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VENTILATION CONTROL OF THE NEW SAFE CONFINEMENT OF THE CHORNOBYL NUCLEAR POWER PLANT BASED ON NEURO-FUZZY NETWORKS

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Abstract. *The accident at the Chornobyl Nuclear Power Plant (ChNPP) in Ukraine in 1986 became one of the largest technological disasters in human history. During the accident cleanup, a special protective structure called the Shelter Object was built to isolate the destroyed reactor from the environment. However, the planned operational lifespan of the Shelter Object was only 30 years. Therefore, with the assistance of the international community, a new protective structure called the New Safe Confinement (NSC) was constructed and put into operation in 2019. The NSC is a large and complex system that relies on a significant number of various tools and subsystems to function. Due to temperature fluctuations and the influence of wind, hydraulic processes occur within the NSC, which can lead to the release of radioactive aerosols into the environment. The personnel of the NSC prevents these leaks, including through ventilation management. Considering the long planned operational term of the NSC, the development and improvement of information technologies for its process automation is a relevant task. The purpose of this paper is to develop a method for managing the ventilation system of the NSC based on neuro-fuzzy networks. An investigation of the current state of ventilation control in the NSC has been conducted, and automation tools for the process have been proposed. Using an adaptive neuro-fuzzy inference system (ANFIS) and statistical data on the NSC's operation, neuro-fuzzy models have been formed, which allows to calculate the expenses of the ventilation system using the Takagi-Sugeno method. The verification of the proposed approaches on a test data sample demonstrated sufficiently high accuracy of the calculations, confirming the potential practical utility in decision-making regarding NSC's ventilation management. The results of this paper can be useful in the development of digital twins of the NSC for process management and personnel training.*

Keywords: New Safe Confinement, ventilation management, neuro-fuzzy network, information technology, fuzzy logic, digital twin

KONTROLA WENTYLACJI NOWEJ BEZPIECZNEJ POWŁOKI CZARNOBYLSKIEJ ELEKTROWNI JĄDROWEJ OPARTA NA ROZMYTYCH SIECIACH NEURONOWYCH

Streszczenie. *Awaria w Czarnobylskiej Elektrowni Jądrowej (ChNPP), która miała miejsce w Ukrainie w 1986 roku, stała się jedną z największych katastrof technologicznych w historii ludzkości. Podczas likwidacji awarii zbudowano specjalną strukturę ochronną – Obiekt "Ukrycie", mającą na celu izolację zniszczonego reaktora od otoczenia. Jednak planowany okres eksploatacji sarkofagu "Ukrycie" wynosił tylko 30 lat, dlatego przy wsparciu społeczności międzynarodowej zbudowano nową strukturę ochronną – "Nowa Bezpieczna Powłoka" (NSC), która została oddana do użytku w 2019 roku. NSC jest dużym i skomplikowanym systemem, którego funkcjonowanie zapewnia znaczna liczba różnych narzędzi i podsystemów. Ze względu na zmienne temperatury i wpływ wiatru, w NSC zachodzą procesy hydrauliczne, które mogą prowadzić do uwolnienia promieniotwórczych aerozoli do otoczenia. Personel NSC zapobiega tym wyciekom, między innymi poprzez zarządzanie wentylacją. W związku z długim planowanym okresem eksploatacji NSC, istotnym zadaniem jest rozwój i doskonalenie technologii informatycznych dla automatyzacji procesów. Celem pracy jest opracowanie metody zarządzania systemem wentylacji NSC opartej na rozmytych sieciach neuronowych. Przeprowadzono badania istniejącego stanu rozwiązywania problemów zarządzania wentylacją NSC oraz wybrano narzędzia do automatyzacji procesu. Za pomocą adaptacyjnego systemu wnioskowania neuro-rozmytego (ANFIS) i danych statystycznych dotyczących funkcjonowania NSC, stworzono modele neuro-rozmyte, które pozwalają na kalkulację kosztów systemu wentylacyjnego metodą Takagi-Sugeno. Weryfikacja zaproponowanych podejść na próbce kontrolnej danych wykazała wystarczająco wysoką dokładność obliczeń, co potwierdza możliwość ich praktycznego zastosowania w procesie podejmowania decyzji dotyczących zarządzania wentylacją NSC. Wyniki pracy mogą być również przydatne przy tworzeniu cyfrowe bliźniaków NSC w celu zarządzania procesami i szkolenia personelu.*

Słowa kluczowe: Nowa Bezpieczna Powłoka, zarządzanie wentylacją, rozmyta sieć neuronowa, technologia informacyjna, logika rozmyta, cyfrowy bliźniak

Introduction

As known, in 1986, an accident occurred at the Chernobyl Nuclear Power Plant (ChNPP), which became one of the largest man-made disasters in modern human history. To protect the population and the environment around the destroyed fourth power block of the ChNPP, a special structure was built, known as the Shelter Object (SO). However, the operational lifespan of the SO was only 30 years. Therefore, with the support of the international community, a new protective structure called the New Safe Confinement (NSC) was constructed and put into operation in Ukraine in 2019. One of the purpose of creating the NSC for the ChNPP is to protect the environment during the removal of radioactive materials from the destroyed fourth power block and the dismantling of its unstable structures [7].

The construction of the NSC provided isolation of the SO from the surrounding environment and created appropriate conditions for transforming it into an environmentally safe system. The NSC can be characterized as a large and complex system equipped with various equipment. The planned operational lifespan of the NSC is 100 years [4, 9]. To manage the processes of the NSC and monitor its condition, a specialized multi-level automated system has been developed and used.

However, the need to improve information visualization regarding the state of the NSC, ensure decision support, and automate the management of its processes necessitates the relevance of developing new information technologies. Taking into account the long operational lifespan of the NSC, approaches have been proposed for developing its IT architecture based on concepts such as "Continuous Development", "Continuous Integration", and "Continuous Deployment" [5].

Among the main tasks of managing the processes of the NSC is preventing releases of air from its main space with radioactive aerosols through existing construction leaks caused by temperature differentials and non-stationary hydraulic processes influenced by wind. Modeling and research have been conducted on the thermogasdynamic and radiation conditions of the NSC and SO, as well as their uncontrolled air exchange with the surrounding environment [8]. The model utilizing Computational Fluid Dynamics (CFD) models and artificial neural networks has been proposed to estimate the volumes of uncontrolled air releases with radioactive aerosols from the NSC into the environment under arbitrary wind speeds and directions [6, 7]. An internal pressure assessment model has been created for the NSC, along with approaches to manage hydraulic flows in order to minimize uncontrolled releases of air with radioactive aerosols when the input ventilation systems are disconnected, thus reducing energy consumption [11]. The concept for a prediction and early detection system for the location and concentration of radioactive aerosols within the NSC has been developed [5], and the methodology has been presented for assessing the concentration of radioactive aerosols during operations related to the removal of fuel-containing materials from the SO [1]. It should be noted that the mentioned results are focused on individual processes of the NSC and do not involve the implementation of comprehensive state management.

One possible solution of this problem is the application of digital twin technology. In general terms, a digital twin is a virtual prototype of a real physical object, product, group of products, or process that collects and reuses digital information [2]. An architecture of the digital twin of the NSC at the ChNPP has been proposed, which includes a system of its models and algorithms [10]. A component of the digital twin development for the NSC is the modelling of decision-making regarding the management of its ventilation system under non-stationary wind loads. Fuzzy logic, proposed by L. Zadeh [14], allows for solving modelling and control tasks in various domains [12], and its combination with artificial neural networks has simplified the model-building processes [3, 13].

1. The aim and objectives of the study

The aim of this study is to develop a method for managing the ventilation system of the NSC based on neuro-fuzzy networks. To achieve this objective, it is necessary to analyze the current state of ventilation system management of the NSC, select approaches for automating the process, construct neuro-fuzzy networks that will model decision-making in ventilation control, and assess the quality of its performance on a test dataset.

2. Methods

Existing approaches to managing ventilation systems in the NSC are aimed at minimizing uncontrolled air leakage along with radioactive aerosols from its main space (MS) to the ring space (RS), and from there to the surrounding environment through the existing network of leaks. The leak area values were theoretically estimated during the design of the NSC at the beginning and end of its 100-year service life. However, after conducting hydraulic tests in 2017–2018, it was determined that the existing leak areas at that time already significantly exceeded their expected values at the end of the NSC's service life. There are forecasts that the values of existing leak areas will increase significantly over time [7]. Figure 1 shows a schematic representation of the conditional hydraulic airflow in the NSC [11].

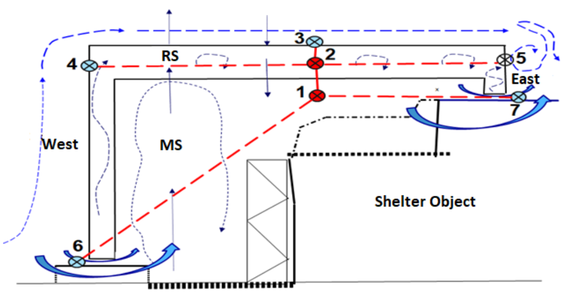

Fig. 1. Conditional hydraulic diagram of airflow movement in the NSC in a longitudinal section: 1 – MS node, 2 – RS node, 3 – node on the external cylindrical surface, 4 – node on the external surface of the western wall, 5 – node on the external surface of the eastern wall, 6 – node on the outer part of the western leaks, 7 – node on the outer part of the eastern releases [11]

As shown in Fig. 1, air masses enter the RS and MS of the NSC and are extracted from them by the ventilation system located on the cylindrical surface of the NSC, its eastern and western walls, as well as through the existing leaks, the size of which is not precisely determined.

Personnel managing the NSC ventilation system make decisions regarding the determination of air flow rates based on current data on climatic conditions (wind direction and speed), pressures in the MS and RS, and fan flow rates in the MS and RS. The creation of a digital twin of the NSC involves developing a control model for its ventilation system. Given the complexity of the process and the presence of uncertainty, it is advisable to apply intelligent information technologies based on fuzzy logic.

The existing NSC management information system contains historical data on decisions made regarding the management of ventilation systems, thus the use of neuro-fuzzy networks can be considered. In these networks, the inference process is based on fuzzy logic methods, while the construction of corresponding membership functions is achieved using neural network training methods, which simplifies the model development. The using of neuro-fuzzy networks allows for the consideration of the non-stationarity of the NSC, which is manifested in the changing leak areas. The network structure enables model adaptation, as it represents the system of fuzzy logical inference in the form of a neural network that is convenient for training, updating, and analysis.

Considering the results of comparative analysis of various types of neuro-fuzzy systems, the availability of information technologies for their implementation, the Adaptive Neuro-Fuzzy Inference System (ANFIS) proposed by R. Jang was chosen for modeling the control of NSC ventilation systems, implemented using MATLAB [3, 13]. The ANFIS network realizes the Takagi-Sugeno fuzzy inference system in the form of a five-layer feedforward neural network. The first layer of the network contains neurons corresponding to the terms of input linguistic variables. Gaussian functions were chosen as membership functions for the terms based on the results of fuzzy clustering of statistical data on decision-making in ventilation system management. The second layer consists of neurons that process the output values of the neurons in the first layer, forming the antecedents of rules. Each neuron in the second layer determines the degree of fulfillment of the corresponding rule in the knowledge base. The third layer consists of neurons that calculate normalized degrees of fulfillment of rules, and the fourth layer computes the rule consequents. The fifth layer contains only one neuron that calculates the final result of the network's operation.

One of the most important components of a fuzzy logic-based control system is the knowledge base, which represents a collection of fuzzy "if-then" rules that define the relationship between the inputs and outputs of the system under investigation. In this work, a Takagi-Sugeno rule base with linear functions as consequents was used for application in the ANFIS system, which has the following general form:

$$R_i{:}\, IF\ x_1\ is\ A_1\ AND\ x_2\ is\ A_2 \ldots x_n\ is\ A_n\ THEN \quad (1)$$
$$y = b_{i1}x_1 + \cdots + b_{in}x_n + b_{i0}$$

where R_i is a rule of the number i of the fuzzy logic inference knowledge base, $x_1 \ldots x_n$ are input variables characterizing of the state of the controlled object, $A_1 \ldots A_n$ are terms of input linguistic variables corresponding to fuzzy variables with specific membership functions $\mu_1(x_1) \ldots \mu_n(x_n)$, through which the expression $x_k\ is\ A_k$ is calculated as $\mu_k(x_k)$, y is the output variable determining the control of the controlled object and $b_{i0}, b_{i1} \ldots b_{in}$ are parameters of a linear function that determines the value of the control variable according to the rule R_i.

The main indicators determined by decision-makers in managing the NSC ventilation system are air consumption for RS and MS. Considering that ANFIS allows the construction of fuzzy logic systems only for a single output variable, it is necessary to develop two separate models for calculating air consumption for RS and MS. Figure 2 shows the structure of the fuzzy logic inference system for controlling RS's air consumption, built in the ANFIS editor of MATLAB.

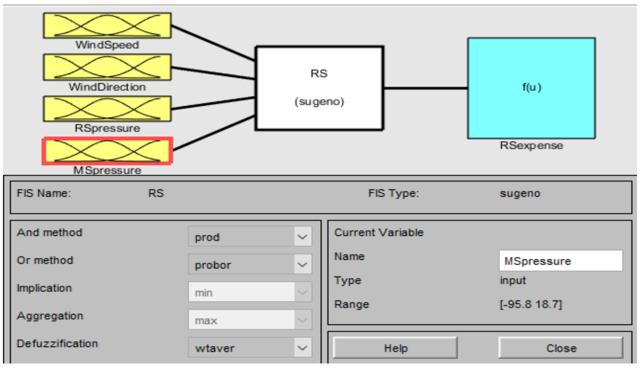

Fig. 2. Structure of the fuzzy logic inference system for controlling RS's air consumption

As seen in Fig. 2, the air consumption of the RS's ventilation system is determined by the wind speed and direction, as well as pressure differentials between RS and the surrounding environment. During the training of ANFIS using 25,170 records of statistical data, 162 fuzzy logic inference rules were generated to calculate RS's air consumption based on the Takagi-Sugeno method. The results of the neuro-fuzzy model training are presented in Fig. 3.

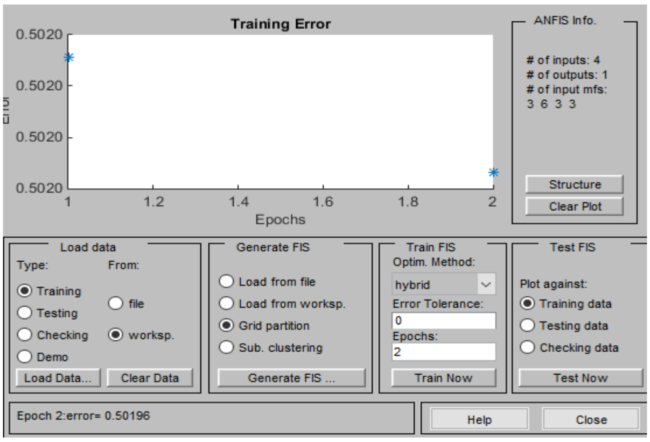

Fig. 3. The results of training the neuro-fuzzy network for controlling RS's air consumption

As shown in Fig. 3, the training was performed using a hybrid optimization method, which yielded a mean square accuracy of 0.50196, corresponding to a relative error of approximately 3.7%. Examples of plots depicting the membership functions of the input linguistic variables and the formed rule base of the fuzzy logic inference system are presented in Fig. 4 and 5, respectively. Based on the results of membership function formation using fuzzy clustering, Gaussian functions were selected as the basic type of membership functions. The number of linguistic variable terms was determined experimentally, aiming to achieve good accuracy while maintaining acceptable computation speed during the system's training. In accordance with the general form of the knowledge base rules (1), fuzzy logical conjunction is used in the rule conditions.

Figure 6 shows the graph depicting the relationship between the air consumption of the RS's ventilation system and the wind speed and direction.

As seen in Fig. 6, when the wind direction angle decreases, the air consumption of the RS's ventilation system exhibits a significantly nonlinear dependence on wind speed.

The accuracy evaluation of the trained neuro-fuzzy inference system on the test dataset containing 2517 records showed an error of 0.43023, which is approximately equal to a relative error of 3.2%. This indicates the system's adequacy and its practical potential for controlling the air consumption of the RS's ventilation system. The results of the accuracy evaluation of the neuro-fuzzy inference system are presented in Fig. 7.

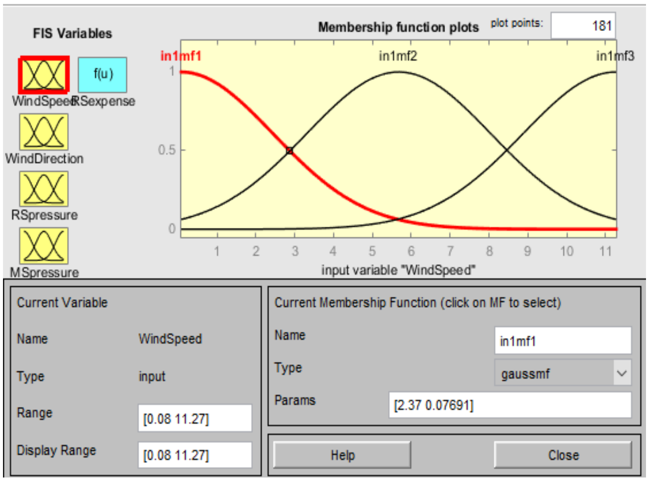

Fig. 4. Membership functions of the input linguistic variable "Wind Speed"

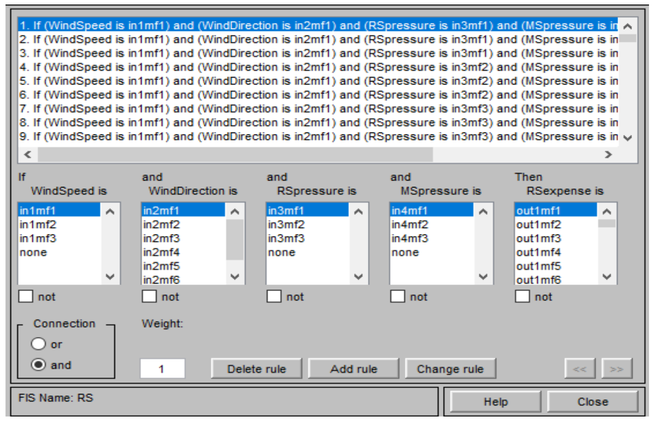

Fig. 5. The rule base for fuzzy control of air consumption by the RS's ventilation system

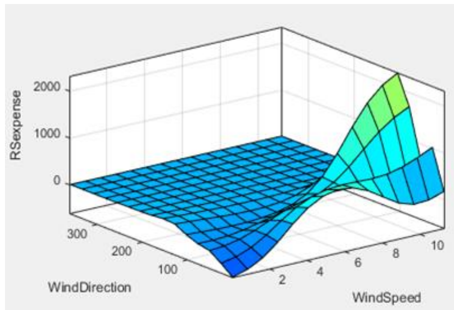

Fig. 6. Dependence of air consumption of the RS's ventilation system on wind speed and direction

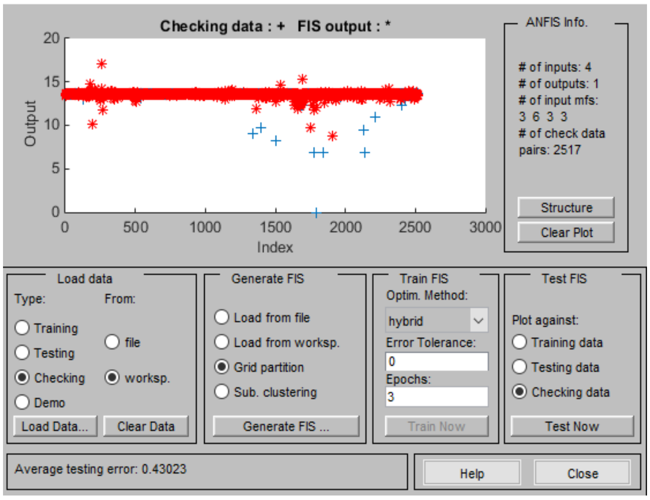

Fig. 7. The results of accuracy evaluation of the neuro-fuzzy network for air consumption of the RS's ventilation system on the test dataset

The control of air ventilation systems of the MS is carried out based on the same input variables as the control of the ventilation system of the RS. The results of training the ANFIS system for controlling the ventilation of the MS based on statistical data are shown in Fig. 8.

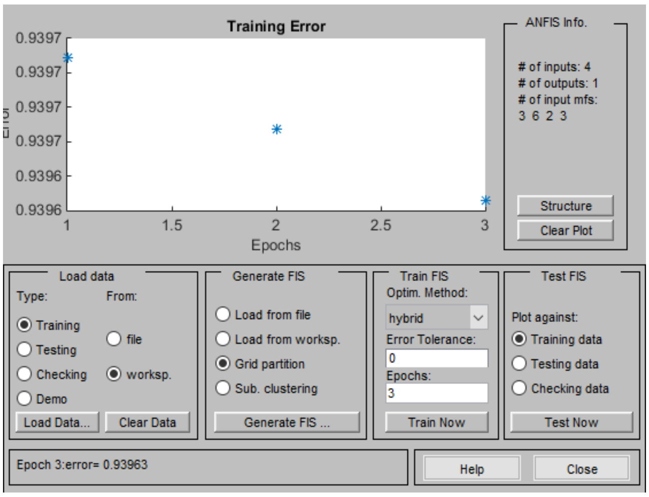

Fig. 8. The results of training the neuro-fuzzy network for controlling MS's air consumption

As shown in Fig. 8, the training accuracy reached 0.93963, which corresponds to approximately a 2.7% relative error on the training data. The knowledge base consists of 108 fuzzy production rules, enabling the calculation of ventilation system MS costs using the Takagi-Sugeno method. The results of the accuracy verification of the neuro-fuzzy network for controlling the expenses of MS's ventilation systems are presented in Fig. 9.

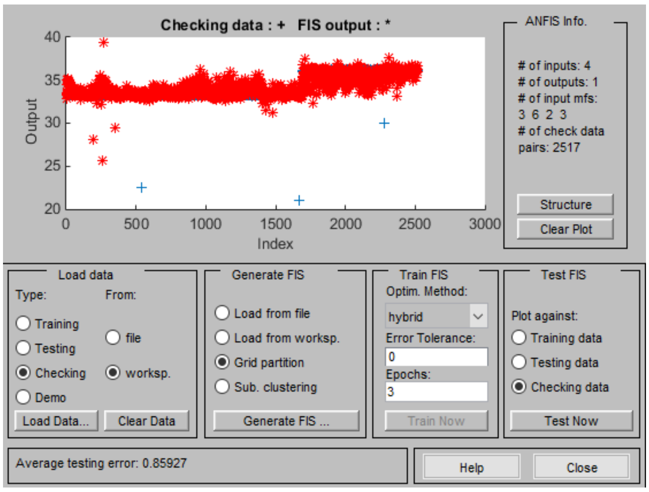

Fig. 9. The results of accuracy evaluation of the neuro-fuzzy network for air consumption of the MS's ventilation system on the test dataset

As observed in Fig. 9, a comparison of the neuro-fuzzy logic system's calculation results with the control dataset, consisting of 2517 records, revealed a deviation of 0.85927 on identical sets of input data, which approximately corresponds to a 2.5% relative error. The high accuracy indicators indicate the practical applicability of this system for managing the costs of MS's ventilation systems.

Based on the developed and trained neuro-fuzzy networks, a ventilation system control method NSC has been devised. The schematic representation of this method is shown in Fig. 10.

As shown in Fig. 10, based on processed sensor readings, input variable values are formed for the developed neuro-fuzzy networks, and using the Takagi-Sugeno method, the expenses of the ventilation systems KP and OO are calculated. These recommended expenses are analyzed and verified by decision-makers (DM). If the ventilation expenses are confirmed, they are transferred as tasks to the NSC's control system.

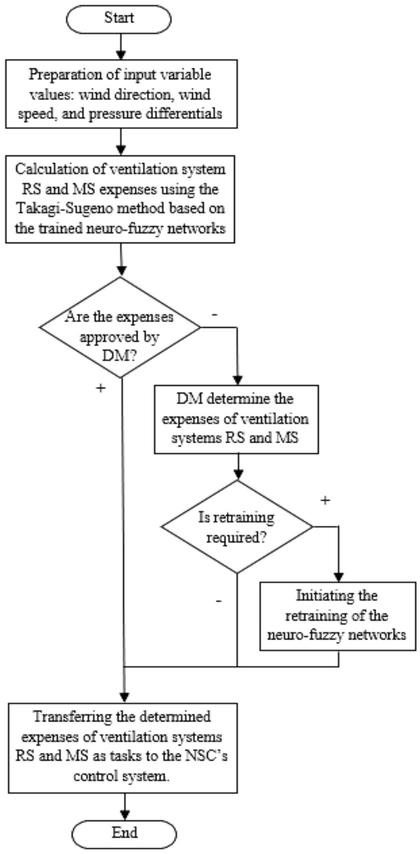

Fig. 10. The diagram of the neuro-fuzzy control method for the NSC's ventilation systems

Otherwise, the DM determines the ventilation expenses independently, after which the need for retraining the neuro-fuzzy models is evaluated. It is proposed to conduct retraining of these models if the deviations between the proposed system and DM values are significant or if the number of deviated decisions exceeds a certain threshold. The DM initiates the retraining of the models, and after making decisions, the results are transferred to the NSC's control system.

3. Conclusions

1) Research on the current state of ventilation management in NSC has been conducted. Decisions regarding the airflow volumes of the ventilation systems are made by operators based on current data on the state of the NSC and wind loads under conditions of uncertainty about existing leak areas. To automate the ventilation management, neuro-fuzzy modeling has been chosen.
2) Using the adaptive neuro-fuzzy inference system (ANFIS) and statistical data on NSC operations, neuro-fuzzy models have been developed, enabling the calculation of its ventilation system expenses using the Takagi-Sugeno method. Validation of the proposed approaches on a test dataset demonstrated sufficiently high accuracy in the calculations, confirming their practical applicability for making decisions regarding NSC's ventilation management.
3) Based on the developed and trained neuro-fuzzy networks, a ventilation system management method for the NSC has been devised. The method involves calculating ventilation system costs using neuro-fuzzy networks and approving or adjusting them by decision-makers.
4) The results of this work can be valuable for the automation and modeling of NSC processes using information technologies, including the development of digital twins of the NSC for process management and personnel training purposes.

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