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Application of Real Options on the Decision-Making of Mining Investment Projects Using the System Dynamics Method

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ABSTRACT Estimating the valuation of mining projects has great significance for investment decision-making. Since the existing valuation methods are not appropriate for mining projects affected by various uncertainties over the long term, this paper presents a hybrid investment evaluation model that is based on real options and system dynamics for mining projects. To address uncertainties and managerial flexibilities that are contained in mining projects, the model integrates the static net present value calculated by traditional discount cash flows and the real options value generated by the Black–Scholes model into the total value of mining projects. Subsequently, the model applies system dynamics modeling to analyze the dynamics of the complicated mining operation system, quantify its variables and interactions, and estimate its volatility, which enables a more accurate real options valuation. A realistic case of the Hongwei uranium deposit in China is the basis for the presented numerical illustration of the model. The findings indicate that investors are prone to losing an opportunity to invest if they only rely on traditional discount cash flows' methods, because the value of the project calculated by discount cash flows is -175.59 million yuan that under zero. However, the results obtained from the method proposed in this paper suggest that the project has a value of 327.65 million yuan.

INDEX TERMS Decision making, estimation, modeling, real options, system dynamics.

I. INTRODUCTION

Making investment decisions for a mining project is a difficult task. That is because mining projects are a complicated business. Not only mining investments are substantial industrial investments with sizeable initial capital layouts that operate in an uncertain environment, but also many investment decisions of mining projects are irreversible [1]. As a consequence, before a mining company will decide to invest in a mining project, one of the critical steps for decision makers is to evaluate the valuation of the mining project.

There exist numerous methods for investment evaluation that are currently in use, which aim to provide decision makers with sufficient information for making investment decisions, including traditional valuation methods and real options (RO) methods [2], [3]. Traditional valuation methods that are based on discounted cash flows (DCF) analysis provide measures such as net present value (NPV), internal rate of return (IRR), payback and maximum cash exposure [4], [5]. In the DCF methods, an implicit assumption is that a project will be undertaken now and continuously operated at a set timescale; until the end of its expected service lifetime, even though the future is uncertain. In this context, DCF methods often fail to respond to the identified economic uncertainty, capture strategic value aspects of various projects, and address technical and management flexibilities [6]–[8]. Thus, DCF-based methods usually underestimate the value of investment projects and produce wrong investment decisions, as well as unexpected business failures.

Faced with the drawbacks of traditional valuation methods, the RO provides valuation methods, such as the Black-Scholes formula or the binomial option-pricing model, have

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been employed as strategic decision-making tools for many years to provide more distinct results [9]–[11]. The first reference to RO was made in 1977 by Myers [12]. Since then, RO has been employed in several areas, such as the oil industry [13], [14], the airline industry [15], transportation systems [16] and business strategies [17], [18].

The literature on real options in mining projects is not new. Brennan and Schwartz [19] firstly used real options in the mining industry. In this study, they introduced a continuous-time stochastic model and developed a theoretical example of a mineral commodity. Dimitrakopoulos and Sabour [20] proposed a simulation-based real options valuation (ROV) method for selecting the most profitable mine design, which can handle multiple uncertainties and the variability of cash flow parameters that characterize mining projects. Sontamino and Drebenstedt [21] developed decision-supported systems for evaluating the feasibility to open a coal mine project in Thailand. Ajak and Topal [22] designed a binomial decision tree model, which centered on using RO in design and decision-making at the mine operational level. Other relevant publications include Inthavongsa *et al.* [23], Zhang *et al.* [24], Siña and Guzmán [25], and Haque *et al.* [26].

Despite the research and applications mentioned above done to improve decision-making in mining investments using RO methods rather than traditional valuation methods, it is noteworthy that the estimation of the parameters of an RO model remains challenging. For example, volatility reflects the uncertainty of an option value for mining projects as the parameter that is one of the most important parameters that is difficult to determine. That is because, for financial options, volatility is relatively simple to determine, which can be acquired by historical price data of stock, and then calculating stock's standard deviation of the historical rate of return. But for real options, the determination of volatility because neither the historical price nor the market price of the option exists. Cobb and Charnes [27] suggested the use of a Monte Carlo simulation model to estimate the volatility parameter for a real investment. Godinho [28] argued this method for introducing a significant upward bias in the estimation of volatility. He proposed alternative Monte Carlo simulation procedures that can yield better estimates of a project's volatility, which enables more accurate valuation. However, considering that the evaluation of mining projects is complicated, dynamic and nonlinear and are plagued with numerous inherent and inner-interacted uncertainties, including technical, geological and economic terms, none of these methods enable a person to estimate the overall benefit streams or costs when a project may have multiple subsequent impacts.

System dynamics (SD), which was proposed by Forrester [29], is an appropriate method for addressing this problem. SD is a computer-aided method for modeling complex systems to understand the patterns of behaviors of different stages over time. More specifically, SD provides a holistic modeling method since it reduces a system to multiple small, individual pieces, which enables the system to be investigated and considers causal relationships in a dynamic and multidimensional manner [30].

There have been some studies address the pioneering research that combines SD and RO to acquire more accurate results. Tan *et al.* [31] incorporated SD into decision tree analysis, which they referred to as an SD-based decision tree method for valuing economic value, which involved managerial flexibility of the alternative energy sectors. Peng *et al.* [32] proposed a general method for the calculation of influencing parameters and the RO value of uncertain investment decision-making projects using SD models. Consistent with the research of Peng *et al.* [32], Kasiri and Sharda [33] proposed a unique combination of SD and RO into a robust and innovative model for analyzing a return on investments in IT. Fitch *et al.* [34] presented an SD model that is employed for the valuation of RO to promote public initiatives, encourage private participation and enhance the economic sustainability of public-private partnerships.

However, to the best of our knowledge, the combination of SD and RO modeling and its application on mining investment decision-making projects is still an open issue. As a response to knowledge gaps found in the literature, the objective of this paper is to incorporate an SD application to extend RO valuation for decision-making of mining investment projects. The RO method overcomes the limitations of conventional DCF and addresses the value of technical and management flexibilities embedded in mining projects. SD simulation enables us to reflect numerous techno-economic factors that are contained in mining operation systems and their interactions during the process of valuation for mining projects. Furthermore, the simulation results of SD can precisely estimate the influencing factors and provide an in-depth assessment for mining investment decision-making projects. Taking advantage of both methods, our research can improve the accuracy of the valuation for mining projects and help decision makers make more scientific decisions for mining investment projects. As an illustrative example, we perform a valuation of the Hongwei uranium deposit in China.

II. RESEARCH FRAMEWORK

In reality, if the market is unfavorable, a mining project can be postponed until the market conditions improve, it can be abandoned during an operation to reduce losses, it may be expanded or extended as market conditions turn better. It means that mining investment projects imply options to defer or shutdown, which is similar to American options in the financial options framework. These options enable decision makers to restrict their loss risks and retain the potential to infinitely raise profits using the managerial flexibilities embedded in mining projects. However, traditional valuation methods disregard these flexibilities, then it cannot fit the actual situation and often underestimate the valuation of mining projects. As a result, during the valuation of mining projects, not only the static NPV calculated from the conventional DCF methods but also the value of the managerial flexibilities embedded in mining projects that are revealed by RO methods should be considered. Namely, the total value of the mining projects can be calculated by the hybrid investment evaluation model, which is expressed as follows:

$$V_{project} = V_{NPV} + V_{option} \tag{1}$$

where

V_{NPV}: the NPV obtained using the traditional valuation methods based on DCF.

V_{option}: the value of options calculated by RO models.

Merton [35] demonstrated that an American call on a share which does not pay a dividend over the life of the option will not be exercised prior to maturity. Thus, by implication, American calls, whose underlying shares do not pay dividends, can be priced by a European call option pricing model [36]. Since the Black-Scholes model is one of the most extensively employed models to provide a theoretical estimate of the price of European options, this paper extends the Black-Scholes model to the application for calculating the value of managerial flexibilities embedded in mining investment projects. The model assumes that:

- interest rates remain constant over the option period and that these interest rates are known;

- the returns on the mineral properties are lognormally distributed; and

- the volatility of these returns remains constant.

The following expression is the Black-Scholes formula used in this study:

$$V_{option} = SN(d_1) - Xe^{-rT}\mathrm{N}(d_2) \tag{2}$$

$$d_1 = \frac{\ln(S/X) + \left(r + \sigma^2/2\right)T}{\sigma\sqrt{T}} \tag{3}$$

$$d_2 = \frac{\ln(S/X) + \left(r + \sigma^2/2\right)T}{\sigma\sqrt{T}} - \sigma\sqrt{T} = d_1 - \sigma\sqrt{T} \tag{4}$$

where

S: present value of expected cash flows.

X: present value of costs.

r: risk-free interest rate.

σ: uncertainty of expected cash flows.

T: time to expiry.

$\mathrm{N}(d_1)$, $\mathrm{N}(d_2)$: cumulative probability distribution function for standard normal distribution.

As previously noted, estimating the parameters of the hybrid investment evaluation model can be difficult, especially the uncertainty of the expected cash flows (σ) in the Black-Scholes model is one of the most difficult parameters to estimate. Since the SD simulation model can address complicated and highly nonlinear problems by feedback loops that couple and quickly arrive at the value of mining projects for any operational strategy, which justifies its broad application in the valuation of mining projects. The SD simulation model is then can be integrated into the hybrid investment evaluation model.

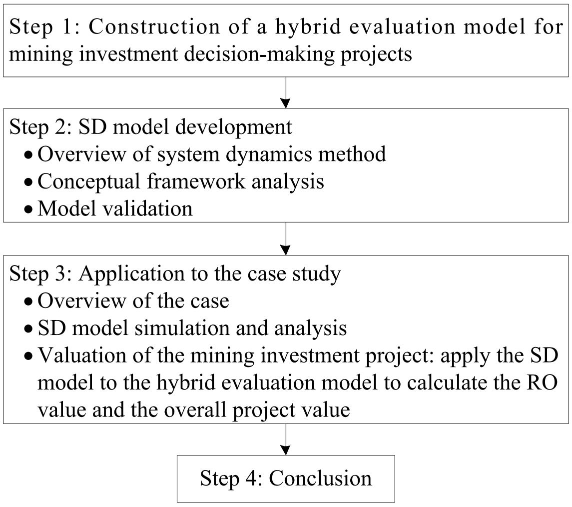

FIGURE 1. Technical roadmap of this paper.

That is to say, after constructing the hybrid evaluation model, one of the critical steps of this research is to develop the SD simulation model for mining production and operation and to test its validity. Then, employing the Hongwei uranium deposit as the engineering background, the SD model can be adapted to possible future scenarios for simulation to acquire different data of mining production and operation for a project in variety of situations. By predicting various outcomes of the SD model, the parameters of the Black-Scholes model can be estimated, and thus, the managerial flexibilities that are embedded in a mining project can be calculated. The final step is to combine the static NPV and the RO value to evaluate the total value of the mining project. Then, the valuation results can help decision makers make more scientific decisions for a mining investment project. Also, the method proposed in this paper can provide a reference for decision-making in other mining investment projects.

The research process can be summarized as the technical roadmap of this paper, as shown in Figure 1.

The remainder of this paper is generalized as follows: In section III, a general SD simulation model for the assessment of production and operation in mining investment projects is presented. Both the overview of system dynamics method and the key steps in modeling are presented in this section. In section IV, the constructed SD model is employed in the simulation for the case of the Hongwei uranium deposit. Then, we explain how the simulation results of the SD model can be applied to the hybrid evaluation model to estimate the value and make decisions for mining investment projects. Lastly, section V summarizes this paper.

III. SYSTEM DYNAMICS MODELING

A. OVERVIEW OF SYSTEM DYNAMICS METHOD

SD modeling is both qualitative and quantitative and usually comprises causal loop diagrams and stock-and-flow models. Qualitative modeling (causal loops diagram) can improve the conceptual system understanding. Quantitative modeling (stock-and-flow models) enables the investigation

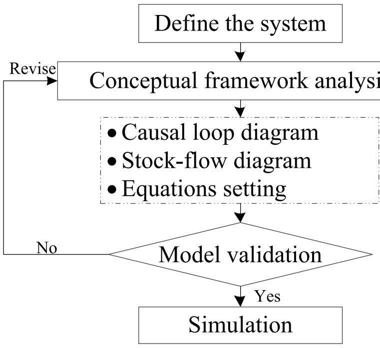

FIGURE 2. Main steps of SD modeling.

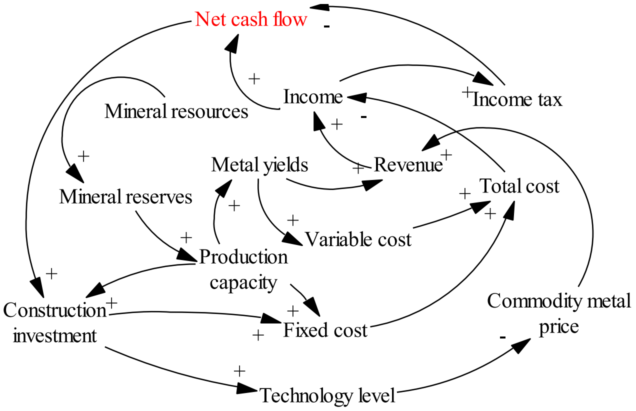

FIGURE 3. General causal loops diagram of production and operation in mining projects.

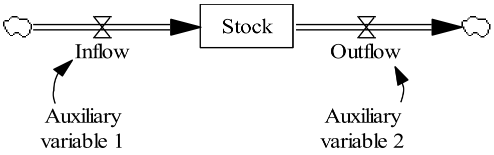

FIGURE 4. General graphical expression of the stock-and-flow diagram.

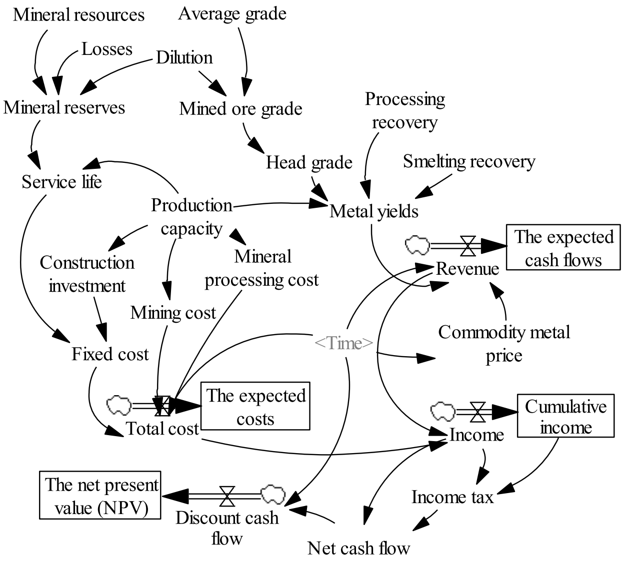

FIGURE 5. General stock-and-flow model of production and operation in mining projects.

and visualization of the effects of different scenarios within the simulation model [37]. Figure 2 presents the main steps of SD modeling.

B. DEFINE THE SYSTEM

For mining enterprises, estimating the valuation of mining projects to make investment decisions is a complicated system due to the existence of numerous techno-economic indexes, which are complex and restrict each other. Some critical parameters, such as the production capacity of endogenous variables or the metal price of exogenous variables simultaneously add additional uncertainties for mining projects. Also, different mining projects have specific differences in production operations and management modes, whereas some standard rules and structures exist in the process of financial forecasting for mining projects. Therefore, the SD simulation model presented in this paper is employed to perform an analysis of the cash flow changes in mining projects.

C. CONCEPTUAL FRAMEWORK ANALYSIS

Figure 3, which shows a general causal loops diagram of production and operation in mining projects, is determined by comprehensively analyzing the factors from the aspects of the production, sales, and costs that affect the cash flow changes and identifying the complicated feedback loops between them. As shown in Figure 2, the lines with arrows establish relationships between the pair of factors; positive signs represent the reinforcing impact; and negative signs represent the balancing effect.

The stock-and-flow diagram is an algebraic representation of the model based on the causal loops that have been identified. Stock characterizes the state of the system and retains a memory of it, which enables description of its status; flow causes the stock to change via inflow or outflow for a period of time and interlinks the stock within the system; the auxiliary variables are the rates to determine the flow values for the period of time [38]. The general graphical expression of the stock-and-flow diagram is shown in Figure 4.

According to Ref. [38], the state equation between stock and flow can be mathematically described as follows:

$$Stock\ (t) = \int_{t_0}^{t} [Inflow\ (t) - Outflow\ (t)]\mathrm{d}t + Stock\ (t_0) \qquad (5)$$

where t_0 is the initial time, t is the current time, $Stock(t_0)$ is the initial value of the stock, $Inflow(t)$ and $Outflow(t)$ are the flow rates and out of stock at any time.

To quantify and simulate the net cash flow changes in mining projects, based on the conceptual structure shown in Figure 3, the general stock-and-flow model of production and operation in mining projects is constructed and shown in Figure 5.

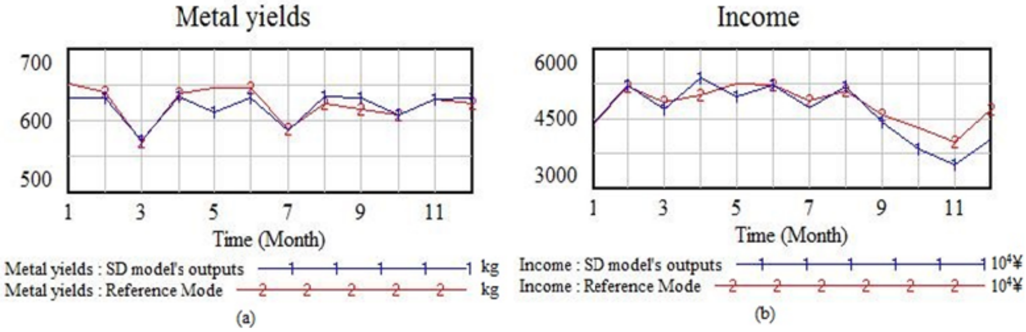

FIGURE 6. Comparisons of the SD model's outputs and the reference modes: (a) metal yields and (b) income.

Both the causal loops diagram shown in Figure 3 and the stock-and- flow model shown in Figure 5 are constructed with Vensim PLE 6.3 software, which provides a user-friendly interactive interface with wide-ranging mathematical functions. In Table 1, all variables contained in this model are classified and briefly described; and the core system equations are presented.

D. MODEL VALIDATION

Model validation, which is the accuracy of the model behavior's reproduction of the structure of the model, is a significant step in the SD modeling hierarchy. Senge and Forrester [40] suggested that SD models should be validated using a structure-verification test, parameter-verification test, extreme-condition test, dimensional-consistency test, boundary-adequacy test, and behavior-reproduction test. However, as Barlas [41] suggested, it is enough to test behavioral validity for SD-based valuation models. That is to say, after defining the causal loops diagram, stock-and-flow diagram, variables, and equations contained in the SD model of production and operation for mining projects, the SD model can be simulated for a reasonable period concerning the initial baseline values of past data. The simulation results are validated to determine whether the SD model represents the actual behavior of the system by comparing the output with previous data.

In this paper, monthly metal yields and income of an underground mine in China, named the Sanshandao gold mine, in 2014 were utilized as reference modes to test the capability of the model to precisely simulate the reality of mining production and operation. The initial values of the relevant techno-economic variables of the Sanshandao gold mine are shown in Table 2, and the mining cost and mineral processing cost are constant. Besides, Table 3 lists the actual data of the monthly production capacity and the commodity gold price that fluctuated over time.

The presented model in discrete time with a one-month time step are simulated, the SD model's outputs of metal yields and income are compared with the reference modes, as shown in Figure 6.

As can be seen, there is good agreement between the simulation data and actual metal yields; and there are some differences between the simulation data and actual income. Referring to [41], we choose the R-square (R^2) and the root mean square percentage error (RMSPE) as statistical validity indicators because they have more significant advantages in reliability, sensitivity, and other protection than other indicators. Regarding metal yields, the values of R^2 and RMSPE are 0.98 and 2.11%, respectively, whereas the values of R^2 and RMSPE are 0.93 and 6.96%, respectively, for income. Overall, it can be concluded that the SD model presented in this paper shows a remarkable consistency between the model simulation and the actual situation.

IV. APPLICATION OF A CASE STUDY

In this section, an application of the research on investment decisions of mining projects based on real options and system dynamics is demonstrated. The application involves an estimation of the value for an underground mine named the Hongwei uranium deposit using the hybrid investment valuation model and making investment decisions for this project.

A. OVERVIEW OF THE CASE

The Hongwei uranium deposit, which is affiliated with the China National Nuclear Corporation, was forced to suspend construction in 1979 and did not restart until 2009. Its mineral resources and the average grade have been verified to be 179.843×10^4t and 0.173%, respectively. According to the current feasibility study, under the circumstance of the production capacity is 15×10^4t/a and the uranium metal price is 75×10^4¥/t, the static NPV of the project estimated by the conventional DCF methods is 139.16 million yuan considering the nominal discount rate is 8%, which proves the project is economically feasible.

However, referring to the website of https://www.cameco.com, the current uranium metal price is nearly 40×10^4¥/t, for which the exchange rate of the US dollar against RMB is 6.8. Then, according to the conventional DCF methods, the estimated NPV of the project for the same production capacity is −175.59 million yuan that under zero, which will cause rejection of the project. It can be concluded that the uranium metal price is a critical variable that affects the uncertainty of decision-making. Also, determination of the production capacity is another significant portion that

TABLE 1. Variables and equations of the presented SD model.

Variable	Unit	Type	Equations
〈Time〉 [1]		Shadow variable	
Mineral resources	10^4t	Constant	
Average grade	%	Constant	
Losses	%	Constant	
Dilution	%	Constant	
Processing recovery	%	Constant	
Smelting recovery	%	Constant	
Mining cost	¥/t	Auxiliary	f_1(production capacity)
Mineral processing cost	¥/t	Auxiliary	f_2 (production capacity)
Mineral reserves	10^4t	Auxiliary	Mineral resources×(1-Losses)/(1-Dilution)
Mined ore grade	%	Auxiliary	Average grade×(1-Dilution)
Head grade	%	Auxiliary	Mined ore grade
Production capacity[2]	10^4t	Auxiliary	Mineral resources×(1-Losses)/(Expected service life×K×(1-Dilution))
Service life[3]	a	Auxiliary	INTEGER ((Mineral reserves-0.5)/Production capacity+3+1)+1
Metal yields	t	Auxiliary	Head grade×Production capacity×Processing recovery×Smelting recovery ×10000
Construction investment	10^4¥	Auxiliary	f_3 (production capacity)
Fixed cost	10^4¥	Auxiliary	Construction investment×discount rate×(1+ discount rate)^Service life/((1+ discount rate)^Service life-1)
Commodity metal price	¥/t	Auxiliary	with Lookup [(Initial time, Final time) ~ (Initial price, Final price)]
Income tax	10^4¥	Auxiliary	IF THEN ELSE(Cumulative income>0, Income*0.3 , 0)
Total cost	10^4¥	Rate	Mining cost + Mineral processing cost + Fixed cost
Revenue	10^4¥	Rate	Commodity metal price×Metal yields
Income	10^4¥	Rate	Revenue-Total cost
Net cash flow	10^4¥	Auxiliary	Income-Income tax
Discount cash flow	10^4¥	Rate	Net cash flow/(1-Discount rate)^〈Time〉
The expected costs	10^4¥	Level	INTEG(Total cost,0)
The expected cash flows	10^4¥	Level	INTEG(Revenue,0)
Cumulative income	10^4¥	Level	INTEG(Income,0)
The net present value (NPV)	10^4¥	Level	INTEG(Discount cash flow,0)

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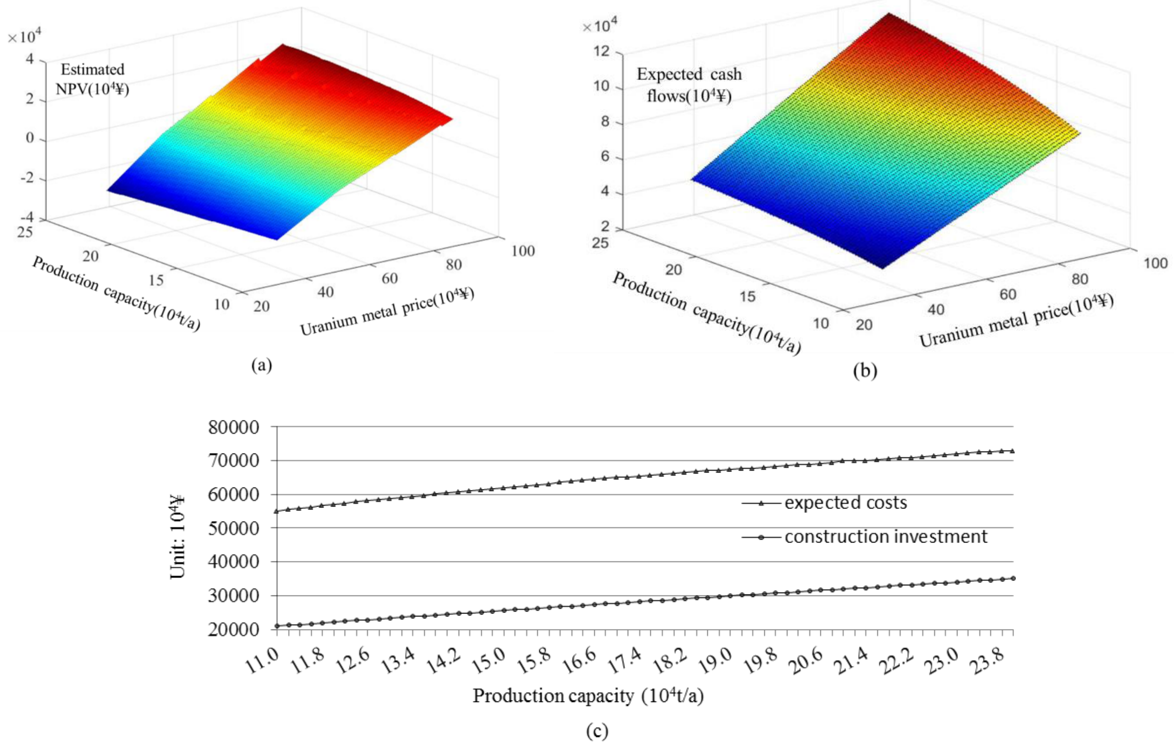
[1] <Time> is the current time during the simulation of the SD model. The unit of <Time> can be a day, month, and year. Before simulating the SD model, the initial time, the final time, and the time step must be determined.

[2] The variable of the Production capacity in this model is uncertain; it can be estimated by referring to Zheng and Cai [39]. The expected service life is equal to 6.5×Mineral resources^0.25×(1±0.2), where the unit of Mineral resources is million ton; and K is the reasonable spare coefficient of mineral resources, which floats between 1.3 and 1.5 for an underground mine. The Mining cost, Mineral processing cost, and Construction investment are related to the production capacity, and different functions exist at different mines. Therefore, before simulating the SD model, the quantity relationships of these three variables concerning the production capacity need to be determined.

[3] Considering 3 years of construction and 1 year of new production, the productivity is 50%.



(a) (b) (c)

FIGURE 7. **Simulation results under the different conditions of the production capacity and uranium metal price: (a) estimated NPV; (b) expected cash flows; and (c) expected costs & construction investment.**

TABLE 2. **Initial values of the relevant techno-economic variables of the Sanshandao gold mine.**

Variable	Unit	Value
Mineral resources	10^4t	2051.28
Average grade	g/t	2.023
Losses	%	4.50
Dilution	%	6.65
Fixed cost	10^4¥/month	5199.71
Mining cost	¥/t	122.16
Mineral processing cost	¥/t	43.03
Processing recovery	%	94.23
Smelting recovery	%	97.45

influences the valuation of the project. Due to dual pressure on the uncertainties of the uranium metal price and production capacity, the Hongwei uranium deposit has to be revalued by applying the hybrid investment valuation model presented in this paper, which can assist decision makers to make more accurate valuations and scientific investment decisions for the mining project.

Table 4 shows the essential techno-economic indicators for the mining operation in the Hongwei uranium deposit and briefly describes the adapted changes in the equations for its SD simulation model.

B. SD MODEL SIMULATION AND ANALYSIS

As noted in Table 1, the expected service life and the reasonable production scale of the Hongwei uranium deposit is calculated based on Ref. [39].

$$\begin{aligned}&\text{Expected service life}\\&\quad= 6.5 \times \text{Mineral resources}^\wedge 0.25 \times (1 \pm 0.2)\\&\quad= 6.5 \times 1.79843^\wedge 0.25 \times (1 \pm 0.2)\\&\quad= 6.5 \sim 10\text{a}\end{aligned}$$

$$\begin{aligned}&\text{Reasonable production scale}\\&\quad= \frac{\text{Mineral resources} \times \text{(1-Losses)}}{\text{Expected service life} \times \text{K} \times \text{(1-Dilution)}}\\&\quad= \frac{179.843 \times (1-10\%)}{(6 \sim 10) \times (1.3 \sim 1.5) \times (1-10\%)}\\&\quad= (11 \sim 24) \times 10^4\text{t/a}\end{aligned}$$

In addition, the website https://www.cameco.com provides necessary information about the statistics of the uranium metal price. The fluctuation of the uranium metal price from 2000 to 2018 is between 35×10^4¥/t and 90×10^4¥/t, considering that the exchange rate of the US dollar against RMB is 6.8.

Therefore, the relevant techno-economic indicators of the mining operation in the Hongwei uranium deposit, as shown in Table 4, are input into the SD simulation model presented in this paper; and simulate the SD model, where the variable of the production capacity ranges between 11×10^4t/a and

TABLE 3. Statistics of production capacity and commodity gold price that fluctuated over time.

Month		1	2	3	4	5	6
Production capacity	10^4t	35.61	35.64	32.22	35.67	34.52	35.65
Commodity price	¥/g	244.85	258.07	266.23	260.13	259.00	257.78
Month		7	8	9	10	11	12
Production capacity	10^4t	33.01	35.74	35.57	34.32	35.51	35.58
Commodity price	¥/g	262.43	257.04	245.70	241.69	231.30	239.54

TABLE 4. Essential techno-economic indicators for the mining operation in the Hongwei uranium deposit.

Indicator	Type	Unit	Value or Equation
Losses	Constant	%	10
Dilution	Constant	%	10
Processing recovery	Constant	%	98; where: the amount of tailings is 30% of the production capacity, and the average grade of tailings is 0.01%;
Smelting recovery	Constant	%	84
Construction investment	Auxiliary	10^4¥	1079.386×Production capacity+9293.492
Mining cost	Auxiliary	10^4¥	(0.099×Production capacity^2-8.318×Production capacity +358.195)× Production capacity
Mineral processing cost	Auxiliary	10^4¥	(0.093×Production capacity^2-4.032×Production capacity +205.841)× Production capacity
Discount rate	Constant	%	8; where: the discount value chosen is the same as the value applied in the current feasibility study to guarantee the comparability of the estimated NPV

24 × 10^4t/a using 0.2 × 10^4t/a as a step size and that the variable of the uranium metal price varies from 35 × 10^4¥/t to 90 × 10^4¥/t using 0.5 × 10^4¥/t as a step size. After going through all designed scenarios, the simulation results are analyzed as follows:

Figure 7 presents the estimated NPV, expected cash flows, and expected costs and construction investment of the SD simulation model's outputs for different conditions of the production capacity and uranium metal price.

As shown in Figure 7, both a qualitative analysis and quantitative analysis can be performed based on the SD simulation model's outputs:

1) QUALITATIVE ANALYSIS

As shown in Figure 6, regardless of the production capacity, an increase in the uranium metal price cause an increase in the estimated NPV and expected cash flows of the project. Also, with an increase in the production capacity, the expected costs and construction investment of the project increase.

Besides, under the specific conditions of the uranium metal price, the estimated NPV of the project will increase with an increase in the production capacity, which can reflect the character of the scale economy. However, when the production capacity increases to a certain extent, the estimated NPV of the project will decrease as the production capacity continues to increase. That is because excessively increasing the production capacity will increase the enormous investment, which will cause negative burdens for the mining operation.

2) QUANTITATIVE ANALYSIS

By statistically analyzing the simulation results presented in Figure 6, the average values of the expected cash flows and expected costs, which are 723.43 million yuan and 367.98 million yuan, respectively, can be obtained. Since the parameter in Eqs (3) and (4), which is the uncertainty of expected cash flows, is associated with the mean and standard deviation of the expected cash flows and can be determined as follows:

$$\begin{aligned}\sigma &= D/\overline{ECF} \\ &= \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}\left(ECF_i-\overline{ECF}\right)^2\right)}/\overline{ECF} \\ &= 27\%\end{aligned} \tag{6}$$

where

D: standard deviation of expected cash flows;
$\overline{ECF}$: mean of expected cash flows;
ECF_i : expected cash flows under the current scenario;
i: the number of scenarios design

TABLE 5. Parameters in the hybrid investment evaluation model.

Parameter	Unit	Value	Description and data resource
V_{NPV}	10^4¥	7326	Estimated NPV (mean value of NPV generated by simulation results)
S	10^4¥	72343	Expected cash flows (mean value expected cash flows generated by simulation results)
X	10^4¥	36798	Expected costs (mean value expected costs generated by simulation results)
r	%	4.5	Risk-free interest rate (pre-tax, long-term and nominal government bond interest rate)
σ	%	27	Uncertainty of expected cash flows (generated by simulation results that refer to Eq.(8))
T	a	10	Time to expiry

C. VALUATION OF THE MINING PROJECT

Based on the overview of the case and the statistical analysis of the simulation results that were previously presented, the value of the Hongwei uranium deposit is calculated by the application of Eqs. (1) - (4). Table 5 lists the financial parameters in the hybrid investment evaluation model.

$$\begin{aligned}
d_1 &= \frac{\ln(72343/36798) + \left(0.045 + 0.27^2/2\right) \times 10}{0.27 \times \sqrt{10}} \\
&= 1.746 \\
\mathrm{N}(d_1) &= 0.9596 \\
d_2 &= \frac{\ln(72343/36798) + \left(0.045 + 0.27^2/2\right) \times 10}{0.27 \times \sqrt{10}} \\
&\quad - 0.27 \times \sqrt{10} \\
&= 1.746 - 0.27 \times \sqrt{10} = 0.892 \\
\mathrm{N}(d_2) &= 0.8138 \\
V_{option} &= SN(d_1) - Xe^{-rT}N(d_2) \\
&= 72343 \times 0.9509 - 36798 \times e^{-0.045 \times 10} \times 0.8138 \\
&= 50324 \\
V_{project} &= V_{NPV} + V_{option} = 7326 + 50324 \\
&= 57650
\end{aligned}$$

Based on these results, the hybrid investment evaluation model proposed in this paper provides the Hongwei uranium deposit's valuation of 576.50 million yuan, compared with −175.59 million yuan, as estimated by conventional DCF methods. Obviously, the uncertainties and managerial flexibilities embedded in the project affect its valuation, whereas the traditional valuation methods underestimate the value of the project.

V. CONCLUSION

The real options valuation method, which substantially differs from traditional investment valuation methods, makes more accurate assessments, since it considers future uncertainties, as well as dependencies and dynamism. This paper has presented a hybrid investment valuation framework that is based on real options and system dynamics to evaluate the value of mining projects. As a basic model, the hybrid investment evaluation model is employed to reflect both the static NPV and the real options value in mining projects. However, a mining operation is a complex system; endogenous and exogenous factors underlie the opportunity to create uncertainties and continuously change the valuation. Real options valuation encounter difficulties estimating these uncertainties. Then, using SD, we identify and quantify various factors and their complex interactions, reflect these in the valuation, evaluate its volatility, and thus, enable the real options valuation to overcome one of its limitations.

The evaluation of a mining project using the method proposed in this paper was performed for the Hongwei uranium deposit. The analysis showed that the project should have been rejected because its current value is determined to be −175.59 million yuan, as calculated by traditional DCF method. However, considering the uncertainties and managerial flexibilities, the valuation of the project is 576.50 million yuan that more than zero. Therefore, this project is economically feasible. Our method is useful for improving the accuracy of the valuation for mining projects and enabling decision makers to make additional scientific investment decisions.

Despite the value of our method, it has several limitations. The quantity of relationships of investment and cost concerning the production capacity may differ among different mining projects. In these cases, the equations of the SD model should be carefully and adaptively modified. The uncertainty of the geological resources and the best overall value of the project are not considered in this paper. To address this issue, we require an appropriate optimization model and more complicated SD model, which are areas for future research.

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