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STUDY TO ASSESS ELECTRICITY GENERATION IN A THERMAL POWER PLANT USING FAULT TREE ANALYSIS MODEL

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Abstract. *This paper presents the application of Fault Tree Analysis model for availability assessment of thermal power plant. Reliability analysis as well as availability evaluation is performed for performance evaluation of thermal power plant. Equipment maintenance data is collected from maintenance history for which the goodness of fit test viz Kolmogorov-Smirnov is conducted and parameters for the best distribution are determined. Further, reliability of subsystems at various time intervals is calculated. The Fault Tree Analysis models were developed for performance evaluation of thermal power plant. These models are employed for the subsystems of plant and furthermore availability indices are evaluated. The overall availability of 87.77% is evaluated using Fault Tree Analysis model. The comparative results are obtained from the study, which revealed that the Fault Tree Analysis model provides an availability index of the system closer to real-time data.*

Keywords: reliability analysis, availability analysis, thermal power plant, Fault Tree Analysis.

1. Introduction

In the context of increasing demands on the reliability and efficiency of electric power systems, the analysis of factors affecting the generation of electricity at thermal power plants (TPP) is of particular importance. Most of the existing thermal power plants are operated for a long time, which leads to wear of the main equipment, an increase in the number of failures and a decrease in installed and available capacity. As a result, there is an increased likelihood of under-generation of electricity, disruption of load schedules, and increased operating costs. Traditional methods of estimating electricity generation are usually based on statistical data and regulatory indicators of equipment reliability. However, such approaches do not always make it possible to identify cause-and-effect relationships between individual failures of technological circuit elements and the resulting decrease in plant output. This limits the ability to make informed management decisions in the field of equipment maintenance, repair, and modernization [1,3,4,7,8,10,13].

One of the promising tools for system analysis of reliability of complex technical facilities is the Fault Tree Analysis (FTA) method [11,12]. This method allows us to formalize the logical structure of the occurrence of emergency conditions, to establish the relationship between the primary failures of elements and the final undesirable event – a decrease or loss of electricity generation. The use of the fault tree model provides a visual representation of the mechanisms for generating power losses, and also makes it possible to quantify the contribution of each piece of equipment to the overall risk of underperformance. The purpose of this study is to develop and apply a fault tree analysis model to evaluate power generation at a thermal power plant, taking into account failures of the main and auxiliary equipment. As part of the work, the key technological subsystems of thermal power plants (boiler, turbine, generator, fuel supply, water treatment and electricity supply systems for their own needs) are considered, the fault tree structure is formed and the impact of failures on the level of actual electricity generation is assessed. Alternative reliability modelling approaches such as Markov models, Bayesian networks, and Petri nets are widely used in power system analysis. Markov models provide accurate state-transition representation but may become computationally complex for large-scale systems. Bayesian networks allow modelling of dependent failures but require extensive probabilistic information. Petri nets are suitable for dynamic systems but involve significant modelling effort. In the present study, FTA was selected due to its transparency, analytical simplicity, and suitability for real industrial operational data.

The practical significance of the study lies in the possibility of using the obtained model to increase the validity of decisions on managing the technical resource of equipment, optimizing repair impacts and reducing power losses. The proposed approach can be applied both in analysing the operation of a specific plant and in developing strategies to improve the reliability and efficiency of thermal power plants in general.

2. Plant description

A thermal power plant (TPP), is a complex multi-level energy facility designed for the simultaneous production of electrical and thermal energy based on the conversion of chemical fuel energy into mechanical and further into electrical energy. The main types of fuel used are coal, natural gas and fuel oil, the choice of which is determined by regional resources, economic and environmental factors. The functional block diagram of TPP presented in Figure 1. There are major equipment: a) turbine, b) generator, c) IDF (Induced Draft Fan), d) FDF (Forced Draft Fan), e) PAF (Primary Air Fan), f) BFP (Boiler Feed Pump), g) CWP (Circulating Water Pump), h) CEP (Condensate Extraction Pump), i) boiler, j) chimney, k) CM (Coal mill), l) condenser, m) HPH (High Pressure Heater), n) LPH (Low Pressure Heater), o) APH (Air Preheater), p) ESP (Electrostatic Precipitator). The boilers burn fuel and generate superheated steam with high parameters (pressure and temperature). The resulting steam is supplied to the turbine, where its thermal energy is converted into mechanical energy of rotation of the shaft connected to the electric generator. The generator, in turn, converts mechanical energy into electrical energy, which is supplied to the power grid [1,3,10].

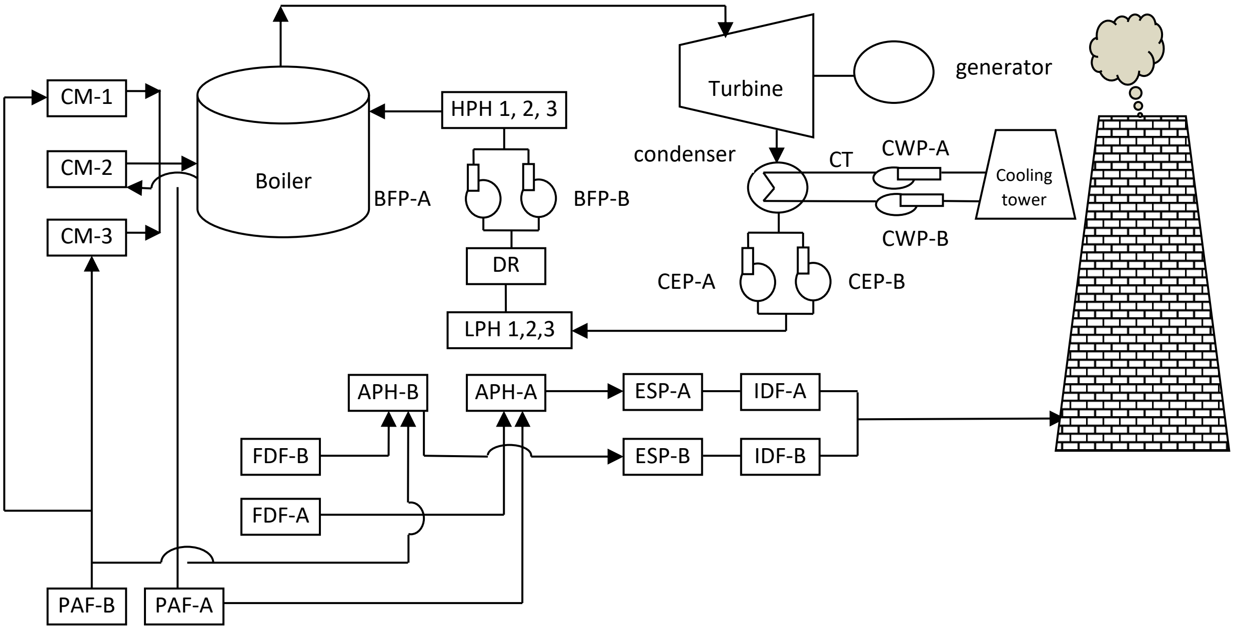

Fig. 1 Model of thermal power plant for electricity generation

The operation of thermal power plants is characterized by high complexity and interdependence of technological nodes. Malfunction of any element – boiler, turbine, generator, fuel supply system or automation can lead to a decrease in power, deterioration in the quality of electricity, or a complete shutdown of the unit. In conditions of equipment wear, variable load conditions and exposure to external factors, the probability of failures increases, which directly affects the volume of electricity generation and the reliability of energy supply. In this regard, the TPP is considered as a complex technical system with a hierarchical structure of failures. The use of the Fault Tree Analysis (FTA) model makes it possible to formalize the cause-and-effect relationships between failures of individual elements and the final event a decrease or loss of electricity generation. This approach ensures the identification of critical nodes, the assessment of the contribution of individual failures to the overall risk, and the formation of informed decisions to improve the reliability and efficiency of the plant.

2.1 Modelling the availability of thermal power plants

A thermal power plant belongs to the class of complex technical systems, the functioning of which is characterized by a multilevel structure and a significant number of interrelated elements. In this regard, the analysis of the availability of thermal power plants is a prerequisite not only for ensuring the operability of individual components, equipment and subsystems, but also for sound planning of maintenance and repair activities. Accessibility modelling is a systematic approach based on the step-by-step decomposition of a power plant into subsystems, equipment, and individual components. This approach allows us to take into account the impact of element failures, as well as the frequency and duration of restoration work on the integrated indicator of installation availability. The reliability and maintainability indicators of the elements directly determine the probability of finding a thermal power plant in working condition. For systems whose elements are connected in a sequential configuration, the assessment of overall availability is usually carried out using the analytical expression (1), which makes it possible to determine the contribution of each element to reducing the availability of the entire system [7,8,9,10,14].

$$Av = \prod_{i=1}^{n} Ai \tag{1}$$

where: A_v – overall availability of the Thermal Power Plant (TPP); Ai – availability of the i-th component (or subsystem) of the plant; n – total number of components (subsystems) included in the reliability model.

For the current work, availability of TPP is investigated and assessed by FTA method.

2.2 FTA modelling of TPP

The fault tree diagram allows you to obtain information about the unavailability of the system and thereby determine the degree of criticality of various pieces of power plant equipment. Within the framework of this study, the fault tree analysis (FTA) model for the station is formed using the logical elements "OR" and "AND", which is illustrated in Figure 2 [11,12,13].

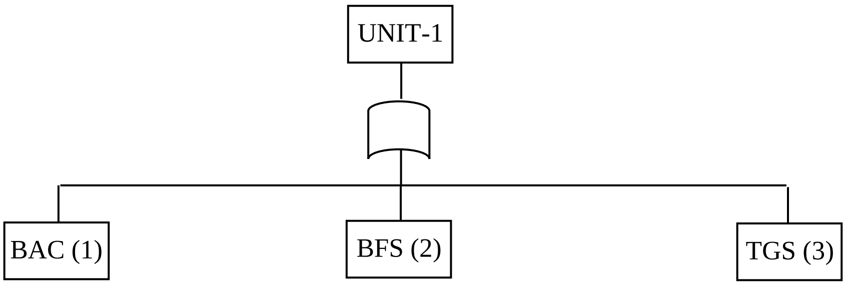

Fig. 2. FTA model of thermal power plant

After forming the FTA model at the subsystem level, the corresponding unavailability of the system is estimated using the cut-set method based on a probabilistic approach, the main provisions of which are summarized below.

$$q_{U-1} = 1 - \prod_{i=1}^{3} (1 - q_i) \tag{2}$$

where: $q_{(U-1)}$ – probability of failure (unavailability) of subsystem $U-1$ or the top event in the Fault Tree Analysis (FTA) model; q_i – probability of failure (basic event probability) of the i-th component.

In constructing the FTA model, several assumptions were adopted. It was assumed that failures of individual components are statistically independent and that failure rates remain constant within the considered operating period. Each element was modeled in a binary state (operational or failed). Common-cause failures and dynamic interactions between components were not explicitly considered. These assumptions correspond to classical FTA methodology and allow analytical estimation of subsystem and system unavailability.

3. Result and Discussion

To ensure the assessment of the availability of thermal power plants, maintenance data is collected based on the operational and repair logs of the power plant and used in further availability analysis. Due to the complexity of the TPP system under consideration, it is divided into three main subsystems for analytical evaluation, namely: the boiler air circulation system, the boiler furnace, and the turbo generator. The assessment of the availability and unavailability of TPP subsystems is based on the development of a fault tree analysis model (FTA). The summary values of the availability and unavailability of TPP subsystems obtained using the FTA model are presented in Table 1. The availability indices presented in Table 1 were obtained from a statistical analysis of operational data of the first power unit of the thermal power plant over an observation period of 17,520 hours (equivalent to two years of operation) [1,3]. Seasonal load variations and scheduled maintenance activities were observed during this period. These operational factors may influence failure frequency and recovery time, which in turn affect the calculated reliability and availability indicators.

Table 1. Summary of FTA model-based availability index

Subsystem	Unavailability	Availability
BAC (Boiler and Air Circuit)	0.000191	0.999809
BFS (Boiler Feedwater System)	0.053442	0.946558
TGS (Turbine–Generator System)	0.044167	0.955833

This expression corresponds to the inclusion–exclusion expansion presented in equation (2) and provides an exact solution for an OR-type top event under independence assumptions. The total unavailability of the first power unit of the plant, determined using the FTA model, is 0.122260.

$$q_{U-1} = 0.122260$$

Accordingly, the availability of the power unit is: $A_{U-1} = 1 - q_{U-1} = 0.877740$ (87.77%)

The total availability of the first power unit of the station, calculated using the FTA model, is 0.877740 (87.77%). The conducted research has shown that the FTA approach allows obtaining system availability values close to the indicators observed in real time. However, when using the FTA method, the effect of system redundancy is not taken into account. The results of the analysis confirmed that FTA is the most appropriate method for assessing station availability. In the future, a reliability analysis is performed for various time intervals of the station's operation, which is discussed in the following sections.

It should be noted that explicit modelling of equipment redundancy (e.g., standby pumps or parallel fans) was not incorporated into the present FTA structure. The subsystems were represented primarily in a series configuration at the analytical level. Therefore, the obtained availability value may represent a conservative estimate. Inclusion of redundancy mechanisms could potentially increase the calculated availability indices.

4. Reliability Analysis thermal power plant

Reliability analysis includes evaluating parameters, building models, and determining the likelihood that the system will function satisfactorily for a specified period of time [8,14]. For a normal distribution, the probability density function is estimated using equation (3), and reliability is estimated using equation (4). Similarly, in the case of the Weibull distribution, the reliability indicator is determined by equation (5).

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{t-\mu}{\sigma}\right)^2} \tag{3}$$

$$R(t) = 1 - F(t) \tag{4}$$

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}} \tag{5}$$

where: *F(t)* – probability density function of the random variable t (for example, time to failure of equipment in a TPP); t – random variable (typically operating time or time to failure); μ – mean value (mathematical expectation) of *t*, represents the average operating time; σ – standard deviation, characterizes the dispersion of operating time around the mean value; π – mathematical constant (≈ 3.14159); e – base of the natural logarithm; $R(t)$ – reliability function; θ – characteristic life of the component, it determines the time scale of the distribution.

As part of this study, data on previous thermal power plant failures is collected and systematized in the form of recovery time (TTR) and time between failures (TBF). To determine the most appropriate theoretical failure distribution, we consider the Weibull, lognormal, exponential, and normal distributions. The parameters are estimated using the maximum likelihood method, and the approximation quality is checked using the Kolmogorov–Smirnov criterion (K-S). The purpose of choosing the best distribution is to determine the statistical model that best describes the available data set. The K-S consent criterion allows us to assess the degree to which the data on TPP failures correspond to the selected distribution of the general population [5,6]. The various theoretical distributions for the TBF index of subsystems are presented in Tables 2 - 4.

Table 2. Best- fit distribution of BAC

Equipment	K-S test							Parameters
	Exp. 1P	Exp. 2P	Log. normal	Normal	Weibull 2P	Weibull 3P	Best fit distribution	
PA Fan	28.36	21.75	9.4083	0.0149	1.1328	0.0022	Normal	μ=12684.66 σ = 8462.17
FD Fan	95.56	76.06	1.8067	1.377	1.5740	12.06	Normal	μ=19322.12 σ=5859.22
APH	50.84	43.77	13.27	0.0007	0.8754	0.00019	Normal	μ=15445.70 σ=8928.90
ESP	95.56	76.06	1.8067	1.3777	1.5740	12.0619	Normal	μ=19322.12 σ=5859.22
ID Fan	56.99	57.94	76.028	15.115	55.1115	41.6604	Weibull 3P	β=0.35967 θ=12372.54 γ=10.78

Table 3. Best –fit distribution for BFS

Equipment	K-S test							Parameters
	Exp. 1P	Exp. 2P	Log-normal	Normal	Weibull 2P	Weibull 3P	Best fit distribution	
Boiler Drum	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22
Boiler tubing	84.78	22.83	0.5787	0.316e-4	0.10e-4	0.55e-4	Weibull-2P	β=2.61432 θ=19371.3
Fuel firing system	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22
Superheater	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22
Economizer	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22
Reheater	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22

The choice of the most appropriate theoretical distribution for the time between failures (TBF) was carried out using the Kolmogorov–Smirnov (K–S) goodness-of-fit criterion**.** This method evaluates how well a theoretical distribution matches the observed (empirical) data. For each equipment item, empirical TBF data were first obtained from operational records. Then, several candidate distributions (exponential, lognormal, normal, and Weibull) were fitted to the data using the maximum likelihood method. The K–S statistic is defined as the maximum absolute difference between the empirical distribution function $F_n(x)$ and the theoretical cumulative distribution function $F(x)$:

$$D = max|F_n(x) - F(x)|$$

The value D quantifies the deviation between the model and the actual data. The smaller the value of D, the better the agreement between the theoretical distribution and the observed data.

Table 4. Best-fit distribution of TGS

Equipment	K-S test							Parameters
	Exp. 1P	Exp. 2P	Log. normal	Normal	Weibull 2P	Weibull 3P	Best fit distribution	
Turbine Governing	95.56	76.06	1.8067	1.377	1.574	12.06	Normal 2P	μ=19322.1 σ=5859.22
Turbine Lubrication	75.51	66.54	26.2606	1.867	5.780	0.4821	Normal-2P	μ=17243.5 σ=7819.99
Generator Oil system	99.87	66.89	0.1805	11.52	13.8136	1.775	Lognormal-2P	μ=9.0955 σ=0.393221
Generator Gas	95.56	76.06	1.8067	1.377	1.5740	12.06	Normal 2P	μ=19322.1 σ=5859.22
Generator Exct.	95.56	76.06	1.8067	1.377	1.5740	12.06	Normal 2P	μ=19322.1 σ=5859.22

For each equipment unit, the K–S statistic was calculated for all candidate distributions, and the distribution with the minimum K–S value was selected as the best-fit model. This approach ensures that the chosen distribution most accurately reflects the statistical behavior of failures. In this work, the reliability of the TPP estimated on series arrangement of the subsystem via Equation (6).

$$Rs(t) = \prod_{i=1}^{n} Ri(t) \tag{6}$$

where: *Rs(t)* – reliability function of the system, it denotes the probability that the entire system operates without failure up to time *t*; *Ri(t)* – reliability function of the *i*-th component, it represents the probability that component *i* operates without failure up to time *t*; n – total number of components in the system. Now the overall reliability of TPP is given by Equation (7).

$$R_s(t) = R_{BAC}(t) \times R_{BFS}(t) \times R_{TGS}(t) \tag{7}$$

$Rs(t)$ – overall reliability of the TPP; $R_{BAC}(t)$ – reliability of the Boiler and Air Circuit (BAC) subsystem; $R_{BFS}(t)$ – reliability of the Boiler Feedwater System (BFS); $R_{TGS}(t)$ – reliability of the Turbine–Generator System (TGS); *t* – operating time.

The reliability of the subsystem at different time levels is determined and presented from Figures 3-5. It follows from the graphs presented above that as the operating time increases from 0 to 17520 hours, the overall reliability of the installation decreases significantly. The probability of trouble-free operation of the ID fan, generator oil system, BFP for a period exceeding one year (8760 hours) is less than 50%.

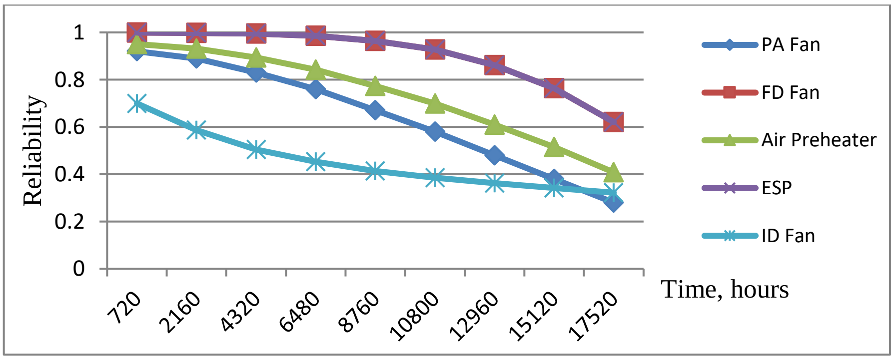

Fig. 3. Reliability Analysis of BAC

Based on the reliability analysis carried out, taking into account the performance of the equipment after one year of operation, the planning of maintenance of critical equipment should be carried out with increased priority. The maintenance schedule is determined by the level of criticality of each element, and information about the failure rate of the system contributes to a more efficient allocation of maintenance resources.

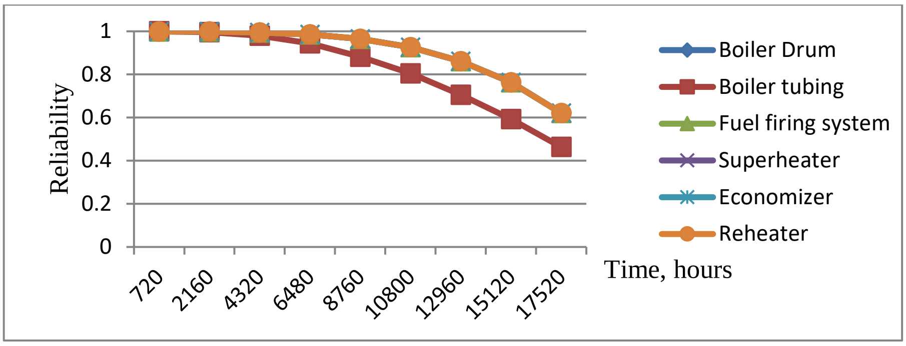

Fig. 4. Reliability analysis of BFS

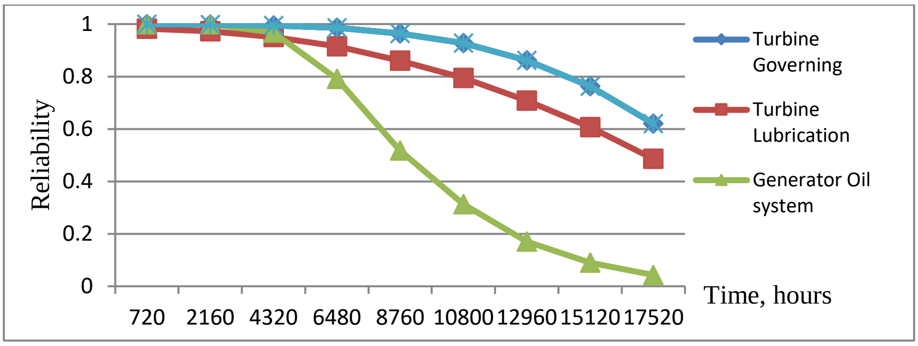

Fig. 5. Reliability analysis of TGS

The use of estimated reliability values makes it possible to determine the degree of criticality of equipment and systems. The results of the analysis show that individual systems are the most vulnerable in terms of operational readiness, which necessitates the urgent adoption of corrective measures. The findings made it possible to adjust maintenance schedules based on the actual operating conditions at the enterprise. In addition, the results of the reliability analysis serve as the basis for managerial decision-making, allowing you to plan maintenance activities by subsystem and rationally allocate resources.

5. Conclusion

As part of this study, an analysis of the reliability of thermal power plants was performed based on operational maintenance data obtained for various subsystems in real time. To assess the availability of the system, the FTA model was developed and applied, the results of which are presented in the paper. The study showed that using the FTA approach makes it possible to obtain availability values that are closest to real operational data, while the impact of system redundancy is not taken into account in this technique. In addition, an analysis of the reliability of TPP subsystems for various periods of operation was carried out, which revealed that the probability of trouble-free operation of the ID fan, generator oil system, BFP over the last year of operation is less than 50%. Failure of any of these subsystems can lead to the shutdown of thermal power plants, and therefore they are classified as critically important and require special monitoring [14, 15]. The obtained results and conclusions of the study can be used to improve the reliability of equipment and increase the volume of electricity generation at thermal power plants.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Nygymanova A.: Conceptualization, Methodology, Investigation, Data analysis, Writing – original draft; **Ongar B.:** Data curation, Statistical analysis, Validation, Writing – review & editing; **Sarsenbayev Y.:** Supervision, Scientific consultation, Methodology review, Writing – review & editing. The final manuscript was read and approved by all authors.

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