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Original Article

Fuzzy optimization of radon reduction by ventilation system in uranium mine

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ABSTRACT

Radon and radon progeny being natural radioactive pollutants, seriously affect the health of uranium miners. Radon reduction by ventilation is an essential means to improve the working environment. Firstly, the relational model is built between the radon exhalation rate of the loose body and the ventilation parameters in the stope with radon percolation-diffusion migration dynamics. Secondly, the model parameters of radon exhalation dynamics are uncertain and described by triangular membership functions. The objective functions of the left and right equations of the radon exhalation model are constructed according to different possibility levels, and their extreme value intervals are obtained by the immune particle swarm optimization algorithm (IPSO). The fuzzy target and fuzzy constraint models of radon exhalation are constructed, respectively. Lastly, the fuzzy aggregation function is reconstructed according to the importance of the fuzzy target and fuzzy constraint models. The optimal control decision with different possibility levels and importance can be obtained using the swarm intelligence algorithm. The case study indicates that the fuzzy aggregation function of radon exhalation has an upward trend with the increase of the cut set, and fuzzy optimization provides the optimal decision-making database of radon treatment and prevention under different decision-making criteria.

1. Introduction

A large number of radioactive pollutants, radon, and radon daughters, are entrained in the uranium mining process, which once affects the operating environment and product safety to a certain extent. The porous medium formed after uranium ore blasting also called the loose body, is characterized by low strength and poor stability. The migration speed of radon in different overburden layers quantitatively explains the causes of radon anomalies in the fault soil [1]. Three overburden physical models are established, including internal fissure, fissure system-fault zone, and non-homogeneous, to explain the phenomenon of synchrony between surface radon anomalies and fault zone positions and the influence of overburden thickness on the shape of radon concentration curve [2]. Rao et al. dealt with the forward and inverse approaches to address fractional radon diffusion problems in an uncertain environment in which the Mittag-Leffler functional approach was proposed to handle the fuzzy fractional radon transport mechanism. Fractional differential equations may model specific issues more efficiently than integer order differential equations [3]. The ventilation system of a uranium mine involves different roadways, stopes, and working faces, which can form a ventilation network. The ventilation parameters impact radon exhalation at network nodes, resulting in radiation safety and operational risks. Due to a large number of parameters and uncertainty in the radon exhalation model, it cannot describe the radon exhalation dynamics by the classical deterministic method and can better solve the radon exhalation modeling problem by the membership function [4–6]. Radon reduction by ventilation is an essential measure for radiation protection, which promotes the development of ventilation protection technology because of the interaction between exhalation percolation diffusion law and ventilation mode in uranium mines [7]. The three-dimensional steady-state radon transmission model of a single-headed tunnel revealed that the higher the temperature in the tunnel, the higher the radon concentration in all parts of the tunnel [8]. The variation law of underground radon concentration is derived by changing the length of the ventilation pipe to set parameters such as initial radon

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concentration, radon exhalation rate, wind speed, wind pressure, temperature, humidity, and wall smoothness [9].

The fuzzy attributes of parameters extend the radon exhalation dynamics model, such as diffusion coefficient, convection velocity, overburden thickness, and ore body width involved in radon reduction by ventilation, which will seriously affect the change law of radon precipitation [10]. Therefore, it is essential for optimal control of radon reduction by ventilation under the resource environment constraints under the fuzzy parameter environment. Fuzzy model optimization is generally solved by converting it into a deterministic model, but some fuzzy models cannot be converted. Otherwise, the inherent properties of the fuzzy model will be changed, and the actual law of radon precipitation cannot be satisfied. The efficient solution of multi-objective non-linear optimization problems with uncertain parameters is represented as intuitionistic fuzzy numbers, but every real-life situation cannot be justified and modeled using the linear functions, so the efficient solution methodologies such as Zimmermann's technique, maximum additive operator technique, γ-operator technique have been extended by defining the non-linear membership functions [11]. Cheng et al. presented a new modified teaching learning-based optimization algorithm called the fuzzy adaptive teaching learning-based optimization algorithm, which used three measures from the search space, namely, quality measure, diversification measure, and intensification measure [12]. Wu et al. proposed the piecewise linear fuzzy geometric mean (PLFGM) approach to improve the accuracy and efficiency of estimating the fuzzy priorities of criteria [13]. Carnero applied failure mode and effects analysis (FMEA), by combining an intuitionistic fuzzy hybrid weighted Euclidean distance operator, and the multi-criteria method Potentially All Pairwise Ran Kings of all possible alternatives (PAPRIKA) [14]. Chiu et al. proposed an interval fuzzy number (IFN)-based mixed binary quadratic programming–ordered weighted average (OWA) approach for forecasting the productivity of a factory, case indicating that it was superior to several existing methods in terms of various metrics for evaluating the forecasting accuracy [15]. Kim and Jung raised an α-level estimation algorithm for ridge fuzzy regression modeling. By incorporating α-levels in the estimation procedure, a fuzzy ridge estimator that does not depend on the distance between fuzzy numbers is constructed [16].

The fuzzy aggregate function model does not necessarily have derivatives and continuity, and there may be multi-modal functions. The classical optimization algorithm performs point search, which is difficult to obtain the global optimal solution, while the swarm intelligence algorithm is a group search algorithm that does not require derivative information and can find the global optimal solution. Wang suggested a fuzzy simplified swarm optimization algorithm (fSSO) to resolve the multi-objective optimization problem consisting of energy consumption, cost, and signal transmission quantity of the transmission process in WSNs under uncertainty [17]. Therefore, this paper reconstructs the fuzzy model of ventilation radon reduction by using fuzzy mathematics and a swarm intelligence algorithm to realize the optimal control decision-making scheme with different possibility levels and importance degrees. This optimal decision scheme provides a database for improving and promoting the optimal control of radon reduction by ventilation and realizes the flexible management of radiation protection and safety.

2. Methodology

2.1. Radon exhalation dynamics

2.1.1. Radon concentration distribution equation

The key to radon control ventilation in the quarry lies in controlling the radon percolation exhalation from broken loose bodies. The calculation coordinates of the crushed loose media are chosen (Fig. 1). When the percolation within the crushed media dominates, the radon transport equation is equation (1).

$$-v\frac{dC}{dx}-\lambda C+\frac{F\alpha}{\omega}=0 \tag{1}$$

By the boundary conditions: $x=0, C=\left(1-\frac{1}{\omega}\right)C_0$; $x\rightarrow\infty, C\rightarrow\frac{F\alpha}{\lambda\omega}$, the solution of this differential equation is obtained as equation (2).

$$C=\frac{F\alpha}{\lambda\omega}-e^{-\frac{\lambda}{v}x}\left[\frac{F\alpha}{\lambda\omega}-\left(1-\frac{1}{\omega}\right)C_0\right] \tag{2}$$

Where C is the radon concentration of the broken loose body, Bq/m^3;F is the average radon exhalation coefficient of the local type body of the broken loose body; α is the ability of local type bodies to produce movable radon, Bq/(m^{3}s); λ is the decay constant of radon; ω is the relaxation coefficient, that is, the ratio of the volume after crushing to the volume before crushing; υ is the radon percolation rate, m/s; x is the depth into the loose body along the percolation direction, m; C_0 is the radon concentration value at the inlet side, Bq/m^3.

At the outlet side $x=x_0$:

$$J=C\cdot v=\frac{F\alpha v}{\lambda\omega}-v\cdot e^{-\frac{\lambda}{v}x_0}\left[\frac{F\alpha}{\lambda\omega}-\left(1-\frac{1}{\omega}\right)C_0\right] \tag{3}$$

Where J is the radon exhalation rate, Bq/(m^{2}s).

If the thickness of the crushed loose body is relatively thin and the percolation velocity is relatively high to satisfy $\frac{\lambda}{v}x_0 \ll 1$, equation (3) becomes equation (4).

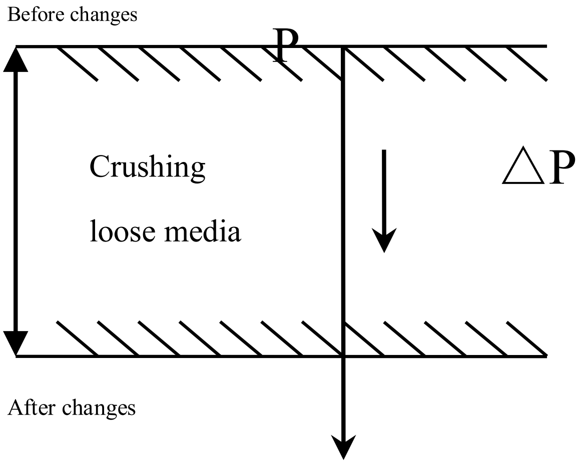


Fig. 1. Calculation coordinates of percolation flow with sudden change of pressure outside for the broken loose medium with finite thickness.

$$J = C \cdot v = \frac{F\alpha v}{\lambda\omega} - (v - \lambda x_0)\left[\frac{F\alpha}{\lambda\omega} - \left(1 - \frac{1}{\omega}\right)C_0\right] \tag{4}$$

2.1.2. Related factors analysis of radon exhalation rate

① Radon exhalation coefficient F, the radius of radioactive gas is equivalent to r_e, when the initial radon concentration is zero, the radon exhalation coefficient of local types of bodies can be calculated in equation (5).

$$\overline{F} = \frac{3D}{r_e\lambda}\left(\sqrt{\frac{\lambda}{D}}cth\sqrt{\frac{\lambda}{D}}r_e - \frac{1}{r_e}\right) \tag{5}$$

Where D is the diffusion coefficient of radon in the local type body, m^2/s; r_e is the equivalent radius of the local type of loose body in the stope, m.

② Removable radon capacity of the broken loose medium in stope α.

$$\alpha = 2.562 \times 10^{-3}\rho U K_p S_e \tag{6}$$

Where S_e is the ejection coefficient of loose scattered gas in the stope, %; ρ is the density of the broken jet medium, 10^3 kg/m^3; U is the natural uranium content, %; K_p is the equilibrium coefficient of uranium and radium.

③ Permeability of broken loose media k.

$$k = 234\eta^3 d_{20}^2 \tag{7}$$

Where η is medium porosity, $\eta = 1 - \frac{1}{\omega}$; d_{20} is the equivalent particle size, and the particle size when the cumulative content is 20%, m.

④ Coefficient of hydraulic conductivity ε.

The change in air pressure will not affect the deformation of the medium. The medium can be regarded as a rigid body, then

$$\varepsilon = \frac{k}{\mu\eta\beta} \tag{8}$$

Where μ is the gas viscosity coefficient, Pa·s; β is the air compression coefficient, m^2/N.

⑤ The seepage velocity in the broken medium v.

For broken loose media, the seepage pressure difference can be expressed by equation (9).

$$\Delta p = hXQ^2 \tag{9}$$

Where Δp is the pressure difference between the upper and lower surfaces of seepage, Pa; h is ventilation resistance coefficient, $Pa \cdot s^2 \cdot m^{-7}$; X is the length of the manhole, m; Q is ventilation air volume $m^3 \cdot s^{-1}$.

The seepage velocity in the broken medium is equation (10).

$$v = -\frac{k}{u}\frac{dp}{dx} = \frac{hkQ^2}{u} \tag{10}$$

The ventilation resistance coefficient is equation (11).

$$h = \varepsilon\frac{L}{S^3} + \xi\frac{\rho_a}{2XS^2} \tag{11}$$

Where ε is the friction resistance coefficient, $N \cdot s^2 \cdot m^{-4}$; L is the equivalent perimeter of the ventilation shaft, m; S is the equivalent cross-sectional area of the ventilation shaft, m^2; ξ is the local resistance coefficient; ρ_a is the air density, $Kg \cdot m^{-3}$.

2.1.3. The correlation analysis of ventilation parameters and radon concentration

The correlation equation (12) of ventilation parameters and radon concentration is obtained by substituting equation (10) of seepage velocity into equation (2).

$$C = \frac{\overline{F}\alpha}{\lambda\omega} - e^{-\frac{\lambda u}{hkQ^2}x}\left[\frac{F\alpha}{\lambda\omega} - \left(1 - \frac{1}{\omega}\right)C_0\right] \tag{12}$$

According to the relationship between radon exhalation rate and radon concentration, the relationship between ventilation parameters and radon exhalation rate on the crushed body surface of the quarry is obtained as equation (13).

$$\min J = vC = \frac{\overline{F}\alpha hkQ^2}{\lambda u\omega} - \frac{hkQ^2}{u}e^{-\frac{\lambda u}{hkQ^2}x_0}\left[\frac{\overline{F}\alpha}{\lambda\omega} - \left(1 - \frac{1}{\omega}\right)C_0\right] \tag{13}$$

Where h is the ventilation resistance coefficient, $Pa \cdot s^2 \cdot m^{-7}$; x is the length of the pedestrian vent shaft, m; Q is the ventilation air volume $m^3 \cdot s^{-1}$.

2.2. Fuzzy radon exhalation dynamics

In view to the radon exhalation coefficients as fuzzy numbers, fuzzy equation of radon exhalation rate can be obtained according to equation (13), which will get the fuzzy decision scheme of radon reduction by ventilation.

$$\min J = vC = \frac{\tilde{\overline{F}}\tilde{\alpha}\tilde{h}\tilde{k}Q^2}{\lambda\tilde{u}\tilde{\omega}} - \frac{\tilde{h}\tilde{k}Q^2}{\tilde{u}}e^{-\frac{\lambda\tilde{u}}{\tilde{h}\tilde{k}Q^2}x}\left[\frac{\tilde{\overline{F}}\tilde{\alpha}}{\lambda\tilde{\omega}} - \left(1 - \frac{1}{\tilde{\omega}}\right)\tilde{C}_0\right] \tag{14}$$

$$C = \frac{\tilde{\overline{F}}\tilde{\alpha}}{\lambda\tilde{\omega}} - e^{-\frac{\lambda\tilde{u}}{\tilde{h}\tilde{k}Q^2}x}\left[\frac{\tilde{\overline{F}}\tilde{\alpha}}{\lambda\tilde{\omega}} - \left(1 - \frac{1}{\tilde{\omega}}\right)\tilde{C}_0\right] \le \tilde{C} \tag{15}$$

Step 1 Fuzzy coefficients

We set the fuzzy coefficient of radon reduction by ventilation as a triangular fuzzy number set $\tilde{A}$, whose fuzzy-cut is α.

$$A(\alpha) = [A_L(\alpha), A_R(\alpha)], 0 \le \alpha \le 1 \tag{16}$$

where, $A_L(\alpha) = M_{\min} + (M - M_{\min})\alpha$ is the left endpoint of α cut set; $A_R(\alpha) = M_{\max} - (M_{\max} - M)\alpha$ is the right endpoint of α cut set; fuzzy set $V_m = \{(M_{\min}, M, M_{\max}) | \forall M_{\min} < M < M_{\max}, M_{\min}, M, M_{\max} \in R\}$, then

$$(\tilde{A})_\alpha = \left[(\tilde{A})_\alpha^L, (\tilde{A})_\alpha^R\right] \tag{17}$$

Then fuzzy objective and fuzzy constraint conversion f forms are

$$\min f(Q,x)=\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{L}(\tilde{\alpha})_{\alpha}^{L}(\tilde{h})_{\alpha}^{L}(\tilde{k})_{\alpha}^{L}Q^{2}}{\lambda(\tilde{u})_{\alpha}^{R}(\tilde{\omega})_{\alpha}^{R}} -\frac{(\tilde{h})_{\alpha}^{R}(\tilde{k})_{\alpha}^{R}Q^{2}}{(\tilde{u})_{\alpha}^{L}}e^{-\frac{\lambda(\tilde{u})_{\alpha}^{L}}{(\tilde{h})_{\alpha}^{R}(\tilde{k})_{\alpha}^{R}Q^{2}}x}\left[\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{R}(\tilde{\alpha})_{\alpha}^{R}}{\lambda(\tilde{\omega})_{\alpha}^{L}}-\left(1-\frac{1}{(\tilde{\omega})_{\alpha}^{L}}\right)(\tilde{C}_{0})_{\alpha}^{L}\right] \tag{18}$$

$$(C)_{\alpha}^{L}\leq c(Q,x)=\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{R}(\tilde{\alpha})_{\alpha}^{R}}{\lambda(\tilde{\omega})_{\alpha}^{L}} -e^{-\frac{\lambda(\tilde{u})_{\alpha}^{R}}{(\tilde{h})_{\alpha}^{L}(\tilde{k})_{\alpha}^{L}Q^{2}}x}\left[\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{L}L(\tilde{\alpha})_{\alpha}^{L}}{\lambda(\tilde{\omega})_{\alpha}^{R}}-\left(1-\frac{1}{(\tilde{\omega})_{\alpha}^{R}}\right)(\tilde{C}_{0})_{\alpha}^{R}\right]\leq(C)_{\alpha}^{R} \tag{19}$$

Step 2 Fuzzy objective membership function

Firstly, the extreme value interval of the fuzzy objective function of radon reduction by ventilation (equations (20) and (21)) is obtained using the immune particle swarm optimization algorithm (IPSO) so as to obtain the fuzzy objective equation (equation (24)).

$$f_{\alpha}^{-}=\min_{(Q,x)\in F_1} f(Q,x)=\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{L}(\tilde{\alpha})_{\alpha}^{L}(\tilde{h})_{\alpha}^{L}(\tilde{k})_{\alpha}^{L}Q^{2}}{\lambda(\tilde{u})_{\alpha}^{R}(\tilde{\omega})_{\alpha}^{R}} -\frac{(\tilde{h})_{\alpha}^{R}(\tilde{k})_{\alpha}^{R}Q^{2}}{(\tilde{u})_{\alpha}^{L}}e^{-\frac{\lambda(\tilde{u})_{\alpha}^{L}}{(\tilde{h})_{\alpha}^{R}(\tilde{k})_{\alpha}^{R}Q^{2}}x}\left[\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{R}(\tilde{\alpha})_{\alpha}^{R}}{\lambda(\tilde{\omega})_{\alpha}^{L}}-\left(1-\frac{1}{(\tilde{\omega})_{\alpha}^{L}}\right)(\tilde{C}_{0})_{\alpha}^{L}\right] \tag{20}$$

$$f_{\alpha}^{+}=\min_{(Q,x)\in F_2} f(Q,x)=\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{R}(\tilde{\alpha})_{\alpha}^{R}(\tilde{h})_{\alpha}^{R}(\tilde{k})_{\alpha}^{R}Q^{2}}{\lambda(\tilde{u})_{\alpha}^{L}(\tilde{\omega})_{\alpha}^{L}} -\frac{(\tilde{h})_{\alpha}^{L}(\tilde{k})_{\alpha}^{L}Q^{2}}{(\tilde{u})_{\alpha}^{R}}e^{-\frac{\lambda(\tilde{u})_{\alpha}^{R}}{(\tilde{h})_{\alpha}^{L}(\tilde{k})_{\alpha}^{L}Q^{2}}x}\left[\frac{(\tilde{\bar{\bar{F}}})_{\alpha}^{L}(\tilde{\alpha})_{\alpha}^{L}}{\lambda(\tilde{\omega})_{\alpha}^{R}}-\left(1-\frac{1}{(\tilde{\omega})_{\alpha}^{R}}\right)(\tilde{C}_{0})_{\alpha}^{R}\right] \tag{21}$$

where:

$$F_1=s.t\left\{\begin{matrix} Q\geq 0\\ x\geq 0\end{matrix}\right\} \tag{22}$$

$$F_2=\left\{f(Q,x)\geq f_{\alpha}^{-},x\in F_1\right\} \tag{23}$$

$$\mu_F=\begin{cases}1 & f(Q,x)\leq f_{\alpha}^{-}\\ 1-\left(f(Q,x)-f_{\alpha}^{-}\right)/\left(f_{\alpha}^{+}-f_{\alpha}^{-}\right), f_{\alpha}^{-}<f(Q,x)\leq f_{\alpha}^{+} & \\ 0 & f(Q,x)>f_{\alpha}^{+}\end{cases} \tag{24}$$

Step 3 Fuzzy constraint membership function

$$\mu_C=\begin{cases}1 \quad g_1(x)\leq(\tilde{C})_{\alpha}^{L}\\ \left(C(Q,x)-(\tilde{C})_{\alpha}^{L}\right)\Big/\left((\tilde{C})_{\alpha}^{R}-(\tilde{C})_{\alpha}^{L}\right),(\tilde{C})_{\alpha}^{L}\prec C(Q,x)\prec(\tilde{C})_{\alpha}^{R}\\ 0 \quad C(Q,x)\succ(\tilde{C})_{\alpha}^{R}\end{cases} \tag{25}$$

Step 4 Fuzzy optimization

Given the different degrees of importance of fuzzy objectives and fuzzy constraints of radon reduction by ventilation, an interactive procedure is designed to help a decision-maker to select a solution from the fuzzy optimal solution [18]. Due to the limitations of a single intelligent algorithm, such as speed and accuracy, an intelligent swarm algorithm is built by integrating the excellent performance of the genetic algorithm, immune algorithm, and particle swarm optimization algorithm to realize the fuzzy optimization of the ventilation and radon reduction system. The optimal fuzzy decision model can be obtained by swarm intelligence algorithm according to the rule of maximum fuzzy numbers.

$$\begin{aligned}&ObjV(Q,x)=\max(\beta\mu_F(Q,x)+\gamma\mu_C(Q,x))\\ &s.t\quad \beta+\gamma=1,\beta\geq 0,\gamma\geq 0\end{aligned} \tag{26}$$

Where β is the importance coefficient of the fuzzy target, and γ is the fuzzy constraint.

3. Case study

3.1. Case introduction

Take a large uranium mine in China as an example of radon reduction by ventilation. The underground quarry adopts upward ventilation. Wind flow enters the quarry from the exit tunnel and then flows upward along the patio to the return space, and finally enters the return tunnel along the patio. The length of the quarry is 50 m, the width is 8 m, the loosening factor of the loose body of the quarry is 1.4, the ore grade is 0.11%, the uranium balance factor is 1.05, the emanation coefficient is 12%, the section size of the pedestrian ventilation shaft is about 2 m × 1.8 m, the density of ore is 2.9×10^3 kg/m^3, the temperature of ventilation airflow is 20 °C, the air compression coefficient is approximated as one m^2/N, the air viscosity coefficient is 1.85×10^{-5}Pa·s, the equivalent radon exhalation coefficient is approximated as 1, and the permeability coefficient of the broken loose body is about 1.7×10^{-8} m^2.

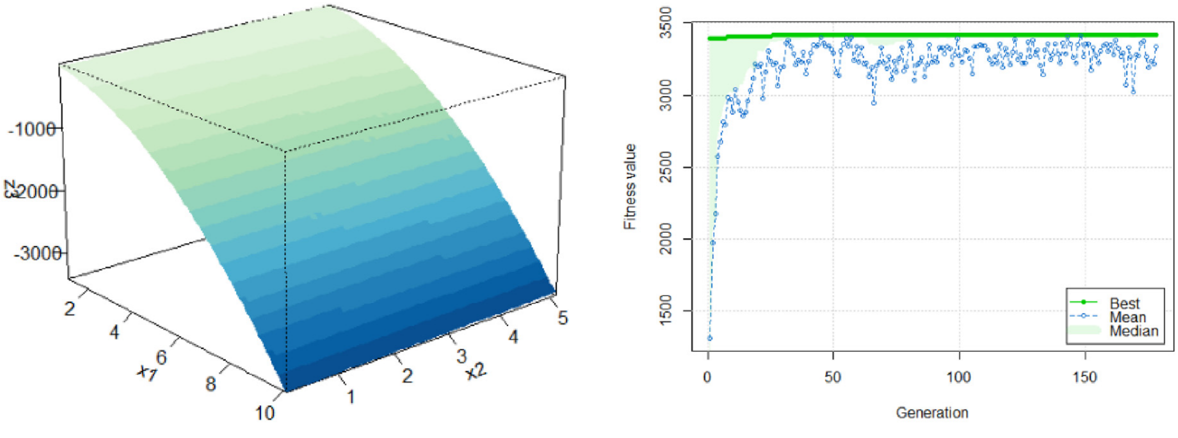
Using these parameters, the ability of the emanation medium to produce mobile radon can be calculated by $\alpha = 10.3$ Bq/(m^3·s), and pressure conductivity is 0.0025 m^2/s. Check the information to determine that the calculated frictional resistance coefficient ε of the quarry is 0.04 N·s^2/m^4, the local resistance coefficient ξ is 5, and the radon concentration of the quarry surface is 1.8kBq·m^{-3}. According to the analysis of safety environment operation requirements, the control value of radon concentration is below 3700Bq·m^{-3}. It is advisable to set the radon exhalation coefficients as fuzzy triangular numbers (Table 1).

3.2. Optimization under fuzzy environment

The paper sets the radon reduction by ventilation parameters with a triangular membership function and its fuzzy cut set. The extreme value interval of the left and right objective equations can be obtained using the swarm intelligence algorithm. It might be appropriate to set the boundary conditions for the ventilation and

Table 1
Triangular fuzzy number of the parametric coefficients of the ventilation radon reduction system.

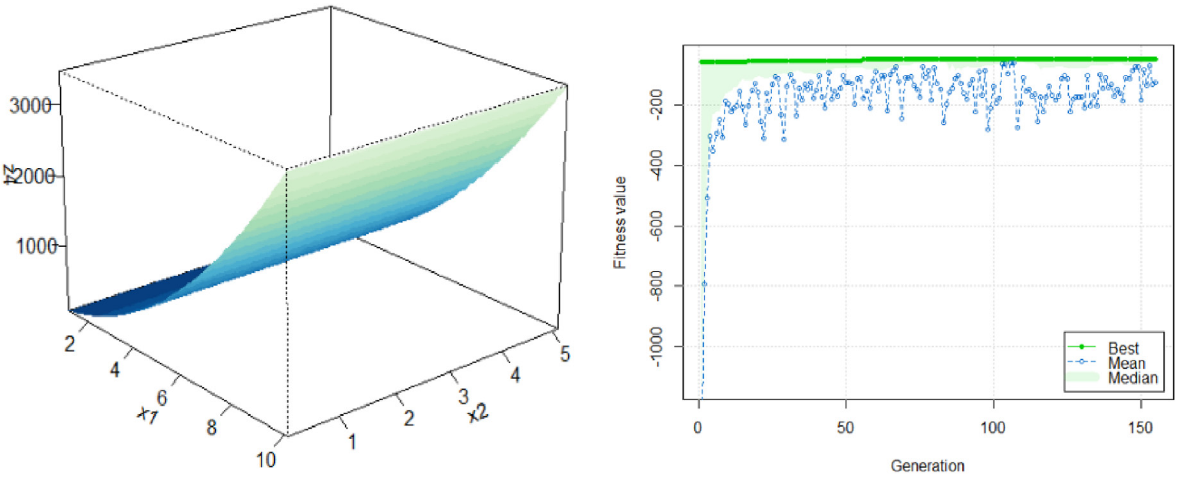
Parameter Name	Parameter Symbol	Parameter Value	Parameter Value Range			Remark
			min	m	max	
Equivalent radon exhalation	$\overline{F}$	1	0.88	1	1.12	
Radon mobility	$\tilde{\alpha}$	10.3	9.1	10.3	11.5	$Bq/(m^3 \cdot s)$
Ventilation resistance	$\tilde{h}$	0.0111	0.0100	0.0111	0.0122	$Pa \cdot s^2 \cdot m^{-7}$
Permeability	$\tilde{k}$	1.7×10^{-8}	1.4×10^{-8}	1.7×10^{-8}	2.0×10^{-8}	m^2
Decay constant	λ	2.1×10^{-6}		2.1×10^{-6}		s^{-1}
Air viscosity	$\tilde{u}$	1.85×10^{-5}	1.65×10^{-5}	1.85×10^{-5}	2.05×10^{-5}	$Pa \cdot s$
Looseness	$\tilde{w}$	1.4	1.2	1.4	1.6	
Radon concentration at the inlet side	$\tilde{C}_0$	1.8	0.8	1.8	2.8	
Radon concentration control	$\tilde{C}_{max}$	3700	3600	3700	3800	$kBq \cdot m^{-3}$



(a) (b)

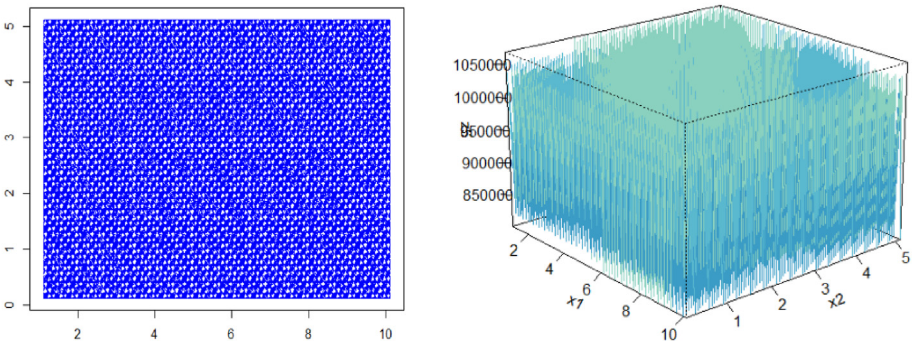
Fig. 2. (a)The left relationship function for radon exhalation between ventilation rate and ore thickness (α cut = 0.2). (b)The optimal solution of the left fuzzy target equation of radon exhalation(α cut = 0.2).

the pile thickness as x1 (1.12, 10.12) and x2 (0.12, 5.12). Among them, when the fuzzy cut set is 0.2, the fitness function value of the left equation is 3421.78, and the optimal solution is [x1 x2] = [10.11238 0.1917754] (Fig. 2). The fitness function value of the right equation is −45.35403, and the optimal solution is [x1 x2] = [1.154508 0.1526092] (Fig. 3).



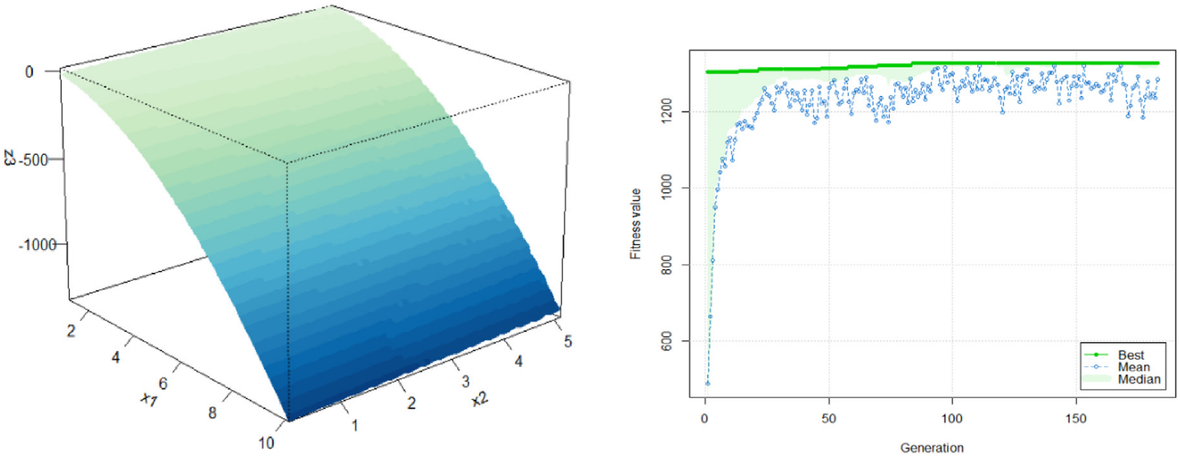
(a) (b)

Fig. 3. (a)The right relationship function for radon exhalation between ventilation rate and ore thickness(α cut = 0.2). (b)The optimal solution of the right fuzzy target equation of radon exhalation(α cut = 0.2).



(a) (b)

Fig. 4. (a) Projection diagram of fuzzy integration function for radon exhalation.
(b) Three-dimensional diagram of fuzzy integration function for radon exhalation (α cut = 0.2, β = 0.6, γ = 0.4).

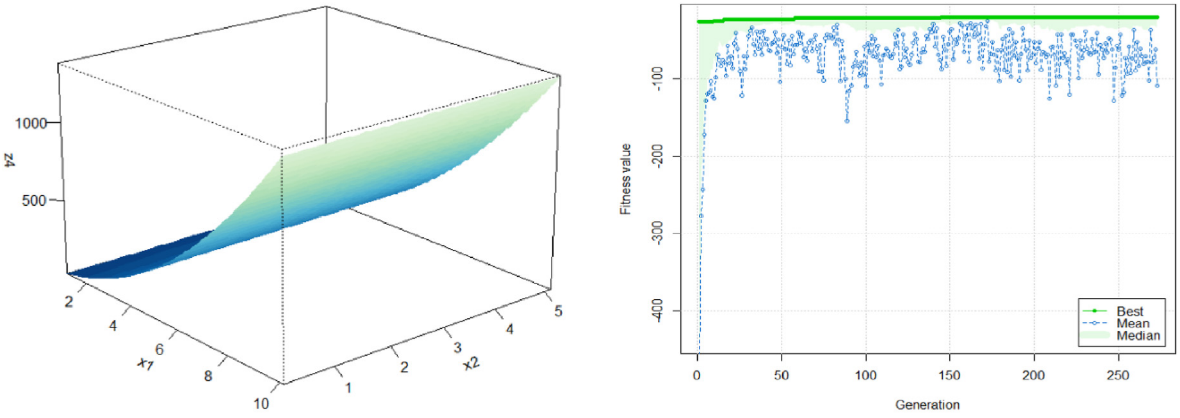


(a) (b)

Fig. 5. (a) Three-dimensional diagram of the left fuzzy target(α cut = 0.8).(b) The optimal solution of the left fuzzy target(α cut = 0.8).

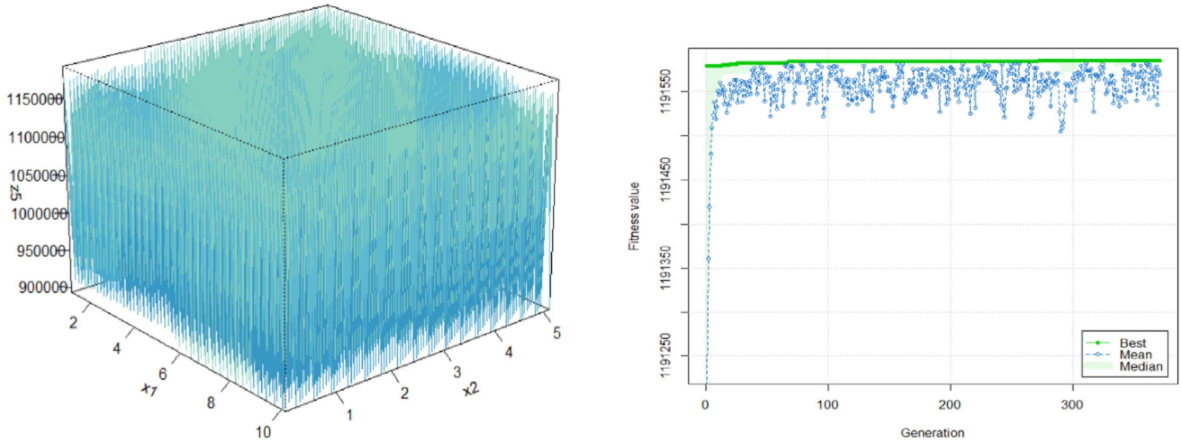
The integrated fuzzy set function is constructed by combining the importance of fuzzy objectives and constraints. When the fuzzy target is 0.6 and the fuzzy constraint is 0.4, the optimal solution is [x1 x2] = [1.134045 5.114978] (Fig. 4).

And so on, when the fuzzy cut set is 0.8, the iterative optimization of left and right extreme value interval for radon extraction



(a) (b)

Fig. 6. (a) Three-dimensional diagram of the right fuzzy target(α cut = 0.8). (b) Optimal solution of the right fuzzy target(α cut = 0.8).



(a)

(b)

Fig. 7. (a) Three-dimensional diagram of fuzzy integration function for radon exhalation (α cut = 0.8, β = 0.8, γ = 0.2). (b) Optimization of the fuzzy integrated target (α cut = 0.8, β = 0.8, γ = 0.2).

Table 2
Optimal control parameters of ventilation radon reduction under different possibility levels and importance.

α cut set	β	γ	Q	x	*ObjV*
0.2	0.8	0.2	12.6564	5.8406	0.9944
	0.6	0.4	10.6336	20.2982	0.9888
	0.5	0.5	12.8090	46.8663	0.9719
0.5	0.8	0.2	13.4475	41.7139	1.0000
	0.6	0.4	8.4939	20.3877	1.0000
	0.5	0.5	14.7531	32.6625	1.0000
0.8	0.8	0.2	19.4537	26.0570	1.0000
	0.6	0.4	19.4927	11.8979	1.0000
	0.5	0.5	10.5608	32.1231	1.0000

of the fuzzy target under different possibility levels (Fig. 5 and Fig. 6). When the fuzzy target is 0.8, and the fuzzy constraint is 0.2, the integrated iterative optimization solution of ventilation radon reduction fuzzy system under different importance of the fuzzy target and the fuzzy constraint (Fig. 7). And so that, according to different fuzzy cut sets and importance conditions, the optimal solution is obtained by the swarm intelligence algorithm, so as to realize the optimal control decision of ventilation radon reduction system under different possibility levels (Table 2).

The example shows that the optimal schemes of radon reduction by ventilation are obtained under different possibility and importance levels by fuzzy mathematics and swarm intelligence algorithms. The fuzzy integration function of radon exhalation has an upward trend with the increase of the cut set, which can provide a better radon treatment and prevention database under different decision-making criteria. That shows the optimal importance of the fuzzy aggregation function under different probability levels and importance levels, which provides an essential reference for decision-making scheme of radon reduction by ventilation and realizing radiation protection safety and human health.

4. Conclusion

Radon reduction by ventilation is an important measure to improve the operating environment of uranium mining. Since many influencing factors and uncertain parameters, the fuzzy ventilation and radon reduction model can be reconstructed by fuzzy mathematics, and then the fuzzy optimization decision can be obtained by the swarm intelligence algorithm. The main conclusions are as follows:

1) **Uncertain parameters analysis of radon exhalation model.** The dynamics parameters of radon migration are all uncertain, such as radon exhalation coefficient, dynamic radon capacity, loosening coefficient in uranium tailings coverage, and the fuzzy dynamic law of radon exhalation can be well revealed by fuzzy triangular numbers.
2) **The extreme value interval of the radon exhalation model.** The objective function of the left and right equations is constructed according to the fuzzy parameter coefficients and different probability levels. The optimal fitness value of the left and right equation is obtained through the immune particle swarm optimization algorithm(IPSO), thus providing flexible management for expanding the uncertainty optimization control of radon exhalation.
3) **Radon reduction by ventilation under different probability levels and importance conditions.** The fuzzy aggregation function is reconstructed according to the importance of the fuzzy objective and fuzzy constraint of radon exhalation, and the case study shows an upward trend with the increase of the cut set. The optimal decision-making database of radon exhalation is obtained by a swarm intelligence algorithm, which guides the construction by providing a critical radon control reference.
4) **Future research plan for Radon reduction by ventilation.** Through the analysis of model instability of radon exhalation dynamics, we should thoroughly discuss the radon exhalation dynamics fuzzy equation, optimize the design of control decision variables of radon reduction by ventilation, and achieve the coordinated optimization of construction quality, cost and radiation safety in uranium mining.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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