Побудовано математичну модель надійності модуля для утримання птиці для аналізу причин його непрацездатності у формі дерева відмов. За допомогою марковської моделі визначено ймовірнісні характеристики всіх причин непрацездатності, а також відсотковий внесок кожної причини для заданого напрацювання до відмови. Показано, що найбільший внесок у загальну відмову вносять інфрачервоний нагрівач та повітронагрівач

Ключові слова: модуль для утримання птиці, модель надійності, дерево відмов, марковська модель

Построена математическая модель надёжности модуля для содержания птицы для анализа причин его неработоспособности в форме дерева отказов. С помощью марковской модели определены вероятностные характеристики всех причин неработоспособности, а также процентный вклад каждой причины для заданной наработки до отказа. Показано, что наибольший вклад в общий отказ вносят инфракрасный нагреватель и воздухонагреватель

Ключевые слова: модуль для содержания птицы, модель надёжности, дерево отказов, марковская модель

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DEVELOPMENT OF A RELIABILITY MODEL TO ANALYSE THE CAUSES OF A POULTRY MODULE FAILURE

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1. Introduction

To grow poultry (chickens, ducks, geese, turkeys, etc.), poultry houses are used as part of poultry farms or poultry factories. To improve the keeping, growth and productivity of the raised birds, they are placed in modules. This method allows maintaining various age categories of poultry within a poultry house, and it can be used on farms as a separate unit. Each module is equipped with an infrared heater and a general ventilation system. The use of these systems provides the necessary zoohygienic conditions in the area of keeping the poultry and produces a positive effect on the poultry's physiological state. Creation of an artificial microclimate has both positive and negative aspects. The positive aspects include maintaining a stable temperature, mobility and humidity in the module and a possibility of changing them in the process of growing poultry. The negative side of the artificially created microclimate is that a failure in the heating and ventilation systems causes death of the poultry. This sets high requirements for the reliability of such systems. Therefore, relevant research is justified by the need to provide evidence-based evaluation of the reliability of a poultry module, in particular to quantify the causes of its failure, which is a problem that occurs while designing and operating poultry houses built as module structures.

2. Literature review and problem statement

Growing poultry in an industrial environment is a challenging task. Young birds are especially sensitive to changes in the environment. In [1], there is research on the influence of an increased temperature and relative humidity on the bodies of broiler chickens. According to the findings, poultry consume less forage under the influence of high temperature and humidity. This adversely affects the growth of the poultry body weight. In [2], it is shown that in a clean environment the bird body assimilates nutrients and supplements better, so it is highly important to maintain temperature and humidity parameters in poultry sheds. To improve the efficiency of poultry houses, it is recommended to use local heating systems with infrared heaters [3–5]. This creates comfortable temperature conditions in the area of heating with the help of direct radiation. In [6], there is an estimation of different heating systems of a poultry house for broiler chickens. Specifically, the study examines a heating system with a direct heating of the air, a system with using infrared brooders, and a "drum" system with infrared heaters. Among the considered systems, the "drum" system is the most effective. The undertaken analysis has revealed that to maintain a given temperature it is expedient to use infrared heating.

To determine stochastic characteristics of the causes of the system's failure, their reliability is described by a fault tree, whose analysis can be performed by several approaches [7]. The first approach is based on a logical and probabilistic method [8, 9] according to which the fault tree determines the logical conditions that are turned into probabilistic expressions. This approach is easy to use, but during the analysis of the causes of the systems' failure it makes a methodological error the value of which depends on the parameters of the elements. The second approach is based on the fault tree analysis by the Monte Carlo method [10]. The disadvantage of this method is the distortion of the modelling results by stochastic fluctuations as well as a significant time use for computing. By the third approach [11, 12], the fault tree is converted into a Markov model, which provides the highest adequacy in the analysis of the causes of the system's failure. A disadvantage of this method is the high dimensionality of the Markov model as well as its limitation by the exponential distribution. The present study uses the third approach, and the restrictions are eased by applying an automated process that is based on tensor analysis [13–15]. This approach is chosen because it will provide the analysis of the causes of the system's failure in keeping poultry with the most adequate and efficient modelling of reliability compared to the logical and probabilistic approach and the Monte Carlo method.

polluted air is regulated by a gate (7), which is set in the exhaust air duct (5). Fresh air is pumped into a static pressure chamber (8) through a supply air duct (10) with the help of a supply fan (11). From the chamber (8), it gets into the box (1) through an air distributor (9). The flow rate of fresh air is regulated by a gate (12) that is set in the supply air duct (10). Purification of the supplied air from dust takes place in a supply air filter (15), and the exhaust air is cleaned from feathers, sawdust and residual feed in an exhaust air filter (16). A heat recuperator (13) is used to transfer heat from exhaust air to supply air, which helps save the heat. A calorifier (14) is installed for additional heating of supply air after the heat recuperator.

The module contains two mutually integrated systems of heating and ventilation, and their interaction should be described in a reliability model.

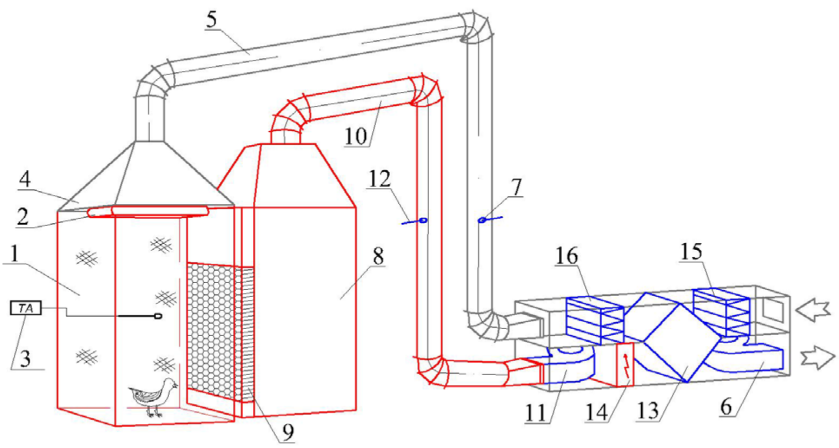


Fig. 1. The scheme of a poultry keeping module: 1 is a box for poultry; 2 is an infrared heater; 3 is a measuring device; 4 is an exhaust umbrella; 5 is an exhaust air duct; 6 is an exhaust fan; 7 is a gate; 8 is a static pressure chamber; 9 is an air distributor; 10 is a supply air duct; 11 is a supply fan; 12 is a gate; 13 is a heat recuperator; 14 is a calorifier; 15 is a supply air filter; 16 is an exhaust air filter

3. The aim and tasks of the study

The aim of the study is to develop a mathematical model of reliability, which is designed to analyse why the module is inefficient for poultry.

To achieve the aim, it is necessary to do the following tasks:

– to build the fault tree of the module for poultry keeping;

– to determine, on the basis of the fault tree, the causes of the module's failure to work;

– to quantify each cause of the poultry module failure.

4. Description of the poultry module

The principle of the module (Fig. 1) for poultry keeping is as follows.

In a box (1), there is a bird that is warmed by an infrared heater (2). A measuring device (3) is designed to obtain information about the parameters of the microclimate in the box (1). Polluted air from the box (1) is removed through an exhaust umbrella (4) and an exhaust air duct (5) with the help of an exhaust fan (6). The intensity of removing

5. The fault tree of the poultry module

Let us construct a mathematical model of reliability of the poultry module in the form of the fault tree that is shown in Fig. 2. The function of the module is to maintain a set of microclimate parameters in the box. A module failure is believed to be catastrophic if the microclimate that is formed in the box potentially threatens the life and health of the poultry inside. A catastrophic failure is marked on the fault tree as a "Top Event" block. Because the model is built for the coldest time of the year with negative ambient temperatures, two main types of failure are distinguished in its operation. The first failure is the temperature mode violation, which consists in a long lowering of the temperature in the box. This segment of the tree is marked in red. As a result, the poultry may die due to hypothermia. The second failure is the ventilation mode violation in the box. This segment of the tree is marked in blue. As a result, the poultry may die due to lack of fresh air. Other violations are believed to have a causal connection to the above or to be such that can be ignored. A critical rejection of the module happens when at least one of the two above-described violations, which is marked as an operation OR in the "Gate 1" block.

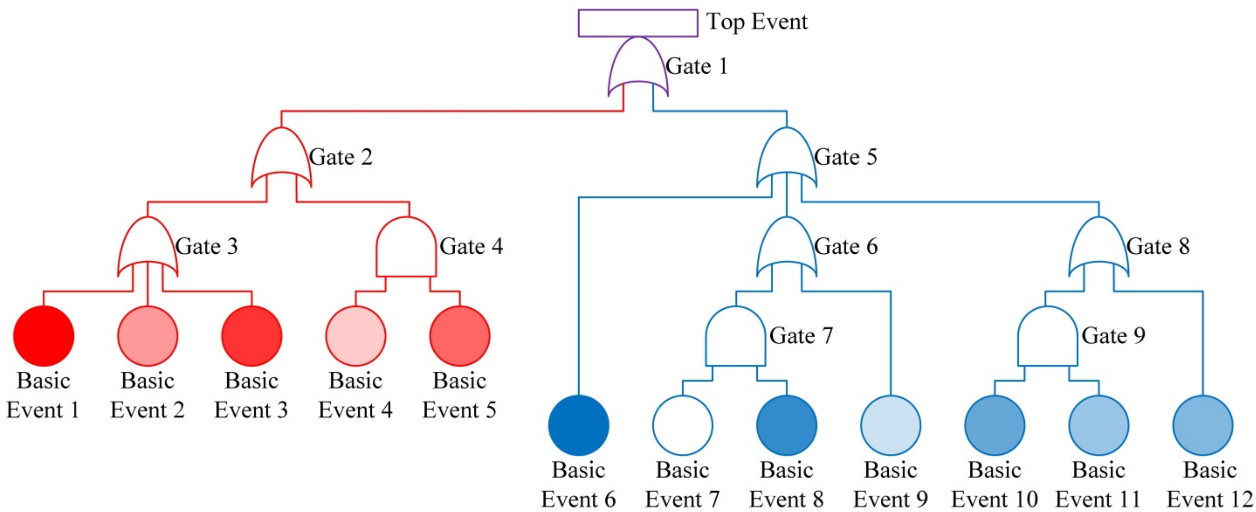


Fig. 2. The fault tree of the poultry module

Such violations are interrelated only slightly. If the box ventilation stops working, the box temperature will grow, but it will not lead to a catastrophic failure. On the other hand, a shutdown of the heating system will not affect the operation of the ventilation system, but a further ventilation of the box will decrease the temperature in it. Since the occurrence of at least one of the above-described violations already means a critical rejection, there is no need to show their interrelation in the fault tree.

Violation of the temperature mode happens due to a depressurization of the module elements or termination of heating the air, which is indicated by the operation OR in the "Gate 2" block. Depressurization causes damage to the integrity of the box (1) ("Basic Event 1"), the static pressure chamber (8) ("Basic Event 2"), and the supply air duct (10) ("Basic Event 3"). Depressurization leading to a catastrophic failure can happen even at damage to the integrity of any one of the above-listed components as indicated by the operation OR in the "Gate 3" block.

It should be noted that damage to the integrity of the exhaust umbrella (4), the exhaust air duct (5), and the recuperator (13) will worsen the microclimate values in the box and module efficiency indicators in general but will not cause a catastrophic failure. A shutdown of the air heating can cause a simultaneous failure of the infrared heater (2) ("Basic Event 4") and the calorifier (14) ("Basic Event 5"), as indicated by the operation AND in the "Gate 4" block. Ventilation failure occurs due to damage to the supply ventilation, the exhaust ventilation, or the heat recovery module ("Basic Event 6"). Catastrophic failures due to a ventilation malfunction occurs in any of the above-mentioned events indicated by the operation OR in the "Gate 5" block. Damage to the supply ventilation causes failure of the supply fan (11) ("Basic Event 7"), provided that the gate (7) ("Basic Event 8") is closed, or complete loss of capacity by the supply air filter (15) ("Basic Event 9"); this condition is designated with the operations OR ("Gate 6") and AND ("Gate 7"). Damage to the exhaust ventilation causes failure of the exhaust fan (6) ("Basic Event 10"), provided that the gate (12) is closed ("Basic Event 11"), or complete loss of capacity by the exhaust air filter (16) ("Basic Event 12"), which is marked as operations OR ("Gate 8") and AND ("Gate 9").

It is necessary to note that damage to the recuperator (13) can be of two types. The first type is the loss of integrity of its frame, causing depressurization of the ventilation system and its connection with the atmosphere. The second type is the loss of integrity of the wall that divides the flow of incoming and outgoing air, causing air pollutants' getting into the supply duct. A critical failure due to a malfunction of the ventilation mode occurs when there is damage of the second type.

The measuring device (3) performs a diagnostic function and is a critical means of preventing a critical failure, but its malfunction does not cause a violation of temperature and ventilation modes in the box. The air distributor (9) is designed for uniform supply of air. The direction of air movement in it prevents clogging holes, which makes its failure impossible.

6. Analysis of the causes of a failure of the poultry module

Using data from the directories MIL-HDBK-217F and NSWC Mechanical has helped determine the reliability parameters of the system elements (Table 1). The use of such guides is justified by the fact that they are currently valid and helpful in analysing the reliability of certified software of the leading international companies ReliaSoft and ALD Service.

The fault tree structure and the reliability parameters of the module are used to develop a homogeneous Markov model (Fig. 3). This model includes 216 states and 270 transitions. Among them, 27 states correspond to the module operation, and 189 states indicate its catastrophic failure. The operation states are marked by circles with the sequence numbers 216, 214, 212, 200, 198, 196, 194, 182, 180, 156, 154, 152, 140, 138, 136, 124, 122, 120, 96, 94, 92, 80, 78, 76, 64, 62, and 60. The initial state of the model is state 216, which corresponds to efficient operation of all elements of the module. The states of a catastrophic failure are united in 9 groups, each of which corresponds to a separate cause of failure. The groups of the states of a catastrophic failure are marked by squares with the sequence numbers 1...9. For ease of displaying in Fig. 3, for each square there are several copies distributed in different parts of the diagram. The transitions that cause catastrophic failures of the module are marked by dashed arrows. The transitions that transfer the system between its operation states are marked by solid arrows. The diagram of states and transitions was the basis for devising a Kolmogorov-Chapman system containing 216 differential equations.

Table 1

Safety parameters for the basic events of the fault tree for the poultry module

The name of the basic event	Description of the basic event	The reliability value, 1/h
Basic Event 1	The box is decompressed	$0.025\ 10^{-6}$
Basic Event 2	The static pressure chamber is decompressed	$0.020\ 10^{-6}$
Basic Event 3	The supply duct is decompressed	$0.015\ 10^{-6}$
Basic Event 4	The infrared heater has failed	$2.0\ 10^{-6}$
Basic Event 5	The calorifier has failed	$3.0\ 10^{-6}$
Basic Event 6	The recuperator has failed	$0.005\ 10^{-6}$
Basic Event 7	The supply fan has failed	$3.0\ 10^{-6}$
Basic Event 8	The gate of the exhaust duct is closed	$1\ 10^{-6}$
Basic Event 9	The supply air filter has been clogged	$0.03\ 10^{-6}$
Basic Event 10	The exhaust fan has failed	$4.0\ 10^{-6}$
Basic Event 11	The gate of the supply air duct is closed	$1\ 10^{-6}$
Basic Event 12	The exhaust air filter has failed	$0.04\ 10^{-6}$

Using a Markov model, let us calculate probability characteristics of the module reliability. The probability of a catastrophic failure of the module for the operating time of 40,000 hours is 0.02409. Fig. 4, *a* contains curves of probabilistic characteristics for causes of a failure, and Fig. 4, *b* shows a distribution diagram by the percentage of each cause of a failure for the operating time of 40,000 hours. To solve the system of 216 differential equations with constant coefficients, we applied the Dormand-Prince method, which is embedded in the mathematical package MATLAB. Since all states of the model are absorbent, there are no computing problems with the rigidity of the system. The integration step is chosen by the numerical method automatically.

Fig. 4 uses the following notation on the causes of the system failure: 1 – due to the incapacity of the infrared heater and the calorifier; 2 – due to the incapacity of the exhaust fan and the closed gate in the supply air duct; 3 – due to the incapacity of the supply fan and the closed gate in the exhaust air duct; 4 – due to the loss of capacity of the exhaust air filter; 5 – due to the loss of capacity of the supply air filter; 6 – due to the box depressurization; 7 – due to the depressurization of the static pressure chamber; 8 – due to the depressurization of the supply air duct; 9 – due to the depressurization of the recuperator.

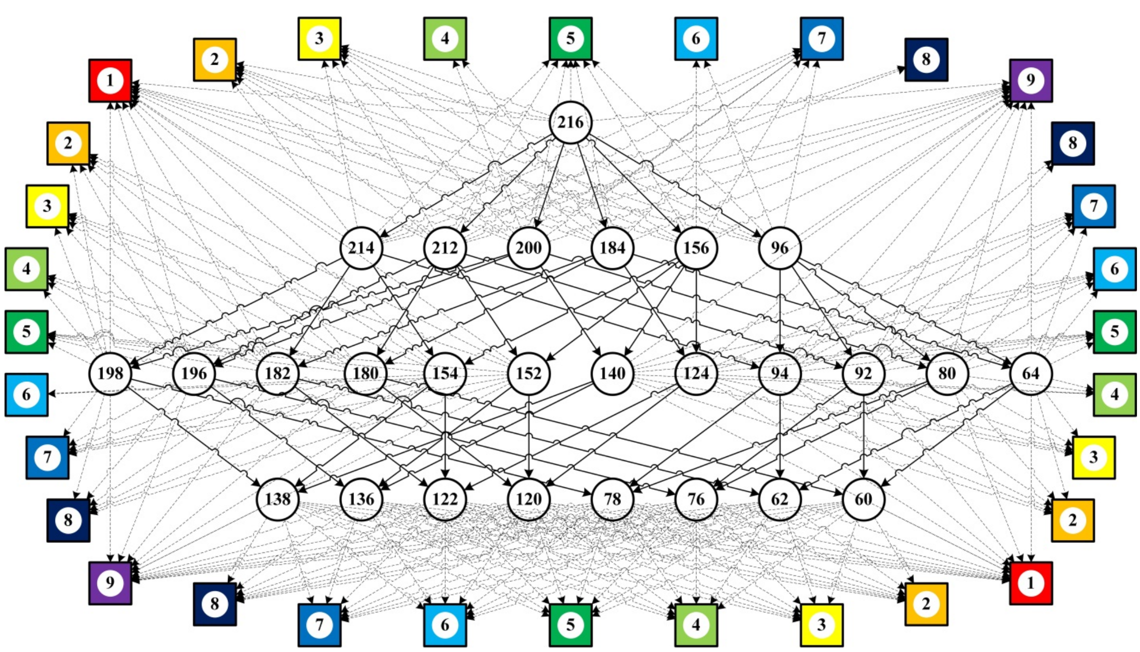
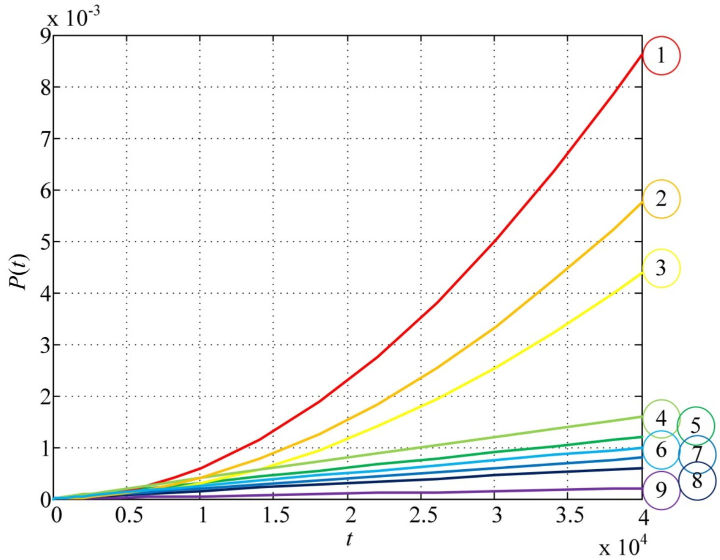
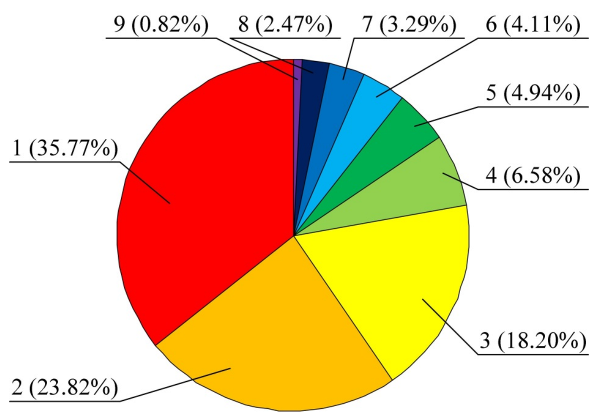


Fig. 3. A diagram of the states and transitions of the poultry module



a



b

Fig. 4. The probabilistic characteristics of the module reliability: *a* contains curves of probabilistic characteristics for reasons of a failure; *b* shows a distribution diagram by the percentage of each cause of a failure for the operating time of 40,000 hours

7. Discussion of the results of the mathematical modelling of the causes of the poultry module failure

All causes of the module failure can be divided into three groups. The first group of reasons – 6, 7, 8, and 9 (Fig. 4) – relates to depressurization of the module elements. The likelihood of the reasons that trigger this group compared to the other causes is the lowest. This is because such a destruction of the integrity of the box, the static pressure chamber, the supply air duct and the recuperator, which would cause a catastrophic failure, is an unlikely event. The second group of reasons – 4 and 5 (Fig. 4) – consists in the loss of capacity of the exhaust and supply air filters. A bigger impact on the module incapacity is caused by the exhaust air filter as a result of a more aggressive pollutant (remnants of feed, feathers, bird droppings, etc.) and a subsequently faster loss of filtering capacity. To reduce the occurrence of these events, it is periodically necessary to clean or replace the working parts of the filters, especially of the exhaust air filter. The third group of factors – 1, 2, and 3 (Fig. 4) – consists in the incapacity of the fans, the infrared heater, and the calorifier. The reliability of the fans is limited by the reliability of the electric motors. Both the calorifier and the infrared heater provide the necessary microclimate in the box. In the case of incapacity of one of them, the other is temporarily able to sustain the module operation, but their simultaneous incapacity is a major cause of a catastrophic failure of the module (the contribution is more than 35 %).

The main advantage of the study is that the mathematical modelling of the causes of the module failure uses the homogeneous Markov model of reliability. This model helps avoid the influence of "unreachable" states, which increases the accuracy of the results. The disadvantage of this approach is the high complexity compared to the commonly used engineering methods that are typically involved in solving similar problems.

The results of this study may be useful in designing life support systems of agricultural sites and modules.

As a poultry house consists of a set of similar modules, the systems that are common for the entire poultry house, such as lighting and power supply, were not considered. The next step of this research is to consider the above-mentioned systems.

8. Conclusions

1. The research findings were used to develop a mathematical model of a poultry module reliability. The model is designed to determine the causes of the module's incapacity, and it is based on a fault tree that mathematically formulates the condition of life support violation. The fault tree is set to recognize that a critical system failure occurs if there is a violation of the temperature control or the ventilation mode. A catastrophic failure is described in the tree by twelve basic events.

2. The causes of the module failure on the basis of the fault tree are determined with a constructed homogeneous Markov model. This model includes 216 states and 270 transitions. According to this model, the system contains 9 reasons that lead to a catastrophic failure of the system.

3. The Markov model has helped determine the probabilistic characteristics of all nine causes of incapacity and the percentage contribution of each of them. It is shown that the largest contribution to the total failure is made by the infrared heater and the calorifier (35.77 %), the exhaust fan (23.82 %), and the supply fan (18.2 %).

The aim of further research is to develop a reliability model to analyse the causes of a failure of a poultry house as a set of similar modules with common life support systems.

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