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System Dynamics Analysis of Man-Machine Efficacy in Plateau Mines

DUIMING GUO, GUOQING LI, NAILIAN HU, AND JIE HOU
School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China

Corresponding author: Guoqing Li (qqlee@ustb.edu.cn)

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ABSTRACT The effects of multiple factors in plateau environments on the working efficiency of equipment operation by personnel makes man-machine efficacy relatively difficult to evaluate. In this study, system dynamics are combined with coupling theory to establish a system dynamics simulation system to quantify the impact of personnel, equipment, and the environment on man-machine efficacy for a plateau environment and analyze the corresponding influencing factors. First, the factors that affect man-machine efficacy and the direct coupling between these factors are identified. Next, expert scoring is used to calculate the coupling between factors to construct a system dynamics model. Finally, the interaction between the influencing factors is used to develop a system dynamics simulation model for the man-machine environment. The results show that man-machine environment influence factors have the most noticeable effect on the man-machine function. The different factors have the same overall effect on the man-machine efficiency, where the impact value slowly increases over the first 0 to 6 hours of working time and then increases significantly. This result shows that the influencing factors have little effect on the man-machine efficiency before 6 hours of working time. The influence of the factors gradually becomes evident after 6 hours of operation time. Therefore, different labor hours are recommended for plateau mining enterprises in practice than for plain areas, where working times should be decreased to under 6 hours.

INDEX TERMS Man-machine efficacy, system dynamics, plateau mines, coupling analysis, man-machine environment system.

I. INTRODUCTION

Man-machine efficacy refers to the working efficiency of personnel and equipment during equipment operation by personnel. Work efficiency has always been a concern for both enterprises and scholars. Ismail studied the effects of various factors on the work efficiency of operators by simulating different light, temperature and humidity conditions in a laboratory. Temperature was found to be the main factor affecting the work efficiency, followed by light and relative humidity [1]. Mook *et al.* studied the relationship between the working efficiency and environmental parameters. A direct relationship between the work efficiency and environmental parameters was found. Staff inattentiveness under uncomfortable environmental conditions reduces work efficiency [2]. Wen used a simulation to determine the optimal working mode for Hong Kong construction workers in a high-temperature environment, along with optimal working and rest periods. The simulation results provide definitive guidance for policy makers [3]. Low pressure and temperature, hypoxia, dryness, strong wind, and intense sunlight radiation [4] in plateau areas are life-threatening conditions. Low-oxygen and low-temperature environments significantly affect human physiological and psychological functions [5]. The partial pressure of oxygen in the atmosphere decreases with increasing altitude, and the resulting decrease in the body's oxygen intake may lead to hypoxia damage to the heart, brain, lung and other organs [6], [7]. Many factors affect man-computer efficacy in these harsh environments with complex change laws. Studies have shown the following early-stage effects of a hypoxic plateau environment on cognitive function: declining visual and auditory perception, attention span and attention transferability, short-term memory, complex thinking judgment and thinking flexibility, etc., [8]. An operator who spends a long time in a low-temperature environment may experience accelerated breathing, headaches, and a slow reaction time, which affects his/her working efficiency and results in bodily harm in

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severe cases. A high-altitude environment also affects production equipment. A plateau region has a lower air pressure and ambient temperature than a plain area. Entry of a low-density medium into a diesel-engine cylinder can decrease the torque and power output, deteriorate combustion, and create start-up difficulties, which have a detrimental effect on the power, emission, economy, reliability, and durability of the engine [9]–[12]. Maintaining other conditions fixed, the effective power of a loader is directly proportional to the atmospheric pressure. That is, as the atmospheric pressure decreases, the effective power gradually decreases by 25-30 kW for every 20-kPa reduction in the average pressure [13]. In summary, extended operation times affect the overall operational efficiency of a man-machine system in a plateau environment. Changes in influencing factors at one moment in time affect the operational efficiency of the system at a later time, resulting in complex man-computer efficacy. Therefore, system dynamics theory is used in this study to analyze the influence of a plateau environment on man-machine efficacy and to study the action relationship among the corresponding influencing factors.

Forrester [14] proposed system dynamics (SD) to solve the problem of information feedback in real systems. SD is a computer-aided method used to model complex systems to understand behavioral patterns at different stages. SD provides a holistic modeling approach by simplifying the system into multiple small individual parts for investigation and considering causality in a dynamic and multidimensional manner [15]. Wu and Ning [16] combined a system dynamics model and geographic information systems to analyze an energy-environment-economy (3E) system both temporally and spatially: the interaction among economics, energy, and the environment and the effects of the key influencing factors were explicitly analyzed. Zhong and Wang [17] used system dynamics to build a model for safety performance in air traffic control, used a simulation to predict the change trend in safety performance, and performed a comparative analysis of the change in safety performance under different parameters to provide decision support for managers. Chang *et al.* [18] identified the security risk factors for prefabricated construction to build a system dynamics model of construction security risk; a simulation was used to predict the risk for a specific time period, and the simulation results were used to evaluated the security risk of prefabricated construction. Yu *et al.* [19] analyzed the ecological security of Jiaozhou Bay in detail by developing an evaluation index system for use in a system dynamics simulation model. Evolutionary game theory has been used to model the interactions between stakeholders in China's coal enterprise internal safety inspection system, including coal-mine owners, coal-mine safety regulation departments, and rank-and-file miners. System dynamics has been used to simulate a multiplayer evolutionary game is to analyze the stability of stakeholder interactions and the impact of different reward and punishment strategies on the game process and the equilibrium state under different scenarios [20], [21]. Liu and Zhu [22] used system dynamics to predict coal mine safety, analyzed the main controllable safety factors in coal mines, established a system dynamics flow chart model and demonstrated the theoretical effectiveness of the model, thus providing a reference for safety managers to make decisions. The key element in formulating a system dynamics model are the equations used to quantify the model variables. However, most variables for the influencing factors of man-machine efficacy are qualitative indexes that cannot be expressed using exact numerical data. This problem is resolved in this study by using risk coupling [23] theory to calculate the coupling degree between various influencing factors to provide data for the system dynamics model.

Coupling is a phenomenon whereby different kinds of factors encounter and interact with other kinds of factors during a developmental process that causes an original value to change. This concept has been widely used in safety security and has been developed for application to ecology, computers, enterprise management, and other fields. Peter [24] summarized the causes and properties of air crashes, integrated existing risk research models, and used a security target as a boundary to model and simulate the development trend of future air traffic accident risk to provide a reference for the study of coupling risk simulation models. Shyur [25] used a proportion risk coupling model adapted for accident prediction, and the model operation results showed the necessity of monitoring the risk coupling process. Vesselinov and Pau [26] designed a coupling model analysis software tool to evaluate risk and performance, which can be applied to risk coupling of other advanced simulation capability modules in environmental management. Li *et al.* [27] used the unascertained-entropy-weight measurement theory of multifactor coupling to construct a vulnerability assessment model of mountain road systems to evaluate the engineering vulnerability of an actual project. Duan X H used the three elements of vulnerability to construct a vulnerability analysis model of transportation systems and used the n-k model to measure the coupling degree of vulnerability factors under three coupling types: single-factor, double-factor and multifactor [28]. Luo [29] established a risk coupling analysis model of rural tourism safety accidents and analyzed four aspects of the rural tourism safety system: human, machine, environment, and management.

In this study, coupling theory is combined with system dynamics to determine the influencing factors of man-machine efficacy in plateau mines and analyze the corresponding change law under multifactor coupling to provide guidance for formulating reasonable working hours in plateau mines. The coupling degree between the influencing factor indexes is calculated to offset the shortcoming that equations cannot be used to incorporate qualitative indexes into a system dynamics simulation. As most of the investigated influencing factors of man-machine efficacy are qualitative indexes, the change trend in the simulated efficacy is employed as the judgment standard.

In this contribution, the factors that affect the man-machine efficacy are analyzed and the coupling model is established

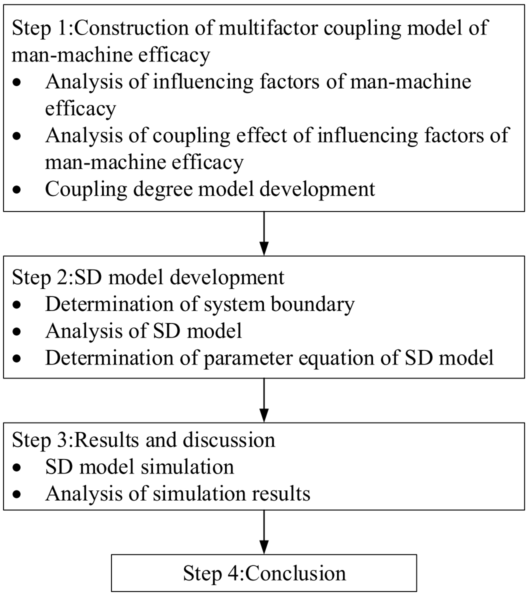

FIGURE 1. **Technical roadmap of this paper.**

at first in Section 2. Afterwards, the dynamic model of man-machine efficacy system is built in Section 3. Finally, important conclusions accompanied by simulation results are summarized briefly in Section 4. The technical roadmap of this paper as shown in the figure below.

II. CONSTRUCTION OF MULTIFACTOR COUPLING MODEL OF MAN-MACHINE EFFICACY IN PLATEAU MINE PRODUCTION

A. ANALYSIS OF INFLUENCING FACTORS OF MAN-MACHINE EFFICACY

Relevant influencing factors for man-machine efficacy must be identified for the system analysis. The working efficiency is limited by the technical level and working state of personnel and equipment during underground mine production; in addition, the plateau environment aggravates the harsh underground working environment, which negatively impacts the operation of personnel and equipment. In this study, a metal mine in Tibet is used as the research background to analyze three categories of influencing factors of man-machine efficacy: personnel, equipment, and the environment. The scientific principles of representativeness, hierarchy, comparability, and comprehensiveness are used to screen numerous influencing factors to select a total of 19 influencing indicators within the three categories. A structural chart for the selected influencing factors is shown in Figure 2 below.

B. ANALYSIS OF COUPLING EFFECT OF INFLUENCING FACTORS OF MAN-MACHINE EFFICACY

Induction is used to show that man-machine efficacy is not reduced by a single factor but rather by the mutual influence, interaction, and progressive development of multiple factors. A critical element of the system analysis is the coupling relationship between influencing factors within the same category, as well as between influencing factors of different categories. Therefore, the effect of coupling between indexes is analyzed below.

1) ANALYSIS OF COUPLING EFFECT BETWEEN HOMOGENEOUS FACTORS

The equipment subfactors directly impact the equipment operational efficiency, which can reduce the working efficiency of the equipment to varying degrees. The subfactors also influence each other, thus increasing the degree of influence on the equipment efficiency. The equipment operation status is normal when the equipment load is within the rated range. Increasing the equipment load beyond the rated range changes the equipment operation status to abnormal, resulting in increased energy consumption for nonproductive activities, such as equipment heating, vibrations, etc. and decreased equipment operation efficiency. The maintenance period also impacts the maintenance effectiveness. A long maintenance cycle increases the operation time of the equipment under a high load, deteriorating the operating environment. Consequent aging and crushing of equipment leads to difficulties in equipment maintenance and unsatisfactory maintenance effectiveness, thus increasing the equipment failure rate. By contrast, an excessively short equipment maintenance cycle increases the equipment maintenance required per unit time, affects the equipment operation time, and indirectly reduces the equipment production efficiency. The maintenance effectiveness directly affects the equipment operation status.

The human subfactors are similar to the equipment factor in directly affect the work efficiency of personnel (similar to

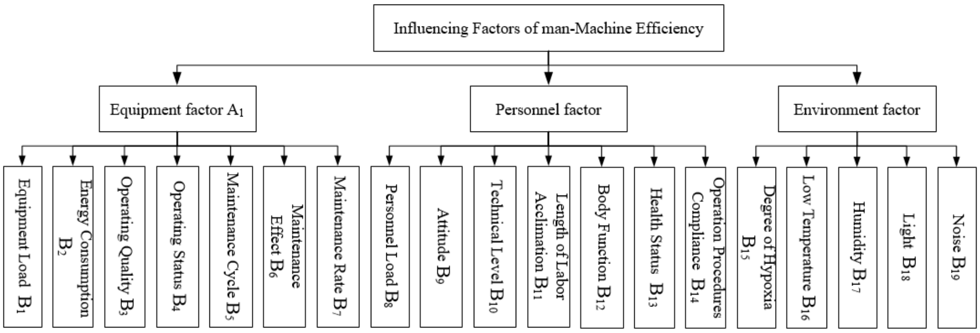

FIGURE 2. **Structural chart of influencing factors of man-machine efficacy.**

the equipment factor) and also affect each other. Physical function quality affects the working ability of underground workers. Personnel with a low physical function are more likely to be tired during operation, thus increasing the personnel labor load. Poor physical function also negatively affects personnel health, and poor health in turn exacerbates the reaction to physical function, resulting in a vicious circle; work attitude is a crucial factor affecting work efficiency. A negative work attitude easily results in carelessness and perfunctoriness during work and reduces the importance of operation regulations, which both decreases work efficiency and increases the likelihood of safety accidents; the poor health of personnel, who may even be working with a disease, affects the normal function of eyes, hands, ears and other organs, thus inhibiting personnel from working at their normal technical level and reducing operational efficiency; thus, many aspects affect the status of plateau acclimatization. The personnel health status plays a key role in the acclimatization of personnel to the plateau environment. Good physical conditions are conducive to improving the ability of personnel to adapt to the plateau environment, thereby shortening the acclimatization time.

2) ANALYSIS OF COUPLING EFFECT BETWEEN HETEROGENEOUS FACTORS

There are three categories of influencing factors of man-machine efficacy. Both the mutual influence between factors within the same category and interactions between factors from different categories should be considered. The personnel working attitude and technical level impact the equipment operational quality. Consider the case where personnel have an unproductive working attitude and a substandard technical level. The personnel cannot perform a respective operation correctly under the working conditions; subsequent low equipment performance and even equipment malfunction increases equipment vibrations and noise and aggravates the underground environment, which affects the personnel function indexes and health state and reduces the overall work efficiency; inefficient energy consumption by the equipment under low-temperature and low-oxygen conditions results in the production of exhaust gas from vehicles and other equipment, thereby aggravating roadway pollution and negatively impacting the operation of equipment and personnel health.

C. COUPLING DEGREE MODEL ANALYSIS OF INFLUENCING FACTORS OF MAN-MACHINE EFFICACY

Many coupling measurement methods are used in China and abroad. The more commonly used methods are the interpretative structural model (ISM method) [30], the N-K model [31], and the coupling degree model. The coupling degree model is selected to measure the effect of coupling between the influencing factors for man-machine efficacy in this study. The system is initially disordered and slowly changes to an ordered state; thus, the coupling effect within a subsystem affects the development of order in the system [32]. The coupling degree model can express the degree of concurrent effects between internal elements [33]. The main steps for constructing a coupling model are given below.

1) CONSTRUCTION OF COUPLING DEGREE INDEX SYSTEM

Expert estimation and analytic hierarchy progress are used to quantify the indexes for the influencing factors of man-machine efficacy, and the order parameters in the system are determined, laying the foundation for the efficacy function given below [34].

2) CONSTRUCTION OF EFFICACY FUNCTION

Consider that the variable $i(i = 1, 2, \dots m)$ is the order parameter of a specific system and $X_{ij}(j = 1, 2, \dots n)$ is the j index value of the i order parameter. The efficiency coefficient U_{ij} of each system to the whole can be expressed as formula (1).

$$U_{ij} = \begin{cases} (X_{ij} - B_{ij})/(A_{ij} - B_{ij}),\ U_{ij} \text{ has positive effect} \\ (A_{ij} - X_{ij})/(A_{ij} - B_{ij}),\ U_{ij} \text{ has negative effect} \end{cases} \tag{1}$$

where:

U_{ij}: the efficacy coefficient, and $0 \le U_{ij} \le 1$;

A_{ij}: the upper limit value of the order parameter in the stable state of the whole system.

B_{ij}: the lower limit value of the order parameter in the stable state of the whole system.

In the formula presented above, the efficacy coefficient U_{ij} represents the consistency degree of each index value to the target. The smaller the efficacy coefficient is, the more inconsistent the index value is. The closer the index value is to 1, the more consistent the index value is [35]. The order degree of each subsystem relative to the whole system can be calculated using the geometric mean or the linear weighting method. The linear weighting method is selected, and the corresponding formula is given below:

$$U_i = \sum_{j=1}^{m} \lambda_{ij} U_{ij}, \quad \sum_{j=1}^{m} \lambda_{ij} = 1 \tag{2}$$

where:

U_i: the orderly contribution of each subsystem to the overall system

λ_{ij}: the weight of each order parameter

The coupling relationships within the man-machine environment are not calculated in this study, that is, only the coupling efficiency coefficient of a specific index is calculated.

3) CONSTRUCTION OF COUPLING DEGREE FUNCTION

Consider that the whole system consists of m subsystems; then, the coupling degree model of the multiple subsystems is expressed below:

$$C_m = m\left\{(u_1, u_2, u_3 \dots u_m)/\left[\prod u_i + u_j\right]\right\}^{1/m} \tag{3}$$

III. CONSTRUCTION OF SYSTEM DYNAMICS MODEL

Qualitative and quantitative analyses are both used in system dynamics modeling and typically involve the construction of a causal loop diagram and a stock-flow diagram.

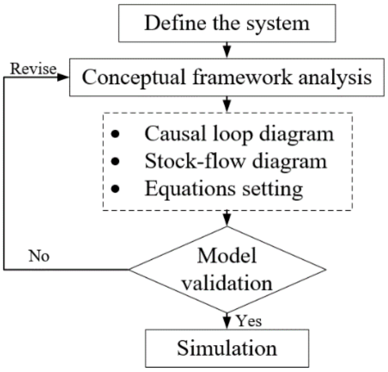

FIGURE 3. Main steps of system dynamics model [37].

Causal loop diagrams are used to qualitatively analyze the relationships within a system to understand the system conceptually. A stock-flow diagram is used to quantitatively analyze the influence of different conditions on the model [36]. Figure 3 shows the main modeling steps of system dynamics.

A. DETERMINATION OF SYSTEM BOUNDARY

The study of man-machine efficacy in plateau mines is complex, because many influencing factors, such as personnel, equipment, and the environment, are involved. The system boundary is first defined based on information specific to the system in a system dynamics analysis. Only factors highly relevant to the research subject are retained to simplify the system analysis. The analysis presented above is used to categorize the system into three subsystems: personnel, equipment, and environment.

B. ANALYSIS OF SYSTEM DYNAMICS MODEL

Figure 4 shows the causal loop diagram of the influencing factors for man-machine efficacy established using Vensim software, showing the interactions among factors for the three categories.

In Figure 4, an arrow denotes a parallel feedback relationship among the influencing factors, where the positive and negative signs of the arrow indicate an increasing or weakening effect, respectively, between two factors. Figure 3 shows the complex mutual influence and interaction relationships among the influencing factors of man-machine efficacy in plateau mines. A factor may be affected by other system factors, and the corresponding influence on man-machine efficacy is then superimposed. For example, the function index is affected by many factors, such as personnel load, altitude, and noise.

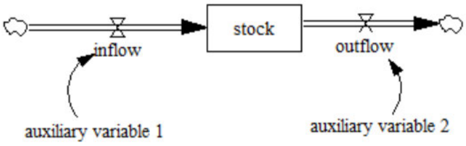

FIGURE 5. General form of stock flow chart.

The causal loop diagram is then used in a quantitative analysis of the system. The stock-flow diagram is an algebraic representation of the causal loop diagram. The stock represents the overall state characteristics of the system and system changes via inflow or outflow; an instrumental variable determines the ratio of the flow value over a prescribed time period [38]. Details of the stock flow chart are presented in Figure 5

The algebraic relationship between stock and flow can be expressed as follows:

$$\mathrm{Stock}(t)=\int_{t_0}^{t}[\mathrm{inflow}(t)-\mathrm{outflow}(t)]dt+\mathrm{Stock}(t_0) \tag{4}$$

where:

t_0: the initial time; and
t: the current time.

The causal relationship among the factors in Fig. 4 and the coupling degree among the factors is used to construct the stock-flow diagram for the three subsystems of the man-machine-environment, as shown in Figure 6 to Figure 9.

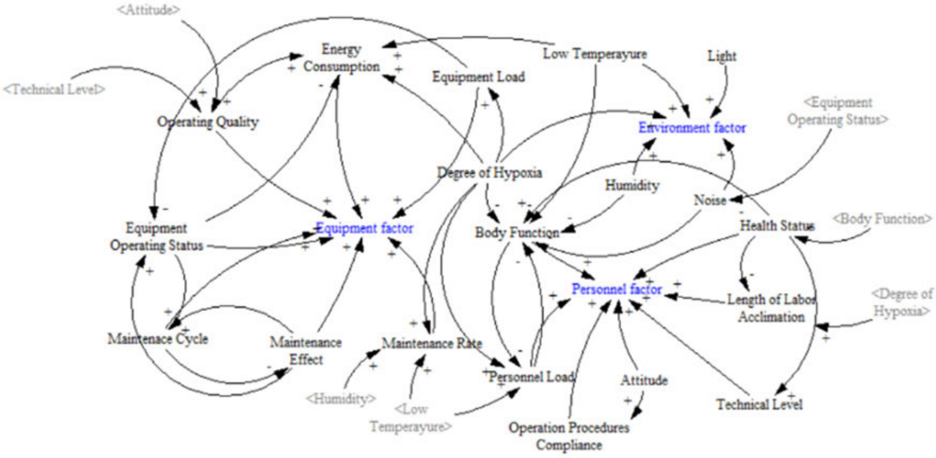

FIGURE 4. Causal loop diagram of factors influencing man-machine efficiency.

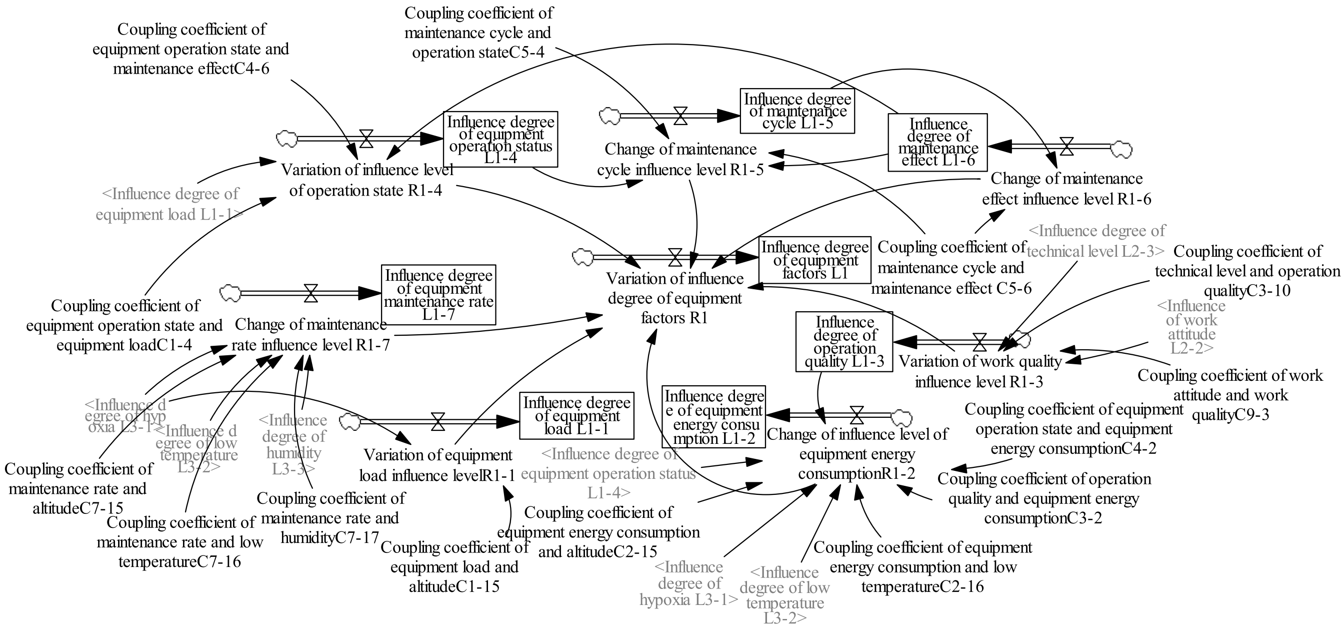

FIGURE 6. Stock flow diagram of equipment subsystem.

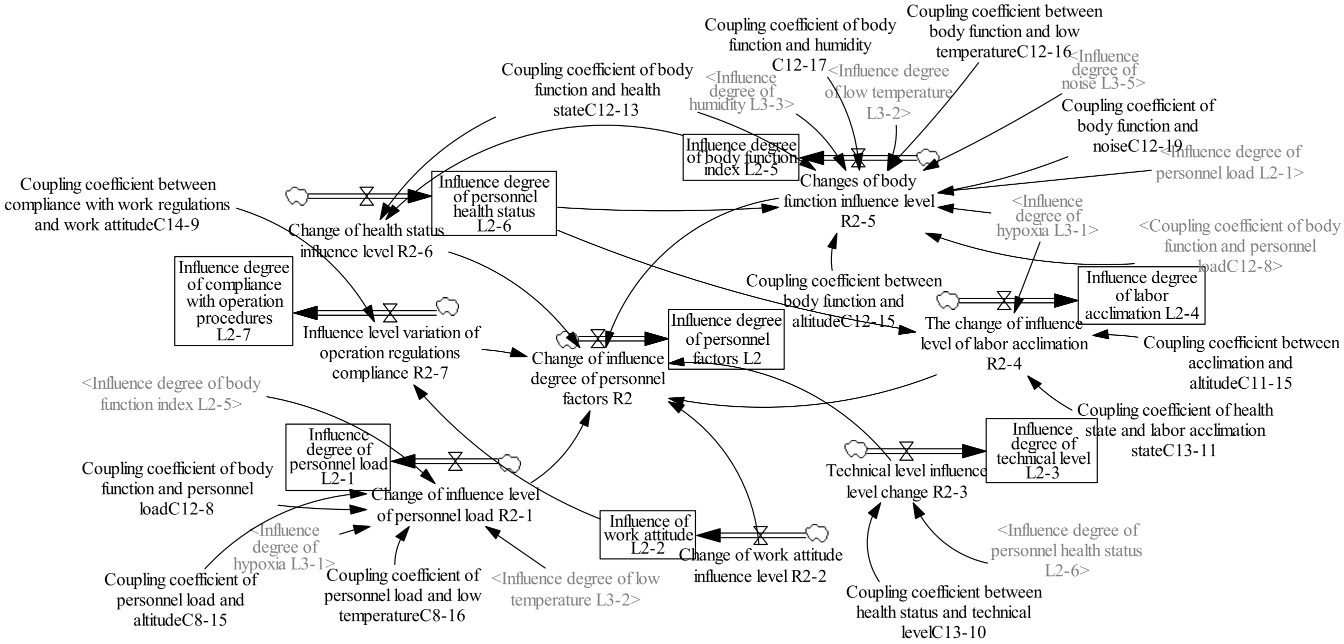

FIGURE 7. Stock flow diagram of personnel subsystem.

C. DETERMINATION OF PARAMETER EQUATION OF SYSTEM DYNAMICS MODEL

The premise of the simulation is that the variables in the stock-flow diagram are assigned and substituted into the stock equation; the constructed stock-flow diagram is then used to calculate the coupling degree between the variables. The order parameter of each influencing factor in the coupling degree model of man-machine efficacy is the expert score for the degree of influence of each factor on the man-machine efficacy: in this study, A_{ij} is 5 and B_{ij} is 0. The scores of each influencing factor are shown in Table 1 below.

The expert scores are used to calculate the coupling degree of the equipment operating status and the equipment load. The higher the score for two factors is, the greater the impact of the factors on the man-machine efficacy is, which corresponds to selecting a positive efficacy function for the calculation.

The efficiency coefficient is:

$$U_{ij} = (X_{ij} - B_{ij})/(A_{ij} - B_{ij}) \tag{5}$$

Substituting the expert score into the equation above yields the following results.

$$U_{i4} = (X_{i4} - B_{ij})/(A_{ij} - B_{ij}) = (4.00 - 0)/(5.00 - 0) = 0.80$$
$$U_{i1} = (X_{i1} - B_{ij})/(A_{ij} - B_{ij}) = (4.30 - 0)/(5.00 - 0) = 0.86$$

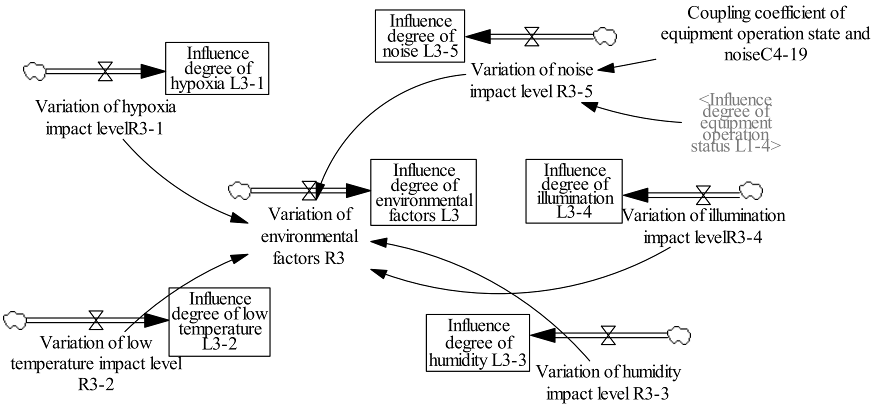

FIGURE 8. Stock flow diagram of environmental subsystem.

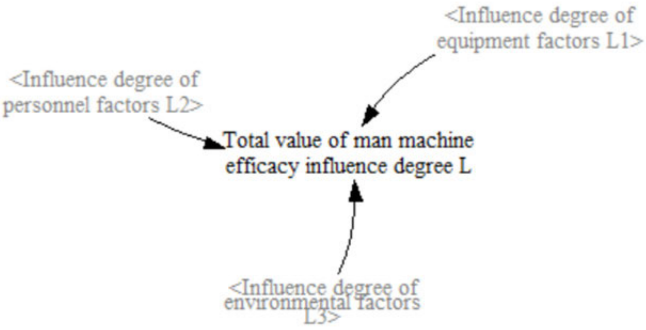

FIGURE 9. Influencing relation diagram of man-machine efficacy.

TABLE 1. Expert scoring results of influencing factors of man-machine efficacy.

Index	Expert Scoring										Score Expectation
B_1	4.50	4.10	4.30	4.30	4.40	4.50	4.00	4.60	4.20	4.10	4.30
B_2	0.50	0.90	0.70	1.00	0.50	0.80	0.40	0.70	0.50	1.00	0.70
B_3	2.30	2.50	2.10	2.40	2.90	2.30	2.40	2.20	2.00	1.90	2.30
B_4	3.70	3.90	4.30	3.50	4.20	3.80	4.30	4.10	4.00	4.20	4.00
B_5	0.50	0.40	0.70	0.40	0.50	0.60	0.40	0.40	0.50	0.60	0.50
B_6	0.70	0.50	0.70	0.50	0.60	0.50	0.50	0.80	0.50	0.70	0.60
B_7	0.50	0.20	0.30	0.40	0.40	0.20	0.30	0.20	0.20	0.30	0.30
B_8	4.70	4.70	4.90	4.90	4.70	4.60	4.80	4.60	4.30	4.80	4.70
B_9	4.00	3.90	3.80	3.60	4.30	3.40	3.70	3.90	3.50	3.90	3.80
B_{10}	4.20	4.50	4.30	4.30	4.50	4.00	4.60	4.50	4.10	4.00	4.30
B_{11}	3.80	4.00	4.20	4.50	3.80	4.10	4.40	4.00	4.30	3.90	4.10
B_{12}	4.00	3.90	4.20	4.30	3.80	4.30	4.60	3.80	4.10	4.00	4.10
B_{13}	3.90	4.00	4.40	4.30	4.20	4.20	4.60	4.00	4.30	4.10	4.20
B_{14}	4.20	3.90	3.90	3.70	4.50	3.40	3.80	3.90	3.70	4.00	3.90
B_{15}	4.90	4.50	4.10	4.60	4.30	4.40	4.60	4.10	4.20	4.30	4.40
B_{16}	1.50	2.30	2.50	2.10	1.40	2.00	2.30	1.90	1.60	2.40	2.00
B_{17}	1.20	0.60	0.90	0.90	1.00	0.50	1.20	1.40	1.00	1.30	1.00
B_{18}	0.40	0.40	0.80	0.50	0.60	0.40	0.50	0.30	0.50	0.60	0.50
B_{19}	0.70	0.90	0.80	1.20	0.50	0.90	0.60	0.80	0.50	1.10	0.80

The coupling degree is then calculated as shown below.

$$C_{1-4}=2\sqrt{\{(U_{i4}\cdot U_{i1})/\,[(U_{i4}+U_{i1})\cdot(U_{i4}+U_{i1})]\}}=0.9993$$

The coupling degree for the other influencing factors for the man-machine efficacy are calculated similarly and shown in Table 2.

The importance of each factor in the stock-flow diagram relative to the system is determined by AHP, using the following steps.

1) ESTABLISHING A HIERARCHICAL MODEL

The influencing factors of the man-machine efficacy are divided into three levels: a target layer, a criterion layer, and an index layer. The specific hierarchical structure is shown in Figure 1. The consistent matrix method is used to determine the weight of the various factors for all the levels. That is, the factors are not compared together but are compared with each other. A relative scale is used to reduce the difficulty of comparing various factors with different properties as much as possible and improve accuracy [39].

TABLE 2. Coupling degree of man-machine efficacy influencing factors.

Serial number	Coupling index	Coupling Factor		Coupling Degree	Serial Number	Coupling Index	Coupling Factor		Coupling Degree
1	$C_{1\text{-}4}$	B_1	B_4	0.9993	15	$C_{12\text{-}15}$	B_{12}	B_{15}	0.9994
2	$C_{4\text{-}6}$	B_4	B_6	0.6736	16	$C_{11\text{-}15}$	B_{11}	B_{15}	0.9994
3	$C_{3\text{-}2}$	B_3	B_2	0.8459	17	$C_{7\text{-}15}$	B_7	B_{15}	0.4889
4	$C_{4\text{-}2}$	B_4	B_2	0.7121	18	$C_{7\text{-}16}$	B_7	B_{16}	0.6736
5	$C_{5\text{-}6}$	B_5	B_6	0.9959	19	$C_{7\text{-}17}$	B_7	B_{17}	0.8427
6	$C_{12\text{-}13}$	B_{12}	B_{14}	0.9999	20	$C_{2\text{-}15}$	B_2	B_{15}	0.6882
7	$C_{13\text{-}11}$	B_{14}	B_{11}	0.9999	21	$C_{2\text{-}16}$	B_2	B_{16}	0.8765
8	$C_{12\text{-}8}$	B_{12}	B_8	0.9977	22	$C_{3\text{-}10}$	B_4	B_{19}	0.9530
9	$C_{13\text{-}10}$	B_{14}	B_{10}	0.9999	23	$C_{9\text{-}3}$	B_9	B_3	0.9693
10	$C_{8\text{-}15}$	B_8	B_{15}	0.9995	24	$C_{5\text{-}4}$	B_5	B_4	0.6285
11	$C_{8\text{-}16}$	B_8	B_{16}	0.9152	25	$C_{14\text{-}9}$	B_{14}	B_9	0.9999
12	$C_{12\text{-}17}$	B_{12}	B_{17}	0.7941	26	$C_{1\text{-}15}$	B_1	B_{15}	0.9999
13	$C_{12\text{-}16}$	B_{12}	B_{16}	0.9389	27	$C_{4\text{-}19}$	B_4	B_{19}	0.7454
14	$C_{12\text{-}19}$	B_{12}	B_{19}	0.7392					

2) CONSTRUCTING JUDGMENT MATRIX

A numerical scale from 1 to 9 is used to express the relative importance of the indicators in each level. A questionnaire survey of relevant experts and staff engaged in high-altitude mine research is used to obtain the index score for each level index score to construct a judgment matrix:

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{pmatrix}, \quad n \le 5$$

where x_{ij} represents the importance of the ith influencing factor relative to the jth influencing factor.

The scaling presented above is used to establish the judgment matrix for each index of equipment factors.

$$A = \begin{bmatrix} 1 & 6 & 3 & 1/4 & 5 & 4 & 6 \\ 1/6 & 1 & 1/3 & 1/7 & 1/2 & 1/3 & 1 \\ 1/3 & 3 & 1 & 1/7 & 3 & 2 & 4 \\ 4 & 7 & 7 & 1 & 8 & 7 & 9 \\ 1/5 & 2 & 1/3 & 1/8 & 1 & 1/2 & 2 \\ 1/4 & 3 & 1/2 & 1/7 & 2 & 1 & 3 \\ 1/6 & 1 & 1/4 & 1/9 & 1/2 & 1/3 & 1 \end{bmatrix}$$

3) CALCULATING THE WEIGHT OF EACH INFLUENCING FACTOR

The judgment matrix is normalized by transforming each column element as follows:

$$x_{ij} = x_{ij} \Big/ \sum_{k=1}^{n} x_{kj}, \quad (i, j = 1, 2, \ldots n) \tag{6}$$

The matrix A_0 is thus obtained:

$$A_0 = \begin{bmatrix} 0.16 & 0.26 & 0.24 & 0.13 & 0.25 & 0.26 & 0.23 \\ 0.03 & 0.04 & 0.03 & 0.07 & 0.03 & 0.02 & 0.04 \\ 0.05 & 0.13 & 0.08 & 0.07 & 0.15 & 0.13 & 0.15 \\ 0.65 & 0.30 & 0.56 & 0.52 & 0.40 & 0.46 & 0.35 \\ 0.03 & 0.09 & 0.03 & 0.07 & 0.05 & 0.03 & 0.08 \\ 0.04 & 0.13 & 0.04 & 0.07 & 0.10 & 0.07 & 0.12 \\ 0.03 & 0.04 & 0.02 & 0.06 & 0.03 & 0.02 & 0.04 \end{bmatrix}$$

The elements of each row of the normalized matrix are summed using the formula below:

$$w_i = \sum_{j=1}^{n} x_{ij}, \quad (i = 1, 2, \ldots n) \tag{7}$$

The following vector is obtained.

$$w_A = \begin{bmatrix} 1.54 & 0.26 & 0.78 & 3.25 & 0.37 & 0.57 & 0.23 \end{bmatrix}^T$$

The vector w_A is normalized as follows:

$$w = w_i \Big/ \sum_{j=1}^{n} w_j, \quad (i = 1, 2, \ldots n) \tag{8}$$

The weight of each factor is thus obtained as:

$$W = \begin{bmatrix} 0.22 & 0.04 & 0.11 & 0.47 & 0.05 & 0.08 & 0.03 \end{bmatrix}^T$$

4) TEST OF MATRIX CONSISTENCY

The consistency of the weight matrix is checked to ensure the validity of the results. First, the maximum eigenvalue of the matrix is calculated using the formula below:

$$\lambda_{\max} = \frac{\sum (AW)_i}{nW_i} \tag{9}$$

The result $\lambda_{\max}=7.34$ is used to calculate the consistency index of the judgment matrix as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{10}$$

In the formula presented above, n is the matrix order and $CI = 0.06$. Then, the consistency ratio is calculated as follows:

$$CR = \frac{CI}{RI} \tag{11}$$

The calculated consistency ratio $CR = 0.04 < 0.1$ shows that the consistency test has been passed. In the formula presented above, RI is the average random consistency index and is a constant. Specific values are provided in table 3 below.

The steps presented above are used to determine the weight of each influencing factor in the indicator layer, which is shown in Table 4 below.

TABLE 3. Average random consistency index RI of the same order matrix.

Matrix order	1	2	3	4	5	6	7	8	9	10
RI Value	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.52

TABLE 4. Weight table of influencing factors of man-machine efficacy.

Criterion Layer Index	Weight	Indicator Layer Factor	Weight
A_1	0.32	B_1	0.22
		B_2	0.04
		B_3	0.11
		B_4	0.47
		B_5	0.05
		B_6	0.08
		B_7	0.03
A_2	0.59	B_8	0.08
		B_9	0.04
		B_{10}	0.25
		B_{11}	0.12
		B_{12}	0.17
		B_{13}	0.31
		B_{14}	0.03
A_3	0.09	B_{15}	0.44
		B_{16}	0.29
		B_{17}	0.13
		B_{18}	0.05
		B_{19}	0.09

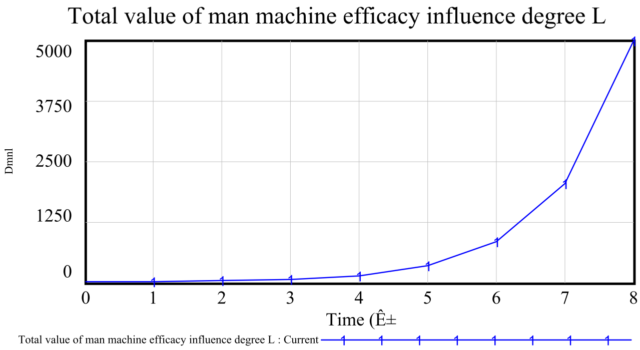

FIGURE 10. Man-machine efficacy influence degree-time chart.

The weights and coupling degrees of the different influencing factors are used to construct the parametric equation of the stock-flow diagram. Table 5 shows the parametric equation.

IV. RESULTS AND DISCUSSION

After the model is established, VENSIM is used to carry out a simulation. The resulting plot of the degree of influence of the factors on the man-machine efficacy versus time is shown in Figure 10 below.

Figure 10 shows that the comprehensive impact of the man-machine environment on the man-machine efficacy is a nonlinear change trend. The man-machine system does not initially operate underground. Therefore, the influencing factors of the machine environment have no impact on the system initially. The influence of external factors on personnel and equipment gradually appears as the operation proceeds.

The relatively flat change trend in the curve over the first 0-6 hours indicates only a slight impact on the man-machine efficacy. After more than 6 hours of work, there is a clear increase in the slope of the influence curve of man-machine efficacy, and the subsequent rapid upward trend in the influence degree of man-machine efficiency with continuously increasing time reflects the considerable impact of man-machine-environment factors on man-machine efficiency, that is, the negative influence of the working efficiency of the man-machine system increases rapidly.

The coupling coefficient between the influencing factors is varied according to whether the factors are homogeneous or heterogeneous to simulate the influence of the coupling on the man-machine function.

A. CHANGE THE INTERNAL COUPLING COEFFICIENT OF HOMOGENEOUS FACTORS

1) CHANGING THE COUPLING COEFFICIENT OF PERSONNEL FACTORS

As the internal coupling of human factors includes C12-13, C13-11, C12-8, C13-10, C14-9, the original system is

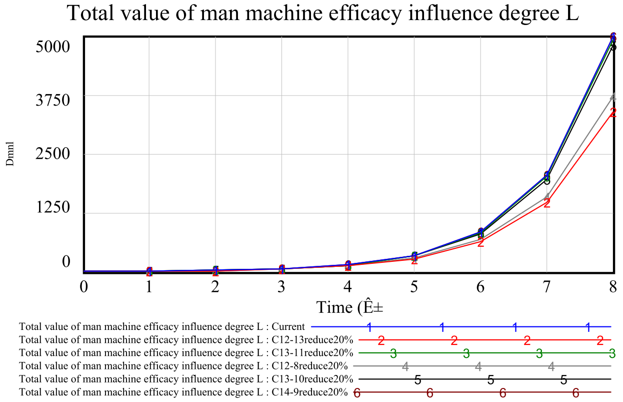

FIGURE 11. Influence of changing coupling coefficient of homogeneous factors on man-machine efficacy.

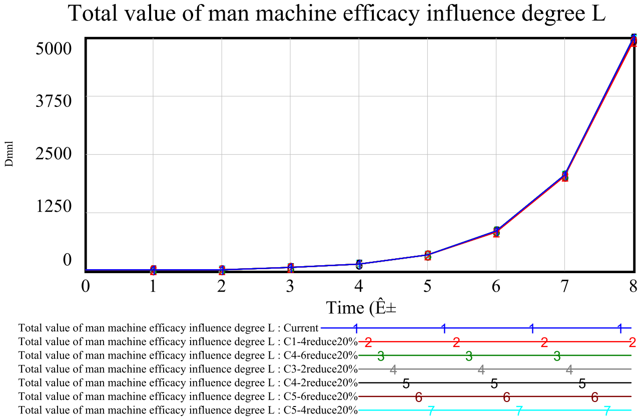

FIGURE 12. Influence of the change of coupling coefficient of homogeneous factors on man-machine efficacy.

simulated five times. The simulation is performed by reducing one of the coupling coefficients by 20% and maintaining the remaining variables unchanged; the corresponding effect of the influencing factors on the man-machine efficacy is then observed. The operation results are shown in Figure 11.

2) CHANGING THE COUPLING COEFFICIENT OF MACHINE FACTORS

As the internal coupling of human factors includes C1-4, C4-6, C3-2, C4-2, C5-6, C5-4, the original system is simulated six times. The simulation is performed by reducing one of the coupling coefficients by 20% and maintaining the remaining variables unchanged; the corresponding effect of the influence factors on the man-machine efficacy is then observed. The operation results are shown in Figure 12.

Figures 11 and 12 shows the specific impacts of the coupling coefficient of the influencing factors on the man-machine efficiency; however, the overall trend is the same as that of the original system, where the change trend in the influence degree is not discernible for the first 6 hours of system operation. There is a clear increase in the curve slope after 6 hours, and the influence value rises rapidly. The influence of personnel on man-machine efficiency is more noticeable than that of equipment, which is consistent with the objective observation that personnel play a leading role in the system. The simulation results show that the changes in C12-8 and C12-13 affect man-machine efficiency more noticeably than other coupling changes. This result shows that coupling between the function index and personnel load, as well as between the health status and functional index of operators, affect man-machine efficiency. Therefore, these two aspects should be monitored during work, such that operators can rest in a timely manner to ensure operational safety. The operators' health status should also be monitored to prevent operators with diseases from working. The vicious

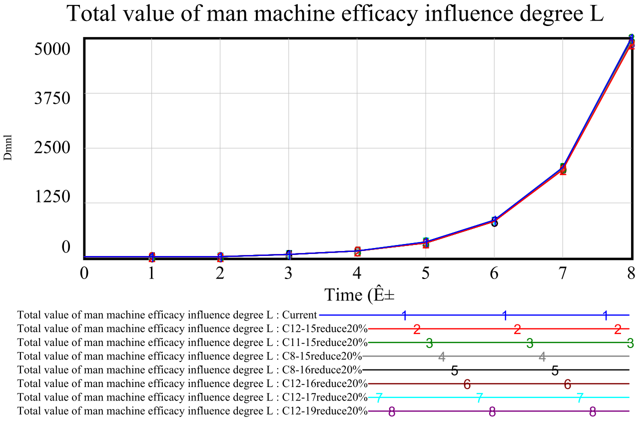

FIGURE 13. Influence of the change of coupling coefficient of heterogeneous factors on man-machine efficacy.

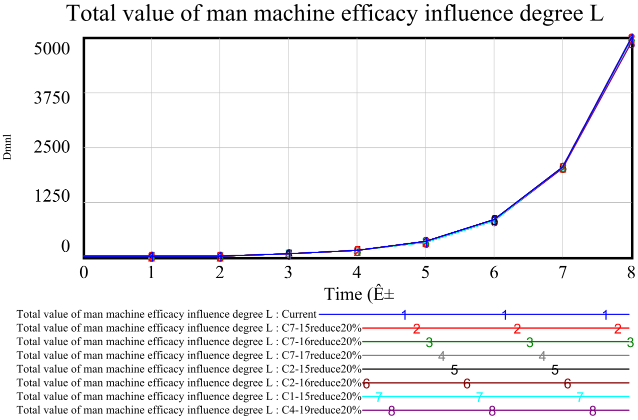

FIGURE 14. Influence of the change of coupling coefficient of heterogeneous factors on man-machine efficacy.

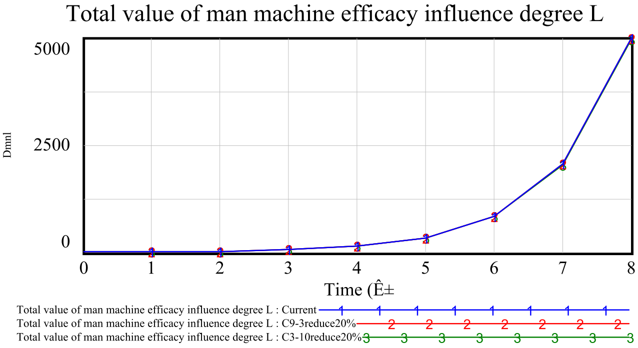

FIGURE 15. Influence of the change of coupling coefficient of heterogeneous factors on man-machine efficacy.

TABLE 5. System dynamics parameter equation of influencing factors of man-machine efficacy.

Variable	Unit	Type	Value	Equation
Initial time	hour		0	
End time	hour		8	
step size	hour	state variable	1	
L_{1}	Dmnl	state variable		L_{1}=INTEG(“R_{1}”,6)
L_{1-1}	Dmnl	state variable		L_{1-1}=INTEG(“R_{1-1}”,4)
L_{1-2}	Dmnl	state variable		L_{1-2}=INTEG(“R_{1-2}”,3)
L_{1-3}	Dmnl	state variable		L_{1-3}=INTEG(“R_{1-3}”,3.5)
L_{1-4}	Dmnl	state variable		L_{1-4}=INTEG(“R_{1-4}”,4.7)
L_{1-5}	Dmnl	state variable		L_{1-5}=INTEG(“R_{1-5}”,3.3)
L_{1-6}	Dmnl	state variable		L_{1-6}=INTEG(“R_{1-6}”,2.9)
L_{1-7}	Dmnl	state variable		L_{1-7}=INTEG(“R_{1-7}”,4.5)
L_{2}	Dmnl	state variable		L_{2}=INTEG(“R_{2}”,3.4)
L_{2-1}	Dmnl	state variable		L_{2-1}=INTEG(“R_{2-1}”,2.6)
L_{2-2}	Dmnl	state variable		L_{2-2}=INTEG(“R_{2-2}”,3.7)
L_{2-3}	Dmnl	state variable		L_{2-3}=INTEG(“R_{2-3}”,4.1)
L_{2-4}	Dmnl	state variable		L_{2-4}=INTEG(“R_{2-4}”,4.5)
L_{2-5}	Dmnl	state variable		L_{2-5}=INTEG(“R_{2-5}”,2.4)
L_{2-6}	Dmnl	state variable		L_{2-6}=INTEG(“R_{2-6}”,3.3)
L_{2-7}	Dmnl	state variable		L_{2-7}=INTEG(“R_{2-7}”,3.7)
L_{3}	Dmnl	state variable		L3=INTEG(“R_{3}”,7.3)
L_{3-1}	Dmnl	state variable		L_{3-1}=INTEG(“R_{3-1}”,2.2)
L_{3-2}	Dmnl	state variable		L_{3-2}=INTEG(“R_{3-2}”,2)
L_{3-3}	Dmnl	state variable		L_{3-3}=INTEG(“R_{3-3}”,3.4)
L_{3-4}	Dmnl	state variable		L_{3-4}=INTEG(“R_{3-4}”,2.9)
L_{3-5}	Dmnl	state variable		L_{3-5}=INTEG(“R_{3-5}”,2.1)
R_{1}	Dmnl	rate variable		$R_{1}=0.22* R_{1-1}+0.04* R_{1-2}+0.11* R_{1-3}+0.47* R_{1-4}+0.05* R_{1-5}+0.08* R_{1-6}+0.03* R_{1-7}$
R_{1-1}	Dmnl	rate variable		$R_{1-1}= L_{3-1}* C_{1-15}$
R_{1-2}	Dmnl	rate variable		$R_{1-2}= L_{3-2}* C_{2-16}+ L_{3-1}* C_{2-15}+ L_{1-3}* C_{3-2}+ L_{1-4}* C_{4-2}$
R_{1-3}	Dmnl	rate variable		$R_{1-3}= L_{2-2}* C_{9-3}+ L_{2-3}* C_{4-19}$
R_{1-4}	Dmnl	rate variable		$R_{1-4}= L_{1-6}* C_{4-6}+ L_{1-1}* C_{1-4}$
R_{1-5}	Dmnl	rate variable		$R_{1-5}= L_{1-6}* C_{5-6}+ L_{1-4}* C_{5-4}$
R_{1-6}	Dmnl	rate variable		$R_{1-6}= L_{1-5}* C_{5-6}$
R_{1-7}	Dmnl	rate variable		$R_{1-7}= L_{3-2}* C_{7-16}+ L_{3-1}* C_{7-15}+ L_{3-3}* C_{7-17}$
R_{2}	Dmnl	rate variable		$R_{2}=0.08* R_{2-1}+0.04* R_{2-2}+0.25* R_{2-3}+0.12* R_{2-4}+0.17* R_{2-5}+0.31* R_{2-6}+0.03* R_{2-7}$
R_{2-1}	Dmnl	rate variable		$R_{2-1}= L_{3-2}* C_{8-16}+ L_{3-1}* C_{8-15}+ L_{2-5}* C_{12-8}$
R_{2-2}	Dmnl	constant		$R_{2-2}=0.13$
R_{2-3}	Dmnl	rate variable		$R_{2-3}= L_{2-6}* C_{14-10}$
R_{2-4}	Dmnl	rate variable		$R_{2-4}= L_{3-1}* C_{11-15}+ L_{2-6}* C_{14-11}$
R_{2-5}	Dmnl	rate variable		$R_{2-5}= L_{3-2}* C_{12-16}+ L_{3-5}* C_{12-19}+ L_{3-1}* C_{12-15}+ L_{3-3}* C_{12-17}+ L_{2-6}* C_{12-14}+ L_{2-1}* C_{12-8}$
R_{2-6}	Dmnl	rate variable		$R_{2-6}= L_{2-5}* C_{12-14}$
R_{2-7}	Dmnl	rate variable		$R_{2-7}= L_{2-2}* C_{14-9}$
R_{3}	Dmnl	rate variable		$R_{3}=0.44* R_{3-1}+0.29* R_{3-2}+0.13* R_{3-3}+0.05* R_{3-4}+0.09* R_{3-5}$
R_{3-1}	Dmnl	constant		$R_{3-1}=0.2$
R_{3-2}	Dmnl	constant		$R_{3-2}=0.15$
R_{3-3}	Dmnl	constant		$R_{3-3}=0.25$
R_{3-4}	Dmnl	constant		$R_{3-4}=0.18$
R_{3-5}	Dmnl	rate variable		$R_{3-5}= L_{1-4}* C_{4-19}$
L	Dmnl	auxiliary variable		$L=0.32*L_{1}+0.59*L_{2}+0.09*L_{3}$

circle of the decline of human body function, the increase in personnel load, and the decline of health status with increasing operation time is thereby circumvented.

B. CHANGING THE COUPLING COEFFICIENT OF HETEROGENEOUS FACTORS

1) CHANGING THE COUPLING COEFFICIENT OF HUMAN AND ENVIRONMENT

As the coupling between humans and the environment includes C12-15, C11-15, C8-15, C8-16, C12-17, C12-16, and C12-19, the original system is simulated seven times. The simulation is performed by reducing one of the coupling coefficients by 20% and maintaining the remaining variables unchanged; the corresponding effect of the influence factors on the man-machine efficacy is then observed. The operation results are shown in Figure 13.

2) CHANGING THE COUPLING COEFFICIENT OF MACHINE AND ENVIRONMENT

As the coupling between machines and the environment includes C7-15, C7-16, C7-17, C2-15, C2-16, C1-15, and C4-19, the original system is simulated seven times. The simulation is performed by reducing one of the coupling coefficients by 20% and maintaining the remaining variables unchanged; the corresponding effect of the influencing factors on the man-machine efficacy is then observed. The operation results are shown in Figure 14.

3) CHANGING THE COUPLING COEFFICIENT OF HUMAN AND MACHINE

As the coupling between humans and machines includes C3-10, and C9-3, the original system is simulated two times. The simulation is performed by reducing one coupling coefficient by 20% and maintaining the other variable unchanged; the corresponding effect of the influencing factors on the man-machine efficacy is then observed. The operation results are shown in Figure 15.

Figures 13 to 15 show that the change trends for the three schemes presented above are consistent with that of the original curve; that is, the influencing factors have a small effect on the man-machine efficiency over the first 0-6 hours and gradually become noticeable with increasing time. The impact of the influencing factors on man-machine efficiency increases rapidly after 6 hours of work. Changing the coupling effect of the heterogeneous factors has little impact on the system operation efficiency overall, and coupling between factors other than the man-environment coupling and the man-machine coupling have little impact on the system operation efficiency. The machine-environment coupling has a slightly more noticeable influence on the system work efficiency than the other couplings, showing that the environment affects the machine operation efficiency and thereby, the overall work efficiency.

V. CONCLUSION

Many factors affect the working efficiency of workers and equipment in underground mines. The change law of man-machine efficiency in high-altitude mines under the coupling effect of multiple factors is determined by using three categories of relevant influencing factors (personnel, equipment and environment) to construct a system dynamics model., The model simulation results show that an increasing trend in the coupling effect between factors on man-machine efficiency with the working time: the influence of the factors on the man-machine efficiency is small for the first 0 to 6 hours and increases rapidly after 6 hours; the effect of changing the coupling degree between factors on the system is analyzed, and the same trend is observed as for the effect of the coupling degree on the efficiency of the man-machine system; the human factor is the homogeneous factor with the most noticeable influence on the system, showing that personnel considerably affect the operational efficiency of the man-machine system. Therefore, it is recommended that the mine operation time in plateau areas be less than that in plain areas and under 6 hours in practice. The results of this study can provide guidance for high-altitude mining enterprises to formulate reasonable work and rest periods to ensure efficient operation of personnel and equipment.

The complexity of the man-machine environment system precludes a quantitative description of the relationships between various factors. Consequently, the coupling degree between factors is used to identify and quantify the influencing factors and the complex relationship between these factors, as well to analyze these factors using a model simulation; thus, the limitation that the relationships among system factors cannot be quantitatively described is effectively overcome. In the future, we will aim to explore the ture relationship between various factors in the system to further improve the system.

APPENDIX

See Table 5.

REFERENCES

[1] A. R. Ismail, C. M. Nizam, M. H. M. Haniff, and B. M. Deros, “The impact of workers productivity under simulated environmental factor by Taguchi analysis,” *APCBEE Procedia*, vol. 10, pp. 263–268, Feb. 2014.

[2] D. G. Mook, *Energy, Arousal and Action*. New York, NY, USA, 1987.

[3] W. Yi and A. P. C. Chan, “Optimal work pattern for construction workers in hot weather: A case study in Hong Kong,” *J. Comput. Civil Eng.*, vol. 29, no. 5, Jul. 2015, Art. no. 05014009.

[4] D. E. Brown, C. M. Beall, K. P. Strohl, and P. S. Mills, “Exhaled nitric oxide decreases upon acute exposure to high-altitude hypoxia,” *Amer. J. Hum. Biol.*, vol. 18, no. 2, pp. 196–202, Apr. 2006.

[5] Y. N. Chen and Y. Q. Wang, “Influence of plateau environment on human body and its prevention measures,” *Occupat. Health*, vol. 30, pp. 1409–1412, Oct. 2014.

[6] Y. Han, G. Yan, Q. Wang, G. Ma, C. Tang, Y. Gu, L. Li, and J. Zhao, “Predominant role of vasoconstrictors over dilatators derived from arachidonic acid in hypoxic pulmonary vasoconstriction,” *Mol. Med. Rep.*, vol. 8, no. 4, pp. 1263–1271, Oct. 2013.

[7] M. H. Wilson, S. Newman, and C. H. Imray, “The cerebral effects of ascent to high altitudes,” *Lancet Neurol.*, vol. 8, no. 2, pp. 175–191, Feb. 2009.

[8] Z. Kuan, Z. Ling-Ling, and F. Ming, “Effect of the plateau environment on the cognitive function of humans,” *Mil. Med. Sci.*, vol. 35, pp. 706–709, Sep. 2011.

[9] P. Benjumea, J. Agudelo, and A. Agudelo, “Effect of altitude and palm oil biodiesel fuelling on the performance and combustion characteristics of a HSDI diesel engine,” *Fuel*, vol. 88, no. 4, pp. 725–731, Apr. 2009.

[10] L. Yu, Y. Ge, J. Tan, C. He, X. Wang, H. Liu, W. Zhao, J. Guo, G. Fu, X. Feng, and X. Wang, “Experimental investigation of the impact of biodiesel on the combustion and emission characteristics of a heavy duty diesel engine at various altitudes,” *Fuel*, vol. 115, pp. 220–226, Jan. 2014.

[11] V. Bermúdez, J. R. Serrano, P. Piqueras, J. Gómez, and S. Bender, “Analysis of the role of altitude on diesel engine performance and emissions using an atmosphere simulator,” *Int. J. Engine Res.*, vol. 18, nos. 1–2, pp. 105–117, Jan. 2017.

[12] Á. Ramos, R. García-Contreras, and O. Armas, “Performance, combustion timing and emissions from a light duty vehicle at different altitudes fueled with animal fat biodiesel, GTL and diesel fuels,” *Appl. Energy*, vol. 182, pp. 507–517, Nov. 2016.

[13] L. Qi and F. Wang, “Study on mechanical efficiency of construction equipment in high altitude environment,” *J. Railway Sci. Eng.*, vol. 14, pp. 1974–1982, Sep. 2017.

[14] J. W. Forrester, “Industrial dynamics,” *J. Oper. Res. Soc.*, vol. 48, no. 10, pp. 1037–1041, Dec. 1997.

[15] G. Egilmez and O. Tatari, “A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact,” *Transp. Res. A, Policy Pract.*, vol. 46, no. 7, pp. 1086–1096, Aug. 2012.

[16] D. Wu and S. Ning, “Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing,” *Environ. Res.*, vol. 164, pp. 70–84, Jul. 2018.

[17] B. Zhong and J. N. Wang, “Safety performance evaluation of the air traffic management system based on system dynamics,” in *Proc. 1st Annu. Conf. Air Traffic Manage. Syst. Technol.* Nanjing, China: Chinese Institute of Command and Control, 2018, pp. 229–233.

[18] C. G. Chang, R. R. Yan, and T. K. Li, “Safety risk assessment and management measures for prefabricated construction based on SD,” *J. Shenyang Jianzhu Univ., Social Sci.*, vol. 20, pp. 371–376, Apr. 2018.

[19] J. Yu, X. Q. Yu, and L. L. Zhou, “An analysis of ecological security in Jiao Zhou bay based on SD model,” *Trans. Oceanol. Limnol.*, vol. 1, pp. 60–65, Jan. 2018.

[20] M. You, S. Li, D. Li, Q. Cao, and F. Xu, “Evolutionary game analysis of coal-mine enterprise internal safety inspection system in China based on system dynamics,” *Resour. Policy*, vol. 67, Aug. 2020, Art. no. 101673.

[21] L. Ma, Q. Liu, Z. Qiu, and Y. Peng, “Evolutionary game analysis of state inspection behaviour for coal enterprise safety based on system dynamics,” *Sustain. Comput., Informat. Syst.*, vol. 28, Dec. 2020, Art. no. 100430.

[22] W. S. Liu and M. Zhu, “The study of coalmine safety prediction based on system dynamics,” *Adv. Mater. Res.*, vols. 466–467, pp. 1045–1049, Feb. 2012.

[23] W. G. Qiao and X. C. Li, “Risk evaluation of coal mine enterprises under role of multi-factor coupling,” *Coal Eng.*, vol. 46, pp. 145–148, Apr. 2014.

[24] P. Brooker, "Air traffic management accident risk. Part 1: The limits of realistic modelling," *Saf. Sci.*, vol. 44, no. 5, pp. 419–450, Jun. 2006.
[25] H.-J. Shyur, "A quantitative model for aviation safety risk assessment," *Comput. Ind. Eng.*, vol. 54, no. 1, pp. 34–44, Feb. 2008.
[26] V. V. Vesselinov and G. Pau, "AGNI: Coupling model analysis tools and high-performance subsurface flow and transport simulators for risk and performance assessments," in *Proc. Comput. Methods Water Resour. 19th Int. Conf.*, IL, USA, Jan. 2012.
[27] W. L. Li, H. M. Li, X. W. Pei, and Y. J. Liu, "Vulnerability assessment of mountainous road system based on multiple-factor coupling," *China Saf. Sci. J.*, vol. 29, pp. 165–170, May 2019.
[28] X. H. Duan, Y. Zhang, and X. L. Hou, "Analysis of the road traffic system vulnerability based on the factor coupling method," *J. Saf. Environ.*, vol. 18, pp. 1749–1755, Oct. 2018.
[29] J. Luo, "Research on mechanism of risk coupling for rural tourism safety," *J. Risk Anal. Crisis Response*, vol. 7, no. 1, p. 45, Apr. 2017.
[30] J. N. Warfield, "Developing interconnection matrices in structural modeling," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-4, no. 1, pp. 81–87, Jan. 1974.
[31] W. Johnson, "Management oversight and risk tree-MORT," *J. Saf. Res.*, vol. 7, pp. 4–15, 1973.
[32] W. G. Qiao, "Analysis of mine accident risk factor coupling and simulation of coupling risk," M.S. thesis, China Univ. Mining Technol., Beijing, China, 2014.
[33] T. Yang and T. Zeng, "A study on the coupling rules between ecological environment and urban competitiveness," *J. Sustain. Develop.*, vol. 1, no. 2, pp. 33–36, Oct. 2009.
[34] S. B. Hao and B. Yu, "Research on coupling degree model and application of the enterprise's technology capacity and technology management capacity," *Forecasting*, vol. 27, pp. 12–15, Jun. 2008.
[35] Q. G. Bi, Y. Bao, and B. S. Li, "Relevancy analysis of the coupling between population structure and regional economy in inner mongolia," *Geographical Res.*, vol. 26, pp. 995–1003, May 2007.
[36] T. Nguyen, S. Cook, and V. Ireland, "Application of system dynamics to evaluate the social and economic benefits of infrastructure projects," *Systems*, vol. 5, no. 2, p. 29, Mar. 2017.
[37] D. Liu, G. Li, N. Hu, and Z. Ma, "Application of real options on the decision-making of mining investment projects using the system dynamics method," *IEEE Access*, vol. 7, pp. 46785–46795, Apr. 2019.
[38] H. R. Nassery, R. Adinehvand, A. Salavitabar, and R. Barati, "Water management using system dynamics modeling in semi-arid regions," *Civil Eng. J.*, vol. 3, no. 9, pp. 766–778, Oct. 2017.
[39] F. Kang and F. Yang, "Exploration on the evaluation system of innovation ability for higher vocational students," *Inner Mongolia Sci. Technol. Economy*, vol. 12, pp. 28–29 and 31, 2018.

DUIMING GUO was born in Baoding, Hebei, China, in 1992. He received the B.S. degree in mining engineering from the North China University of Science and Technology, and the M.S. degrees in mining engineering from the University of Science and Technology Beijing, where he is currently pursuing the Ph.D. degree in mining engineering with the School of Civil and Resource Engineering. He research interests include mining safety and mining ventilation.

GUOQING LI received the B.S. degree in mineral processing engineering and the M.S. and Ph.D. degrees in mining engineering from the University of Science and Technology Beijing.

She is currently a Professor with the University of Science and Technology Beijing. Her work has been funded by many grants, including the National Science Foundation of China and the Ministry of Science and Technology of the People's Republic of China. Her research interests include mining system engineering, mining economics, and intelligent mining. She received many awards from the China Gold Association.

NAILIAN HU is currently a Professor with the University of Science and Technology Beijing. His work has been funded by many grants, including the National Science Foundation of China and the Ministry of Science and Technology of the People's Republic of China. His research interests include mining system engineering, mining economics, intelligent mining, and mining safety. He is a member of a Council of the China Gold Association.

JIE HOU was born in Shenyang, Liaoning, China, in 1989. He received the B.S., M.S., and Ph.D. degrees in mining engineering from the School of Civil and Resource Engineering, University of Science and Technology Beijing. He research interests include informatization of mining enterprises and digital mine and mining system engineering.

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