server.

4.3.2 InfluxDB

InfluxDB is an open-source time-series database (TSDB) [42,44]. n this CPS, it's used on the server to store sensor measurements and current states of control devices and actuators. Stored data can be used by automation algorithms or accessed on demand by users.

4.3.3 Grafana

Grafana is a cross-platform, open-source web application for interactive visualization and analysis. It can create charts, graphs, and network alerts when connected to supported data sources [45]. In this CPS, it's installed on the server to visually display system parameters.

4.3.4 Samba

Samba is free software implementing the SMB (Server Message Block) protocol. It allows access to the Linux-based CPS server's file system from Windows or Android devices, facilitating configuration file access during setup or operation.

4.3.5 Frontail

Frontail is a log viewer useful during server startup, configuration, and system operation. It provides real-time logs, error messages, and sensor/connection interruptions—facilitating troubleshooting.

4.3.6 Amanda Backup

Amanda (Advanced Maryland Automatic Network Disk Archiver) is open-source backup software capable of backing up data on multiple networked computers [46]. After deploying the CPS, backing up its data, whether using Amanda or another solution is essential for reliable recovery.

4.3.7 Visual Studio Code

Visual Studio Code is a free source-code editor available on Windows, Linux, and macOS [47]. It's essential for programming this CPS. Installed on an external computer, it facilitates creating and editing system files, with extensions such as OpenHAB and OpenHAB Alignment Tool.

4.3.8 Solar-PuTTY

Solar-PuTTY is a free standalone network terminal and file transfer tool. Installed on an external computer, it's used for system installation, updates, and editing configuration files on the CPS server—allowing creation and editing of files, directories, and system configuration.

4.3.9 Tasmotizer

Tasmotizer is software used on an external computer to flash ESP32/ESP8266-based controllers with Tasmota firmware. Tasmota is open-source firmware enabling local control of smart devices without cloud services [48]. In this CPS, Tasmotizer is used to flash NodeMCU ESP8266 controllers, and Tasmota enables them to connect via Wi-Fi to the CPS server.

4.3.10 MQTT.fx

MQTT.fx is a tool for testing IoT topics during development [49]. In this CPS, it allows viewing sensors and actuator data messages across MQTT topics. Moreover, it can publish test data to topics subscribed by Mosquitto, enabling testing of the CPS without connected sensors.

4.3.11 MG Configuration

MG Configuration (Modbus Gateway Administrator Configuration – VOLISON) is software for configuring controllers like ADM-5850G, ADM-5832G, and IDM-7842MG . For this CPS, MG Configuration is used to configure the ADM-5832G gateway, which links Modbus RS485 sensors to the CPS server.

4.4 Summary

Selecting software is a key step in implementing the CPS. The chosen software meets criteria set out in the system concept and has undergone preliminary testing to verify configurability. Full compatibility testing must wait until all hardware components are chosen and algorithms for managing various livestock types are implemented. Thus, the next step is to select sensors and additional controllers.

CHAPTER 5. Research and selection of IoT actuators and sensors with required parameters for use in a CPS for animal husbandry facilities

A wide range of sensors, controllers, relays, and other devices are available for building livestock farm control systems. The main challenge is the high cost of professional-grade equipment. Conversely, there is a vast array of lower-cost sensors, albeit with reduced quality.

Environmental conditions also affect sensor suitability. For this project, the following sensors were selected.

5.1 Sensors

For the purposes of this study, the characteristics of various sensors for measuring temperature, relative humidity RH, ammonia NH_3, ammonium NH_4+ , carbon dioxide CO_2, methane CH_4, carbon monoxide CO, hydrogen sulfide H_2S, fine dust particles 2.5μm and 10μm, air velocity SAF, illumination, differential pressure Δp, dissolved oxygen, DO, nitrites, NO_2−, nitrates, NO_3−, hydrogen indicator, pH, and water level were examined, with some of the sensors being combined to measure more than one quantity..

Temperature sensor DS18B20, Maxim Integrated – Analog Device [51], temperature and relative humidity sensor AM2302, Aosong Electronics [52], temperature and relative humidity sensors SHT31 and SHT35, Sensirion [53]. For the purposes of the study, the above sensors are mainly used via a NodeMCU controller to measure temperature and relative humidity RH both indoors and outdoors.

Carbon dioxide sensor MH-Z19B (MH-Z19C) - Winson [54], carbon dioxide sensor Senseair S88 LP, Senseair [55] and carbon dioxide sensor SCD30, Sensirion [53]. For the purpose of the study, the sensors were tested with a NodeMCU controller using the UART protocol.

Ammonia sensor KM21, KLHA [56], for the purposes of the study the Modbus version was chosen, which connects to the system via Modbus gateway ADM-5832G.

Methane sensor MH-Z1341B, Winson [54], which uses a NodeMCU controller to communicate with the system.

Carbon monoxide, temperature and relative humidity sensor - JXBS-3001-CO/TH-RS, Jingxun [57] - uses Modbus gateway ADM-5832G to connect to the system.

Hydrogen sulfide sensor JXBS-3001-H2S, Jingxun [57] - uses Modbus gateway ADM-5832G to connect to the system.

Sensor for fine dust particles (PM2.5 and PM10) RS-PM-2-EX, Renke [58]. For the purposes of the study, the Modbus RS485 variant was chosen, and the Modbus gateway ADM-5832G was used for connection to the system.

Ultrasonic anemometer for air speed and direction RS-CFSFX-N01-3-EX, Renke [58], and for connection to the system again a Modbus gateway ADM-5832G is required.

Differential pressure sensor A2G-50, WIKA [59]. For the purposes of the study, a sensor Variant 1 with a differential pressure measurement range of -100 Pa to 2500 Pa with a Modbus output signal via a Modbus gateway ADM-5832G was selected.

BH1750 light sensor, ROHM Semiconductor [60] and TSL2561 light sensor, ams-OSRAM AG [61] For the purposes of the study, the sensors are used via a NodeMCU controller.

Dissolved oxygen and temperature sensor TriOxmatic 700 IQ, YSI Incorporated [62], ammonium and potassium sensor AmmoLyt Plus 700 IQ, YSI Incorporated [62], nitrite and nitrate sensor NiCaVis 701 IQ NI, YSI Incorporated [62] and pH sensor SensoLyt 700 IQ, YSI Incorporated [62]. For connection to the KFS of these four sensors, the use of an additional IQ SensorNet 282 or 284 controller is required.

Liquid level sensor SL-M5, NN ELEKTRONIK [63], which uses a NodeMCU controller to connect to the system.

5.2 Controllers

5.2.1 NodeMCU Controller

The NodeMCU controller originally developed by the NodeMCU Team is an open-source product. It is produced by various manufacturers such as Amica, Lolin, DOIT, Devkit and many others, and there are several versions of NodeMCU such as V0.9, V1, V2 and V3. There are also two variants with the CP2102 chip or with the CH340, and tests of the various variants did not reveal any difference in performance or functionality. The other difference is in the dimensions of the controller, as most are close to 48mm x 25mm, but some boards with a CH340 chip are wider with dimensions close to 56mm x 31mm. For the purposes of the study, NodeMCU is used to establish a connection between sensors, control buttons, relays for controlling end devices, signal lamps, etc. on the one hand and the KFS server on the other.

5.2.2 Controller Modbus gateway ADM-5832G

The ADM-5832G [50] is an industrial Modbus gateway that can be easily used to seamlessly integrate devices with serial Modbus (MODBUS-RTU/ASCII) and devices with Modbus Ethernet (MODBUS-TCP). For the purposes of the study, NodeMCU is used to establish a connection between the sensors used with Modbus RS485 interface and the system. The two RS-485/422 ports allow the connection of sensors with different Baud rates, as in general one such controller is sufficient to connect all the necessary sensors that work with the Modbus protocol (a total of up to 32 on the two RS-485/422 ports).

5.2.3 IQ SensorNet 282 and 284, YSI Incorporated

The IQ SensorNet 282 and 284 controllers [62] provide a plug-and-play connection between the YSI sensors and the KFS server. This connection can be made using almost any communication protocol, including Modbus TCP, Modbus RTU, PROFIBUS and PROFINET. The YSI IQ SensorNet 282 can connect up to 2 sensors and the 284 can connect up to 4 sensors [62]. They meet all CPS requirements and are suitable for use in the proposed aquaponic system.

5.3 Summary

This chapter examines a number of sensors that meet both the requirements for compatibility of the connecting interface and the range and resolution of the functions they are required to perform in the microclimate control algorithms in various livestock farms. The selected sensors are part of the price-oriented sensors offered on the market. In addition to them, the market offers a large selection of sensors from other manufacturers, with similar parameters and affordable price, which can also be used to implement the system.

The selected additional controllers for connecting sensors and end devices to the system server offer different connection options. Their number for building one or another CPS depends on the number and type of sensors and end devices, and they in turn depend on the control algorithm. If necessary, other similar controllers can be used.

The next step in the development and testing of the considered CFS for microclimate management in animal husbandry complexes is the development of separate algorithms expressing the specifics and needs of different animal species.

CHAPTER 6. Development of intelligent control for the CPS in animal husbandry based on OpenHAB

The proposed Cyber-Physical System (CPS) can be used to control the microclimate in livestock farms intended for raising various types of domestic animals for different purposes. To ensure energy efficiency, increase productivity, and improve animal health, the system must meet strict criteria tailored to the animals' needs and the farming objectives. It is essential to thoroughly study the impact of all environmental parameters on the animals, depending on whether they are raised for meat, milk, eggs, etc. Therefore, this study examines the rearing conditions and develops control algorithms for the most commonly raised livestock. This includes CPS for microclimate control in dairy cow farms, meat pig farms, and broiler chicken farms. A CPS has also been developed for environmental control in an aquaponic system for raising fish and plants. The systems mentioned are discussed below. The chapter also examines the installation, configuration, and setup of the system, presenting the main nodes and how components are interconnected.

6.1 Development of intelligent CPS control for dairy cow rearing

6.1.1 Specifics and environmental requirements for dairy cow rearing

One of the key aspects of modern livestock farms is ensuring an optimal and healthy environment, as well as increasing animal productivity through precise microclimate control, reducing building energy consumption, and optimizing feed intake. A fundamental requirement for any livestock building is to provide the necessary conditions tailored to the physiological needs of the animals housed within it, through technological modeling of natural microclimatic factors and the creation of a desired anthropogenic environment [64]. Air quality and harmful gas levels must also be monitored and controlled. The standards are as follows: ammonia NH_3 < 20mg/m^3 (28ppm) [65 for dairy cows and 5mg/m^3 (7,2ppm) [66] for calves up to 6 months; carbon dioxide CO_2 < 3000ppi [65], with people present < 2500ppm [67], and for calves up to 6 months < 3600 mg/m^3 (2000ppm) [66]; methane CH_4 < 500mg/m^3 (762ppm) [67]; carbon monoxide CO < 0,005 mg/l (4,4ppm) [65]; hydrogen sulfide H_2S < 10mg/m^3 (7,2ppm) [65]; temperature > 5°C, for calves > 10°C [65]. particulate matter < 3 mg/m3 [65]; lighting depending on location > 30lx or > 50lx на in the milking area, > 100lx in the handling area [65]; noise < 75 dB [65]. Optimal values for temperature, relative humidity, and air speed can be found in [65]. In high temperatures, controlling the environment based on the Temperature-Humidity Index (THI) is more important than based on temperature alone.

6.1.2 Sensors and control systems

Depending on the available equipment in the dairy farm, parameters to be monitored and logged can be selected during the initial installation of the system. The system can control blinds, circulation fans, ventilation, heating, water heating for drinking systems, sprinklers, and lighting. Depending on the type of environmental control system, the CPS can either directly manage it or, if the system has its own controller, the CPS can set target control values (via communication through various protocols) or simply turn it on and off for a set period as needed. Based on current research, the CPS has default values for the parameters that must be maintained. These can be modified according to specific needs, both during the initial setup and later to enhance and optimize the system. The CPS management takes into account the prioritization of specific actions required to ensure a safe and optimal microclimate in the dairy farm. The developed control algorithm consists of two parts, with the first addressing emergency mode.

6.1.3 CPS control algorithm for microclimate management in emergency mode

The developed algorithm monitors for exceeding maximum permissible levels of harmful gases, THI, or for temperature drops below the minimum threshold. Upon detecting such an event, it adjusts the shutter positions, ventilation status, and heating. In each case, the system sends a message to the operator with the exceeded value.

6.1.4 CPS control algorithm for microclimate management in normal mode

The algorithm is shown in Figure 6.2. When any value exceeds the set norm, the system switches to emergency mode.

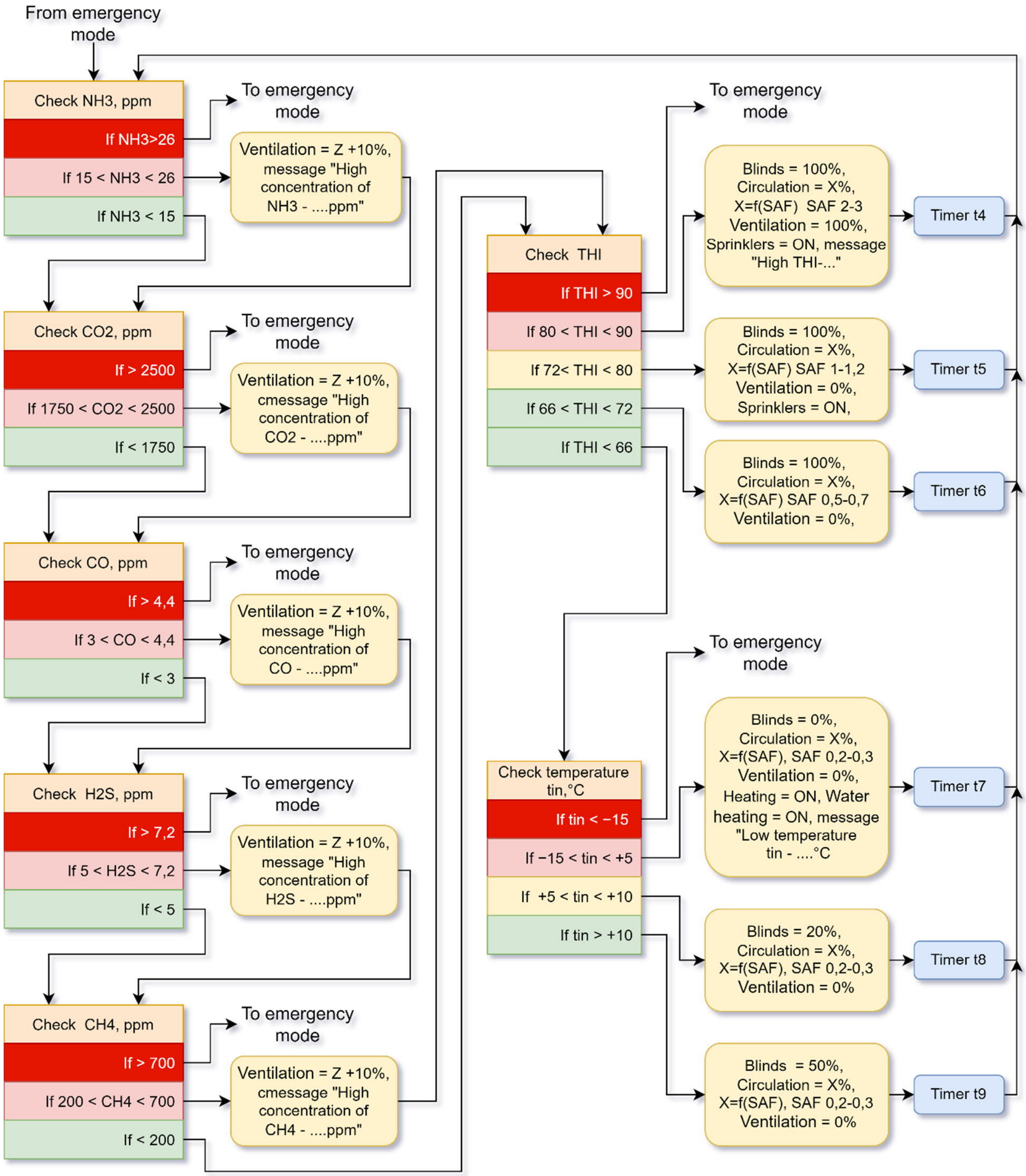

Figure 6.2 Algorithm for microclimate control for dairy cows in normal mode.

6.1.5 Conducted tests of CPS for microclimate control

A prototype of the CPS was developed based on the proposed algorithms. A Raspberry Pi 4 single-board computer was used as the server, running the open-source OpenHAB server. Sensor connections, control devices, automation rules, and more, were defined through text-file configuration. Sensors of all types mentioned above were connected to the system via Modbus and MQTT protocols to test compatibility and potential communication issues. Sensor readings were used to collect data and monitor graphs. Simulated devices resembling real farm equipment were used. The system controlled an electric heater; a PWM-controlled fan; a simple on/off fan; standard and dimmable (PWM) LED lamps; and a small blind driven by a DC motor. Where required by tests, a simulated sensor input was sent via MQTT Broker for example, to simulate a high concentration of harmful chemical gases.

Testing proved that the server could handle the load for automating small to medium-sized livestock farms. For large farms with many sensors, actuators, and automation equipment, a more powerful PC server is recommended. Various automation scenarios are likely to occur on actual livestock farms, the conditions of both large industrial and small family farms were simulated and tested.

Because testing on a real farm was not possible, the following tests were conducted in a bedroom within an apartment equipped with a recuperation unit. This unit was connected through a relay so the system could turn it on and off. The system was set to maintain CO_2 levels below 2000 ppm. It successfully kept CO_2 concentration below this threshold for several days while people exhaled in the room.

Temperature control was tested in an empty, poorly insulated south-facing room by managing an electric heater and an exhaust fan to draw air out, allowing fresh air to enter. The system successfully maintained room temperature within the pre-set range (18 °C–20 °C), despite varying outdoor temperatures and additional solar heating through the south-facing windows during parts of the day.

To test the algorithm's response to an emergency (high concentration of harmful gases in the barn), we simulated sensor inputs outside the defined safety limits for NH_3, CO_2, CH_4, H_2S, and CO via MQTT Broker. Each time, the system reacted appropriately maximizing ventilation and circulation fans (two test fans), fully opening the electric blind, and immediately notifying the operator by email with the measured gas concentration. A similar test was performed for particulate matter PM2.5 and PM10. The alert threshold was lowered so that the system would send a message upon reading above the threshold.

6.2 Development of smart CPS for pig farming

6.2.1 Environmental specifications and requirements for pig farming

Pig farming requires strict control of environmental parameters: temperature, relative humidity RH, air velocity, and concentrations of ammonia NH_3, hydrogen sulfide H_2S and carbon dioxide CO_2. H_2S alone can cause respiratory diseases and even at low concentrations can weaken pigs' immune systems, making them more prone to viral diseases like Influenza A virus (IAV) [68]. Pigs are kept under different conditions depending on their age and purpose, divided into 14 categories [65]. Toxic gas concentration limits must be observed: CO_2 < 2500ppm [65], H_2S accepted up to 5 ppm or even 10 ppm by some sources [69], though others demand zero tolerance [65]. Relative humidity is relatively high, and on warm days cooling spray systems may be used. Air velocity, particulate matter, noise, and illumination should comply with relevant regulations [65].

6.2.2 Sensors and control systems

The proposed Sensors may include indoor temperature, humidity, outdoor temperature, NH_3, CO_2, H_2S, PM, air velocity SAF and illumination. The first two are mandatory. Controllable systems include blinds, fresh-air ventilation, heating, cooling (climate control), spray cooling and humidification/disinfection, disinfectant deployment, and lighting; the first three are mandatory.

All threshold values for temperature, humidity, air velocity, and toxic gas limits can be adjusted by the technologist based on pig breed and selection. Additional categories beyond the fourteen default ones can be created, allowing grouped parameter settings for different pig categories within the same room.

6.2.3 Control algorithm for CPS in pig farms

Pigs are kept in separate premises by category. Before introducing animals, cleaning and disinfection are always performed manually. The algorithm (Figure 6.5) is divided into two parts: initial setup and optional cleaning/disinfection cycle, followed by autonomous environmental control until the pig category changes or the cycle is manually stopped.

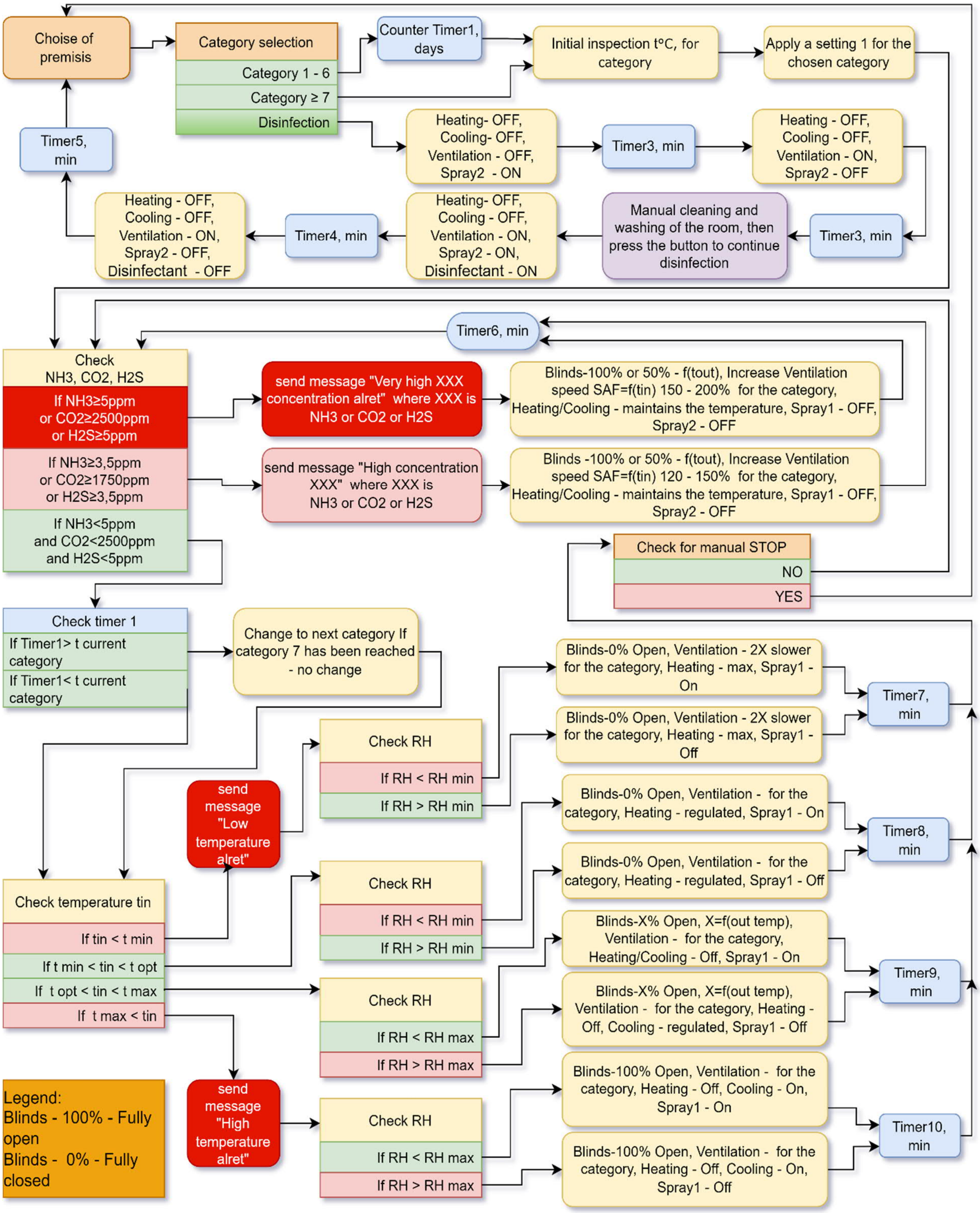

Figure 6.5 Control Algorithm for CPS in pig farms.

6.2.4 Conducted tests of CPS for microclimate management in a pig farm

Tests were conducted in a lab model setup including many listed components: Raspberry Pi 4 server, AM2302 temperature/humidity sensors indoors and outdoors, CO_2 sensor SCD30. The system controlled an electric heater, a fresh-air ventilation recuperation unit, and a blind. Tests were conducted with the outdoor temperature about 15 °C below the target settings (for category 5: 20/23/25 °C), and the category duration was reduced from 7 days to 7 hours for study purposes. When the system was started in a room at 18 °C, it sent an email alert for low temperature, closed the blind, started heating and the ventilation unit. Upon reaching 20 °C, heater power reduced to 50% via PWM. At the optimal 23 °C, the heater switched off; when temperature dropped to 22.4 °C, it resumed at 50%. After 15 minutes, a second, uncontrolled heater was switched on to simulate warming; when temperature reached 23.2 °C, the shutter opened to 30%. At 24 °C, the second heater was switched off and a window was opened for faster cooling. Meanwhile, the system transitioned from category 5 to 6. When the temperature reached 19.8 °C, the roller-shutter closed, and the window was closed; at 19.4 °C, the system turned the heater on again.

An emergency test for high CO_2 was performed by lowering the maximum threshold from 2500 ppm to 1000 ppm. The recuperation unit was replaced with a variable-speed fan set at 1200 rpm under category 5; the blind was closed, and the heater kept the temperature. When CO_2 exceeded 1000 ppm, fan speed increased to 2500 rpm, the blind opened fully, and the system sent an email alert. A window was opened to reduce CO_2 and temperature. During ventilation, temperature dropped below the minimum, blind partially closed to 50%, and the heater switched to maximum.

6.3 Development of intelligent CPS control for broiler farming

6.3.1 Environmental requirements for broiler farming

Broiler farming demands more precise environmental control than other meat-producing animals such as cattle or sheep. Even minor deviations from optimal parameters increase mortality, especially during the early brooding stage, and subsequently reduce productivity [70].

For broilers, the control CPS must monitor parameters including temperature, relative humidity RH, speed of air flow SAF, differential pressure Δp and concentrations of harmful gases like ammonia NH_3 [71], carbon dioxide CO_2, carbon monoxide CO and hydrogen sulfide H_2S [65,70]. Dust and microbial contamination also require monitoring [70]. Lighting intensity and duration, as well as noise levels, are critical [65,72,73,74]. Poor lighting can lead to cannibalism, stress, diseases, and even death [75,76,77]. Some sources recommend 16 hours of light and 8 hours of darkness [78,79], while others report better productivity with alternating shorter light/dark periods [80,81,82]. It is also important to note that the primary parameter defining broiler comfort is the “felt temperature” [70,83,84,85]. This often differs from the ambient air temperature, as it depends on factors including air temperature, floor temperature, RH, air speed (SAF), the birds’ age, and feathering. When air temperature, humidity, and airflow are within acceptable limits, perceived temperature matches ambient temperature. At higher ambient temperatures, increasing airflow prevents broilers from exiting their comfort zone [70]. With the proposed methods, the felt temperature can be calculated and used to operate the system. When the temperature zone is maintained correctly, the energy surplus from the feed is used for growth and weight gain, rather than providing thermal comfort for the broiler. This zone is determined by the felt temperature.

To ensure proper CPS functioning, sensors for indoor temperature t_i, indoor RH, airspeed SAF, NH_3, CO_2, CO, H_2S and fine particulate matter must be positioned within the birds' living zone, approximately 20 cm above the floor. The exceptions are the sensors for measuring the roof temperature t_{ih}, outdoor temperature t_o, outdoor RH_{out} and differential pressure Δp.

6.3.2 Ventilation types in poultry farm

The ventilation system must include a sufficient number of exhaust fans to draw indoor air out, while fresh air enters via multiple adjustable inlets or large tunnel openings at one end of the building. Three common types of ventilation are implemented: minimal ventilation, transitional ventilation, and tunnel ventilation [70].

6.3.3 Sensors and Control Systems

It is necessary to monitor the following parameters: indoor temperature at bird level, ceiling-level temperature, indoor relative humidity, outdoor relative humidity, outdoor temperature, ammonia NH_3, carbon dioxide CO_2, carbon monoxide CO hydrogen sulfide H_2S, fine particulate matter, air velocity SAF, differential pressure (indoor/outdoor), and indoor illumination. The building must also be equipped with the necessary systems for micro-climate control. For the geographic latitude of Bulgaria, these include heating, fresh-air ventilation fans (referred to below as "Ventilation"), circulation fans ("Circulation"), tunnel fans ("Tunnel Ventilation"), fresh-air inlet dampers, tunnel ventilation openings (tunnel dampers), evaporative cooling pads, and lighting.

6.3.4 CPS control algorithm for microclimate management in poultry farm

In the proposed algorithm for autonomous operation under tunnel ventilation mode, the system regulates not the measured temperature t_i, but the felt temperature t_f. The system calculates the felt temperature based on predefined relationships derived from various sources [83,84,85,86], which are supplemented through interpolation and extrapolation. When relative humidity RH exceeds RH_{max} for the corresponding broiler age, the felt temperature increases by predetermined values calculated based on its relationship to the Temperature-Humidity Index THI. The felt temperature t_f is obtained using the following formula:

Formula 6.1 $$t_f = t_i - t_{cw} + t_{cRH}$$

Where t_{cw} is a temperature correction factor dependent on air velocity SAF, and t_{cRH} is a correction based on relative humidity RH.

Two control algorithms have been developed for the system. The first is for preparing the facility before the placement of broilers, maintaining an optimal temperature in the building to adapt floor and wall temperatures. The operational algorithm is divided into a main part and four branches. Based on the detected environmental conditions, the algorithm transitions to one of the branches: the first two branches correspond to minimal ventilation conditions, the third to transitional ventilation and the fourth to tunnel ventilation. In the first three branches, the system maintains optimal conditions for broiler rearing (temperature, relative humidity, air velocity), periodically returning to the main section of the algorithm. f the system transitions into the fourth branch (Figure 6.11), it enters a closed loop, where specific conditions must be met before exiting. In this state, the CPS begins regulating based on the felt temperature t_f.

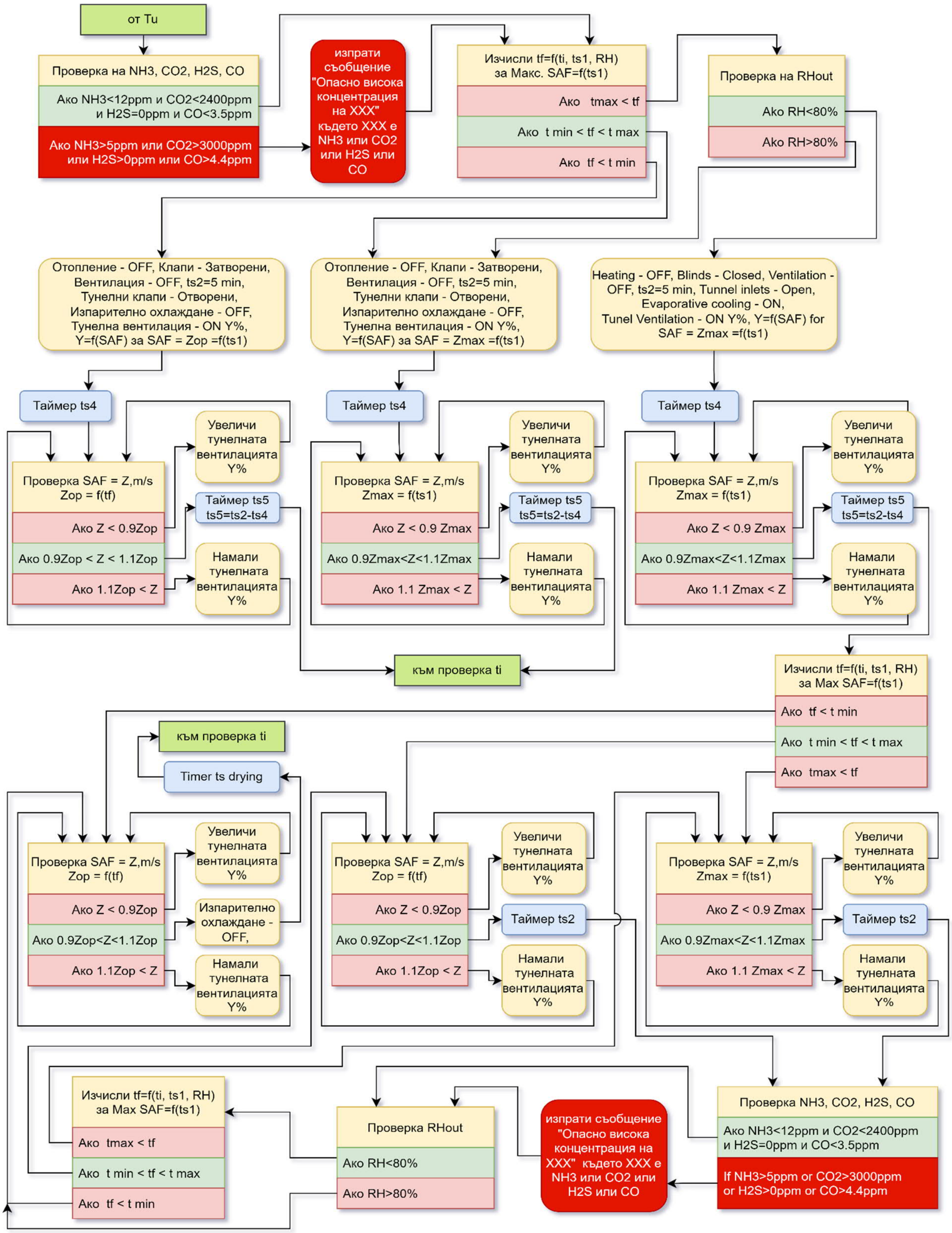
от Tu
Проверка на NH3, CO2, H2S, CO
Ако NH3<12ppm и CO2<2400ppm и H2S=0ppm и CO<3.5ppm
Ако NH3>5ppm или CO2>3000ppm или H2S>0ppm или CO>4.4ppm
изпрати съобщение "Опасно висока концентрация на XXX" където XXX е NH3 или CO2 или H2S или CO
Изчисли tf=f(ti, ts1, RH) за Макс. SAF=f(ts1)
Ако tmax < tf
Ако t min < tf < t max
Ако tf < t min
Проверка на RHout
Ако RH<80%
Ако RH>80%
Отопление - OFF, Клапи - Затворени, Вентилация - OFF, ts2=5 min, Тунелни клапи - Отворени, Изпарително охлаждане - OFF, Тунелна вентилация - ON Y%, Y=f(SAF) за SAF = Zop =f(ts1)
Отопление - OFF, Клапи - Затворени, Вентилация - OFF, ts2=5 min, Тунелни клапи - Отворени, Изпарително охлаждане - OFF, Тунелна вентилация - ON Y%, Y=f(SAF) за SAF = Zmax =f(ts1)
Heating - OFF, Blinds - Closed, Ventilation - OFF, ts2=5 min, Tunnel inlets - Open, Evaporative cooling - ON, Tunel Ventilation - ON Y%, Y=f(SAF) for SAF = Zmax =f(ts1)
Таймер ts4
Проверка SAF = Z,m/s Zop = f(tf)
Ако Z < 0.9Zop
Ако 0.9Zop < Z < 1.1Zop
Ако 1.1Zop < Z
Увеличи тунелната вентилацията Y%
Таймер ts5 ts5=ts2-ts4
Намали тунелната вентилацията Y%
Таймер ts4
Проверка SAF = Z,m/s Zmax = f(ts1)
Ако Z < 0.9 Zmax
Ако 0.9Zmax<Z<1.1Zmax
Ако 1.1 Zmax < Z
Увеличи тунелната вентилацията Y%
Таймер ts5 ts5=ts2-ts4
Намали тунелната вентилацията Y%
Таймер ts4
Проверка SAF = Z,m/s Zmax = f(ts1)
Ако Z < 0.9 Zmax
Ако 0.9Zmax<Z<1.1Zmax
Ако 1.1 Zmax < Z
Увеличи тунелната вентилацията Y%
Таймер ts5 ts5=ts2-ts4
Намали тунелната вентилацията Y%
към проверка ti
Изчисли tf=f(ti, ts1, RH) за Max SAF=f(ts1)
Ако tf < t min
Ако t min < tf < t max
Ако tmax < tf
към проверка ti
Timer ts drying
Проверка SAF = Z,m/s Zop = f(tf)
Ако Z < 0.9Zop
Ако 0.9Zop<Z<1.1Zop
Ако 1.1Zop < Z
Увеличи тунелната вентилацията Y%
Изпарително охлаждане - OFF,
Намали тунелната вентилацията Y%
Проверка SAF = Z,m/s Zop = f(tf)
Ако Z < 0.9Zop
Ако 0.9Zop<Z<1.1Zop
Ако 1.1Zop < Z
Увеличи тунелната вентилацията Y%
Таймер ts2
Намали тунелната вентилацията Y%
Проверка SAF = Z,m/s Zmax = f(ts1)
Ако Z < 0.9 Zmax
Ако 0.9Zmax<Z<1.1Zmax
Ако 1.1 Zmax < Z
Увеличи тунелната вентилацията Y%
Таймер ts2
Намали тунелната вентилацията Y%
Изчисли tf=f(ti, ts1, RH) за Max SAF=f(ts1)
Ако tmax < tf
Ако t min < tf < t max
Ако tf < t min
Проверка RHout
Ако RH<80%
Ако RH>80%
изпрати съобщение "Опасно висока концентрация на XXX" където XXX е NH3 или CO2 или H2S или CO
Проверка NH3, CO2, H2S, CO
Ако NH3<12ppm и CO2<2400ppm и H2S=0ppm и CO<3.5ppm
If NH3>5ppm or CO2>3000ppm or H2S>0ppm or CO>4.4ppm

Figure 6.11 Control algorithm - tunnel ventilation branch T_u.

6.3.5 Conducted tests of the CPS for microclimate management in a poultry farm

Due to the inability to create an experimental setup that includes all types of sensors and control systems, and the fact that the system has not yet been implemented in a functioning poultry farm, testing was carried out in two stages. In the first stage, all sensors were connected to the system and tested for data reading and logging. The following sensors were used: AM2302 for temperature and humidity, SCD30 for CO_2, the Modbus version of the A2G-50 for differential pressure, and the RS-CFSFX-3-EX for airspeed. Sensors for fine particulate matter and illumination had been tested previously in experimental setups for climate control systems in pig farms. In the second stage, instead of real sensor readings, synthesized data for temperature, humidity, differential pressure, and the presence of harmful gases were sent via an MQTT Broker. This allowed simulation of various conditions to verify the system's response.

During the testing, the following initial conditions were set: t_{s1} -14 days, Maximum broiler number - N. Then the system set t_{min} - 24 °C, t_{max} - 27 °C, t_{opt} - 25,5 °C. Once the system was started, data was transmitted to it every 30 seconds. Table 6.13 shows a partial set of rows with some modified values.

Minute	**t_i, °C**	**t_o, °C**	**t_{ih}, °C**	**Δp, Pa**	**CO_2**
0'	22	5	26	25	500
4'	22	15	22	25	500
8'	26	15	30	25	500
14'	25	15	30	25	500
19'	25	15	25	25	2500
24'	24.5	15	25	25	3500
27‘	25	15	25	25	500

Table 6.13 – Simulated data sent via MQTT Broker.

The system started as follows. First, it opened the connected blind, acting as a fresh air inlet, to the indicated position 2 out of a total of seven positions. It started the first fan, acting as a fresh air fan, at the set speed corresponding to position 2 of the inlets and turned on the heater at 100%. After 30 seconds, the system turned off the fan, closed the blind and turned on the second fan, acting as a circulation fan.

At the 5th minute, the cycle ended, and the algorithm started a new one, and the system checked the temperature t_i and took the following actions: turned off the circulation fan, turned on the fresh air fan and opened the blind to position 3. The heating remained at full power. After 30 seconds, the blind was closed, and the fan stopped.

At the 10th minute, the system checked the temperature t_i again and switched from the minimum ventilation mode to the transitional ventilation mode, since the temperature t_i is higher than t_{opt}. The heater was turned off; the blind was opened to position 4 and the fresh air fan was turned on at the corresponding power.

At the 15th minute, the system measured the temperature t_i and switched from the transitional ventilation mode to the minimum ventilation mode. The heater was turned on with a PWM of 10%, the blind was moved from position 4 to position 3, and the fresh air fan was switched to the appropriate power for the given shutter position. After 30 seconds, the fan stopped, the blind closed, and the circulation fan was turned on again.

At the 20th minute, the system measured temperature t_i and detected a carbon dioxide CO_2 level above 80% of the permissible value. The following actions followed: the blind was opened to position 4 instead of 3, the fresh air fan was switched on at the appropriate power, the heater remained running at 10%, and the circulation fan was switched off. After 30 seconds, the fresh air fan was switched off and the shutter was closed.

At the 25th minute, the system measured a temperature t_i and a carbon dioxide level CO_2 above the permissible norm and entered emergency mode for 3 minutes. After that, it sent a message “Warning: high CO2 level - 3000ppm”. The blind opened to position 4, the fresh air fan switched on at the appropriate power and the heater increased its power to 50%.

At the 28th minute, the system measured a temperature t_i and carbon dioxide level CO_2 below the permissible norm. The shutter was opened to position 3, the fresh air fan switched to the appropriate power and the heater was turned on at 10%.

The test above showed that the system (algorithm) can successfully switch to different ventilation modes, as well as enter and exit emergency mode.

6.4 Development of intelligent CPS control for fish and plant cultivation in a deep-water culture aquaponic system

6.4.1 Environmental characteristics and requirements for aquaculture in an aquaponic system

A fundamental requirement for the proper functioning of an aquaponic system is achieving environmental balance. One of the most critical indicators is water quality, which reflects its suitability for specific applications. Depending on the intended use of the water, certain parameters must be met to determine its quality. These parameters have different optimal values for fish, plants, and the development of beneficial bacteria. Therefore, it is essential to find the optimal balance point that allows all organisms to coexist in symbiosis [23,87]. In an aquaponic system, maintaining balance requires monitoring water temperature, pH level, hardness, dissolved oxygen DO, dissolved carbon dioxide CO_2, ammonia NH_3, nitrites NO_2^-, nitrates NO_3^-, alkalinity, and the development of various bacterial groups [23].

6.4.2 Components of the aquaponic system

The aquaponic system, based on the deep-water culture (DWC) method, must include the following components: fish tank, mechanical filter, biofilter, floating rafts, water circulation pump, air pumps with air stones (aerators) and pipe network.

In addition, sensors and actuators are required to implement the proposed Cyber-Physical System for monitoring and regulating water parameters. The system must be equipped with sensors for measuring water temperature (in the fish tank and biofilter), dissolved oxygen DO (in the fish tank, biofilter, and floating rafts), nitrites NO_2^-, nitrates NO_3^-, pH and ammonium NH_4^+ (in the fish tank). To determine the concentration of total ammonia nitrogen TAN and ammonia NH_3, a calculation method is applied based on the concentration of NH_4^+, water pH, and temperature. Monitoring and maintaining these parameters within specific ranges ensures the system remains in balance. Maintaining this balance through parameter regulation defines the functional requirements for the CPS. The required actuators include: water pump, auger for adding pH-lowering substance, auger for adding pH-increasing substance, solenoid valve for water replenishment (in the biofilter), heater and auger for feeding the fish (in the fish tank), air pumps (in the fish tank, biofilter, and floating rafts).

6.4.3 CPS control algorithm for environmental management in an aquaponic system

Two algorithms have been developed for controlling the system. The first ensures proper preparation and bacterial development prior to stocking the fish and planting the crops (Figure 6.15), while the second maintains balance within the aquaponic system (Figure 6.16).

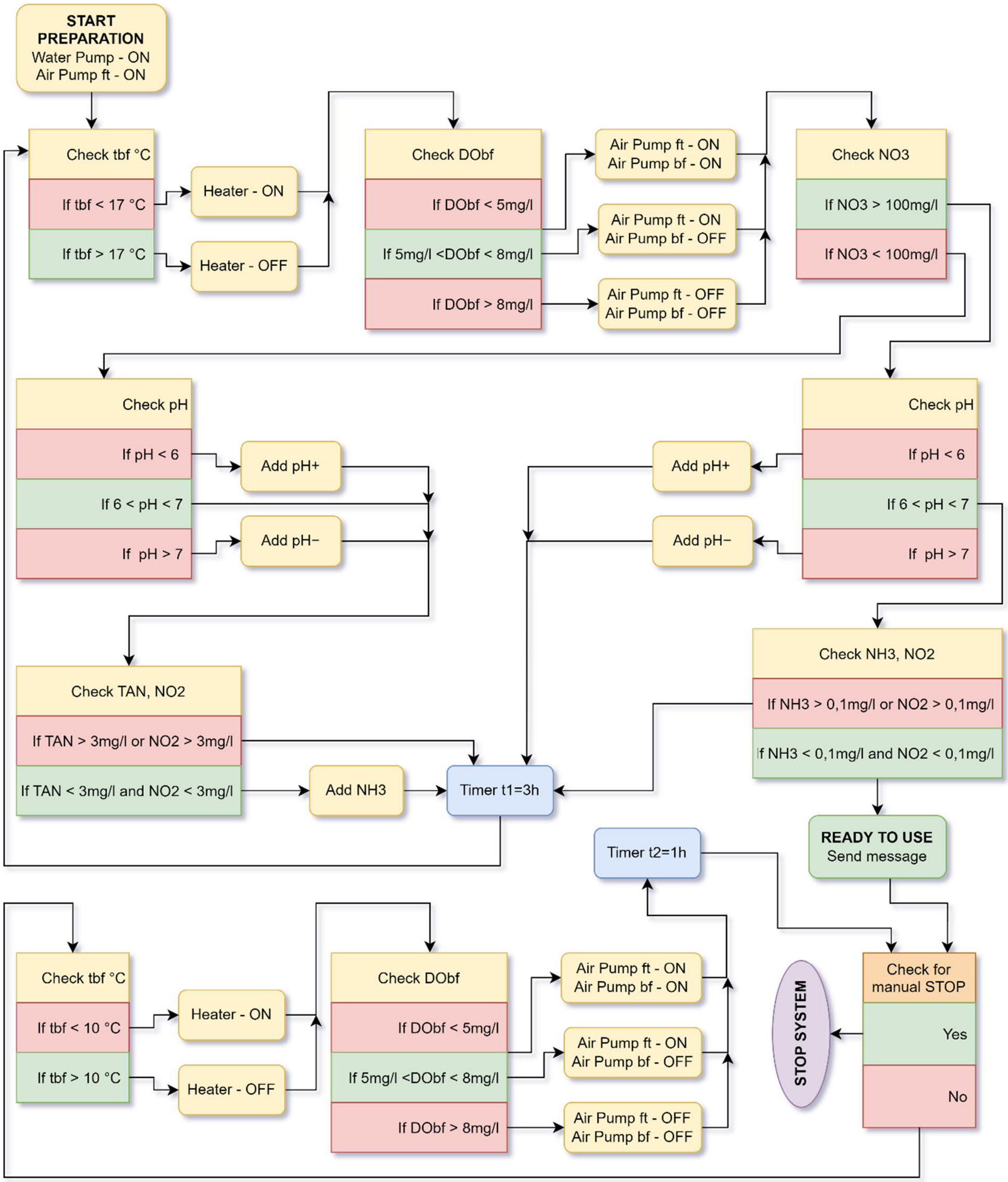

Figure 6.15 – Algorithm for initial startup and bacterial development in an aquaponic system.

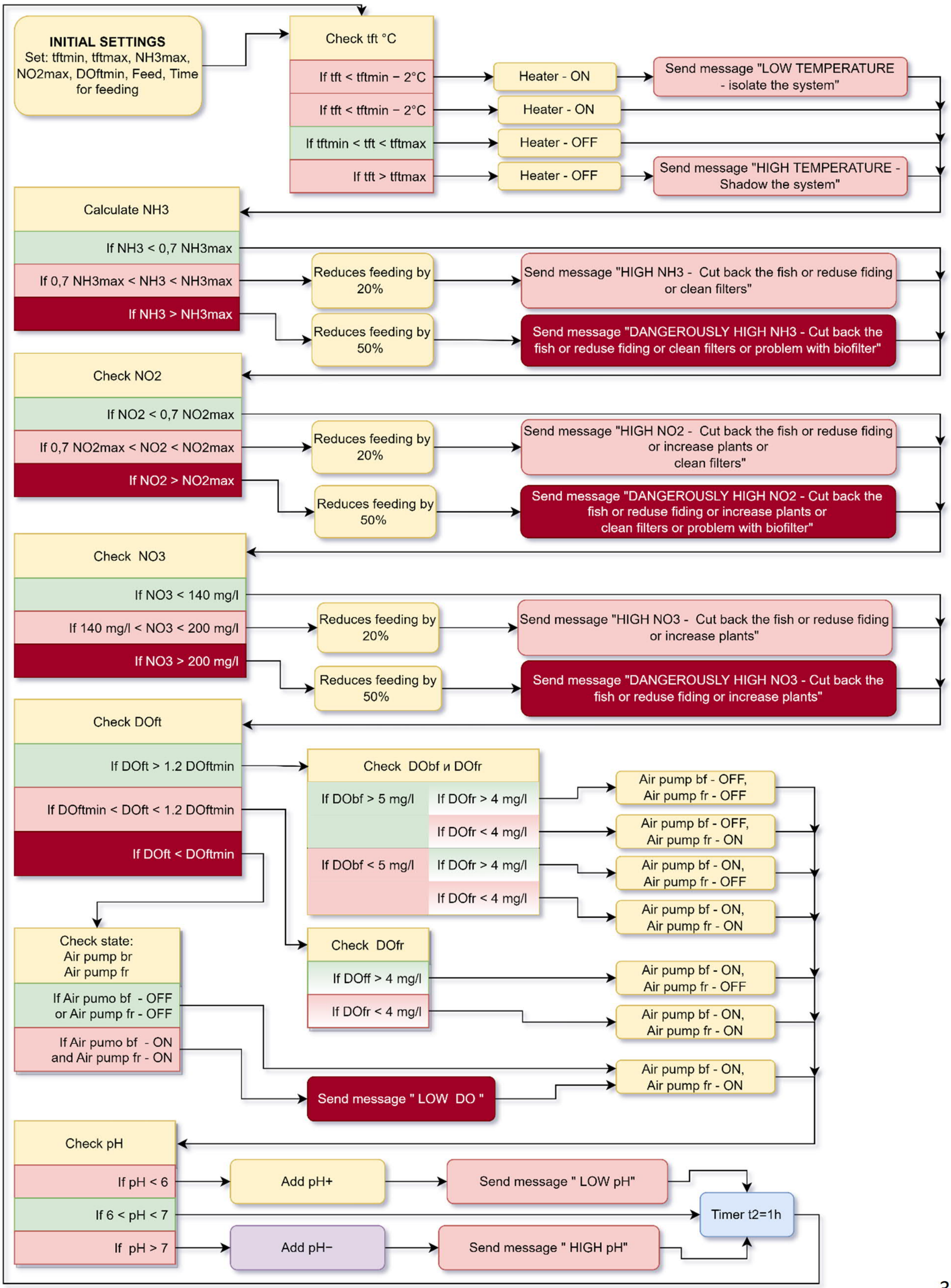
INITIAL SETTINGS
Set: tftmin, tftmax, NH3max, NO2max, DOftmin, Feed, Time for feeding
Check tft °C
If tft < tftmin – 2°C
If tft < tftmin – 2°C
If tftmin < tft < tftmax
If tft > tftmax
Heater - ON
Heater - ON
Heater - OFF
Heater - OFF
Send message "LOW TEMPERATURE - isolate the system"
Send message "HIGH TEMPERATURE - Shadow the system"
Calculate NH3
If NH3 < 0,7 NH3max
If 0,7 NH3max < NH3 < NH3max
If NH3 > NH3max
Reduces feeding by 20%
Reduces feeding by 50%
Send message "HIGH NH3 - Cut back the fish or reduse fiding or clean filters"
Send message "DANGEROUSLY HIGH NH3 - Cut back the fish or reduse fiding or clean filters or problem with biofilter"
Check NO2
If NO2 < 0,7 NO2max
If 0,7 NO2max < NO2 < NO2max
If NO2 > NO2max
Reduces feeding by 20%
Reduces feeding by 50%
Send message "HIGH NO2 - Cut back the fish or reduse fiding or increase plants or clean filters"
Send message "DANGEROUSLY HIGH NO2 - Cut back the fish or reduse fiding or increase plants or clean filters or problem with biofilter"
Check NO3
If NO3 < 140 mg/l
If 140 mg/l < NO3 < 200 mg/l
If NO3 > 200 mg/l
Reduces feeding by 20%
Reduces feeding by 50%
Send message "HIGH NO3 - Cut back the fish or reduse fiding or increase plants"
Send message "DANGEROUSLY HIGH NO3 - Cut back the fish or reduse fiding or increase plants"
Check DOft
If DOft > 1.2 DOftmin
If DOftmin < DOft < 1.2 DOftmin
If DOft < DOftmin
Check DObf и DOfr
If DObf > 5 mg/l
If DOfr > 4 mg/l
If DOfr < 4 mg/l
If DObf < 5 mg/l
If DOfr > 4 mg/l
If DOfr < 4 mg/l
Air pump bf - OFF, Air pump fr - OFF
Air pump bf - OFF, Air pump fr - ON
Air pump bf - ON, Air pump fr - OFF
Air pump bf - ON, Air pump fr - ON
Check DOfr
If DOff > 4 mg/l
If DOfr < 4 mg/l
Air pump bf - ON, Air pump fr - OFF
Air pump bf - ON, Air pump fr - ON
Check state: Air pump br Air pump fr
If Air pumo bf - OFF or Air pump fr - OFF
If Air pumo bf - ON and Air pump fr - ON
Air pump bf - ON, Air pump fr - ON
Send message " LOW DO "
Check pH
If pH < 6
If 6 < pH < 7
If pH > 7
Add pH+
Add pH−
Send message " LOW pH"
Send message " HIGH pH"
Timer t2=1h

Figure 6.16 – Working algorithm.

6.4.3.3 Feeding Cycle

The feeding cycle is illustrated in Figure 6.18. To maintain system balance, if levels of NH_3, NO_2 or NO_3 exceed acceptable thresholds, the system adjusts the amount of feed dispensed and records corrections in memory for the next feeding cycle.

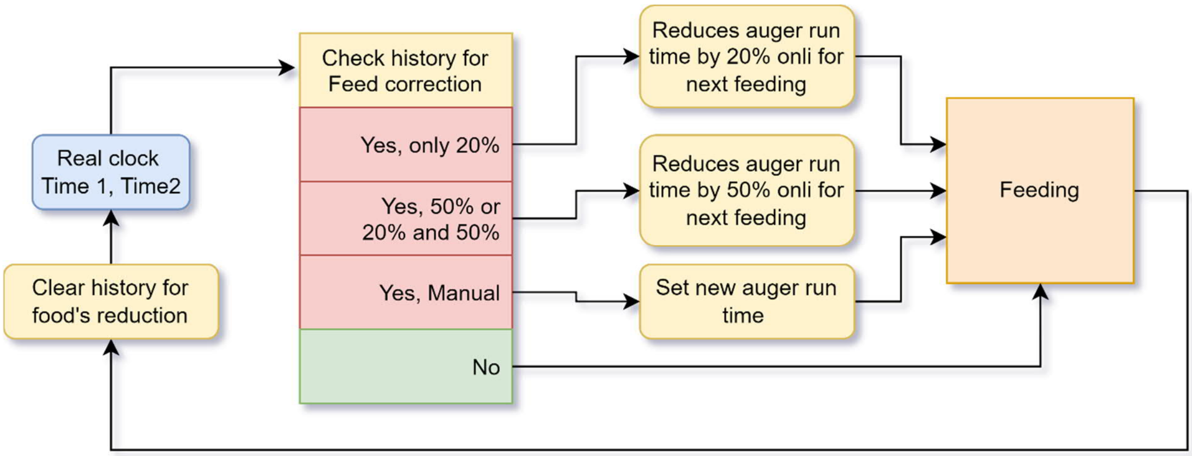

Figure 6.18 – Feeding Algorithm in an Aquaponic System

6.4.4 Conducted tests of the CPS for environmental management in an aquaponic system

A test setup was implemented using a Raspberry Pi 4 (8GB) server with the OpenHAB 3.0 operating system. Software was developed for managing the aquaponic system according to the previously described algorithms. Testing the CPS in a real aquaponic system would require significant time and would need to be conducted in environments with varying water hardness. Therefore, system functionality was tested under laboratory conditions. For this purpose, software and hardware were tested using synthesized data transmitted via MQTT Broker, instead of using actual sensor signals. The system's performance was analyzed using data that would realistically be measured in a real-world setting. This included synthesized values for deviations in water temperature in the fish tank and biofilter, dissolved oxygen levels in the fish tank, biofilter, and floating rafts, as well as nitrite, nitrate, pH, and ammonium NH_4+ levels in the fish tank. The obtained data for ammonium NH_4+ values were converted to ammonia NH_3 and total ammonia nitrogen TAN concentrations using a calculation based on pH and temperature. The actuators were replaced with signal lights to record their operation times. The accuracy of the notifications sent to the operator was also verified. When data was transmitted via the MQTT Broker, it was stored in memory and became available for the system to read. If new data did not reach the server for any reason, the system treated the last recorded values as current. This was necessary because obtaining accurate readings for some water parameters can take several minutes—or even more than 10 minutes. However, this is not an issue, as aquaponic systems are inherently inert and slow to change.

At preset intervals, the data was submitted to the system. The system was configured with the following parameters: t_{bfmin} = 17 °C, 5 mg/L < DO_{bf} < 8 mg/L, 6 < pH < 7, TAN and NO_2- greater than 3 mg/L, until NO_3- eaches values greater than 100 mg/L, after which they must be reduced to values less than or equal to 0.1 mg/L, taking into account the readiness of the system. Upon reading the stored values, the system activated the heater and air pumps in the fish tank and biofilter, triggered the dosing auger (for ammonia addition), and the auger for pH reduction, all based on preset parameters. The calculated values for TAN and NH_3 can also be checked. Monitoring the values confirmed that the system operated correctly according to the input data. After reading the final column values, an email notification was sent to the operator indicating that the startup cycle had been completed.

The system's working cycle was also tested under the following initial conditions: t_{ftmin} = 12 °C, t_{ftmax} = 18 °C, NH_{3max} = 0,4 mg/L, NO_{2max} = 0,4 mg/L, DO_{ftmin} = 4 mg/L, auger operating time for adjusting the pH =12 min., auger operation time feeding food = 18 min., feeding times 12:30 and 19:00. The auger run time was intentionally set much longer than actual feeding duration to facilitate observation during testing. The test started at 10:00, with a cycle duration of 1 hour. The system correctly controlled the air pumps in the biofilter and floating rafts, the heater, and the pH augers. At 12:30, the feed auger activated at the designated time. At 13:00, upon detecting a low pH level, the auger was triggered and a message with the pH value was sent. In the next cycle, when high temperature was detected, the system also sent a notification. At 15:00, a warning was issued for a high NO_2- level, above 70% of the acceptable limit, along with a recommendation to reduce it. A 20% correction was recorded to shorten the feed auger's run time. B 17:00 At 17:00, pH and NH_3, levels were found to exceed the permissible limits, and a message with their values and corrective suggestions was sent. Additionally, a 50% correction to the feed auger's run time was recorded. The next feeding time was reduced by half. The system also reacted to elevated NO_3- levels and low temperature during the final test cycle.

6.5 System Installation and Configuration

The initial setup includes installing OpenHABian on the CPS server, followed by the installation of additional software and configuration of the system for operation. These installations can be performed via the command line, for example using Solar-PuTTY or another terminal, and some of the additional software can be installed directly via menu-based interfaces. Next, existing configuration text files are edited, and new ones are created to configure the system. These files are located in the „openHAB-conf“ directory and its subdirectories. Although they are accessible directly on the server or through a terminal, the most convenient way to create and edit them is using Visual Studio Code. Key configuration files include „addons.cfg“, „basicui.cfg“, „runtime.cfg“ among others. System configuration requires creating at least one file of each type or, for better clarity, multiple files organized in specific folders. These include files with the extensions .persist, .things, .items, .rules, and others, in which the actual system definition is performed. These files describe the connections between physical and virtual components and define the operational rules of the system.

6.6 Summary

The developed control algorithms for various livestock farms provide a high level of autonomy and enable environmental control to be performed without staff intervention, once the initial settings are defined. The CPS can monitor and control different environmental parameters depending on the installed sensor types and control devices. For maximum efficiency, it is recommended that the system includes the full set of components listed above.

The system allows the default parameter ranges to be modified through the graphical interface, according to specific needs. These changes may be based on the requirements of different animal breeds or at the discretion of the farm technologist. The adjustable parameter ranges are set during system configuration but can be updated at any time as needed. This can also be done remotely via the access console using Solar-PuTTY or another terminal, or through Visual Studio Code connected to the system.

To enable user access to the system, a user interface must be developed that allows convenient monitoring of parameters and control of the system. This will be discussed in the following chapter.

CHAPTER 7. Research and development of a graphical interface for the CPS for livestock farming complexes with remote internet-based management using OpenHAB

The graphical user interface (GUI) is a type of user interface that allows users to interact with electronic devices through visual indicators and graphical elements. In this case, the developed GUI for the CPS in livestock farming complexes enables monitoring of parameters, control and regulation of the environment.

For the purposes of this research, two types of GUIs were developed and tested. They can operate simultaneously on the system without interference. These GUIs are based on OpenHAB's Basic UI and HABPanel. Each interface has specific advantages, which are discussed below. In addition, a panel for graphical representation of system parameters was developed and configured in Grafana. All mentioned elements are web-based interfaces.

7.1 GUI development based on Basic UI

As an example, we consider the main graphical interface of the CPS for climate control in a dairy farm, developed using the Basic UI. Figure 7.1 shows a sample view of the interface captured from a desktop monitor. The top panel displays real-time environmental parameters. The second panel shows the measured concentrations of harmful gases. Depending on the number of sensors in the facility, sensors can be added or removed from the panels, the number of panels can be adjusted, and so on. If multiple sensors of the same type (e.g., temperature) are present in a premises, the system can be configured to display and operate based on the average value.

The third panel displays actuators, their current status (on, off, position, speed, etc.), and control buttons for configuring their operation.

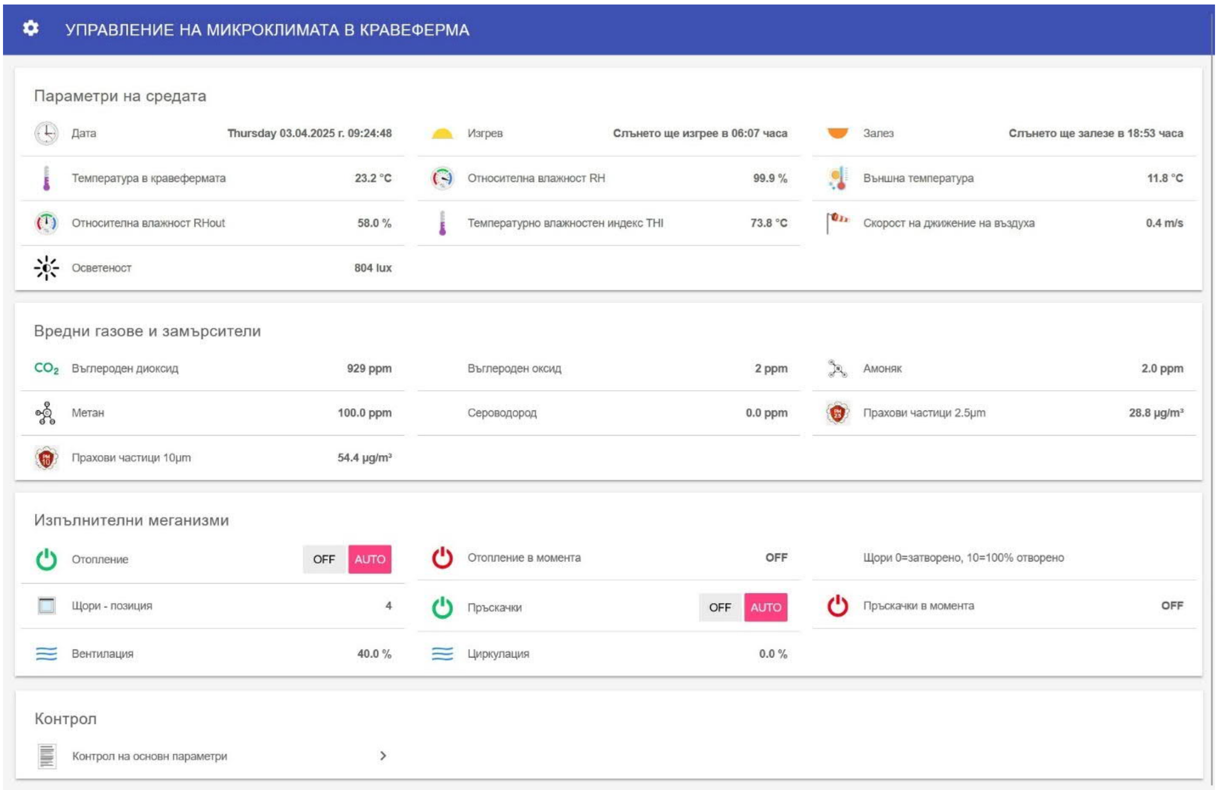

Figure 7.1. Main GUI of the CPS for dairy farm climate control based on Basic UI.

The fourth panel is configured to access a new page that separates control of basic parameters that do not require frequent adjustment, such as optimal temperature or maximum airspeed limits (Figure 7.2).

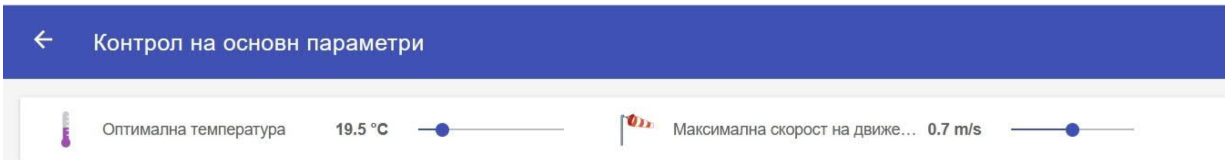

Figure 7.2. Control of basic parameters

This GUI is suitable for all types of devices—from large and small desktop monitors to tablets and even smartphones, since the page layout automatically adapts to the screen size and resolution.

7.1.1 Configuration of the GUI Based on Basic UI

Configuration of the main GUI page is performed by creating a text file with a .sitemap extension in the sitemap directory on the CPS server. Each panel, element, or subpage is described in text, with specific rules for each item. The elements include defining the page name, panel titles, variable names to be displayed, and so on. For each element, icons, units of measurement, value format, and display name are specified.

7.2 GUI development based on HABPanel

The GUI developed using HABPanel (Figure 7.6) has some advantages and disadvantages compared to the Basic UI. Multiple versions can be designed with different layouts for various use cases. HABPanel is better suited for large screens, though it can be configured for smaller ones as well. Besides displaying system parameter values, HABPanel allows setting up a color-coding scheme. For example, green for normal values, orange for elevated, and red for values exceeding safe limits.

Figure 7.6. Switching between views and settings in HABPanel.

Selecting “ACTUATORS” displays the same controls and data as in Basic UI, but with a different presentation (Figure 7.7).

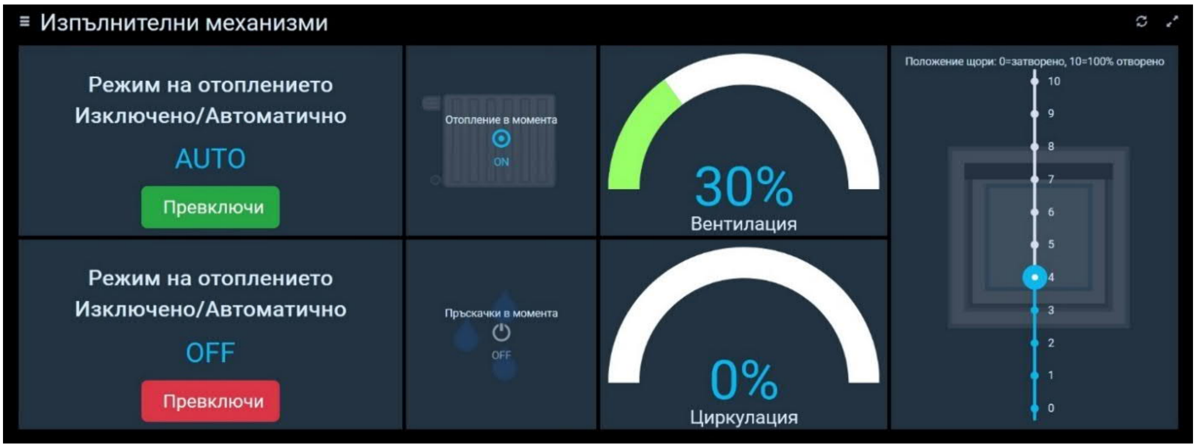

Figure 7.7. Actuator display in HABPanel.

7.2.1 Configuration of the GUI Based on HABPanel

HABPanel offers much greater flexibility in designing the interface. In addition to standard component selection options, users can create and customize templates through direct coding. This allows full control over each component—such as font, text size and color, button size, color and shape, sliders, and other components. Elements can also change color or appearance dynamically based on their status (e.g., on/off), making the interface more intuitive and interactive.

Conclusion

The dissertation work develops algorithms for microclimate management in various livestock farms, as well as for environmental control in an aquaponic system. Similar systems from world-renowned manufacturers and other innovative developments are examined, and a comparative analysis is made with advantages and disadvantages compared to the proposed system.

During the tests, components such as sensors, controllers and a control computer were selected that met the technical requirements for building the system. They were also tested for an extended period of time to establish their suitability and durability.

Different software was selected and tested to verify its suitability for creating the proposed CPS, and it was found that it can work in real time, without visible delays. It has been found that the system can be used for small or medium-sized livestock farms, and as such it is not suitable for very large farms.

Two types of graphical user interfaces have been developed that can work simultaneously without interfering with each other and allow for easy operation of the system from different devices such as a personal computer, tablet or smartphone. The graphical interface can be modified by adding or removing elements, depending on the equipment available on the livestock farm.

Author reference

Major scientific contributions

- ✓ A new method for managing the microclimate in a poultry farm has been developed, which is based on calculating the birds' felt temperature, which is different from the room temperature and depends on the temperature, humidity and air velocity, as well as the age of the chickens. Publication "Algorithm for Autonomous Management of a Poultry Farm by a Cyber-Physical System" in the journal Animals -IMPACT FACTOR - 2.7; CITISCORE – 4.9; SJR – Q1
- ✓ A new method for automatic control of nitrates, nitrites and ammonia in an aquaponic system has been developed by controlling the amount of food supplied to the automatic feeder. Publication "Concept of a Cyber–Physical System for Control of a Self-Cleaning Aquaponic Unit" in the journal AgriEngineering - IMPACT FACTOR - 3.0; CITISCORE – 4.7; SJR – Q1

Major scientific and applied contributions

- ✓ CPS have been developed for microclimate management in a cow farm, a pig farm and a poultry farm, built with cost-oriented components, with the final price being significantly lower than existing solutions on the market. This makes it easily accessible to small and medium-sized farms for which the initial investment for existing systems is prohibitive.
- ✓ The developed CPS for microclimate control in a poultry farm allows for fully autonomous control, in which the system independently changes the parameters of the environment according to the age of the chickens and switches between the three ventilation modes without the intervention of personnel. Existing similar systems only offer switching from minimum to transitional ventilation and vice versa. The proposed system also allows switching to tunnel ventilation mode, thanks to the introduced method for recording the temperature felt by the birds.
- ✓ A CPS has been developed for environmental management in an aquaponic system that offers autonomous control of a much wider range of parameters compared to existing similar systems, while at the same time being able to send recommendations to staff to regulate the amount of fish and plants to achieve and maintain its balance.

Major applied contributions

- ✓ The developed CPS for microclimate management in a poultry farm was implemented and tested in a poultry farm in collaboration with Thracian University in Stara Zagora, contributing to reducing electricity costs and improving the conditions for the birds being raised.

Acknowledgements

I thank my scientific supervisor, Prof. Dr. Nayden Shivarov, for his assistance and guidance throughout the period of my doctoral studies, as well as for his assistance in conducting research and preparing this dissertation.

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