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Yu, S., & Gao, S. (2016). A dynamic programming model for environmental investment decision-making in coal mining. Applied Energy(166), 273-284, rank: A.

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Applied Energy 166 (2016) 273–281

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A dynamic programming model for environmental investment decision-making in coal mining

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HIGHLIGHTS

- A DP model is proposed for investment decision-making of environmental projects.
- The model can obtain the optimum investment strategy to meet the emission standard and to minimize costs.
- The results show that the model is effective and applicable for investment decision-making.

ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form 17 July 2015
Accepted 29 September 2015
Available online 23 October 2015

Keywords:
Coal mine
Pollution treatment
Dynamic programming
Investment decision-making

ABSTRACT

Coal is the widespread fossil fuel on earth. It provides the necessary material foundation for economic development of a country. However, coal mining activities cause a lot of environmental impacts that are hazardous to the health of citizens in mining regions and place costs on the government. According to government laws and regulations, coal mines should invest in related pollution treatment projects to meet the emission standards. How to allocate the limited resources among a set of pollutant treatment projects to minimize the total losses, including penal loss and vacancy loss, from an investment perspective is a typical decision-making problem. Therefore, the present study proposed a discrete dynamic programming procedure to provide an effective solution for decision-making in treatment project investment. Furthermore, a case study involving the Laojuntang coal mine of Zhengzhou Coal Industry (Group) of China on the treatment project investment problem was implemented using the proposed model. The results demonstrate that the proposed model is effective and applicable for environmental investment decision-making at a typical coal mine in terms of minimizing the total losses.
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1. Introduction

As the most abundant fossil fuel on the planet, coal provided around 29.0% of the global primary energy need and generated about 40.4% of the world's electricity in 2012 [1]. Coal mining is one of the core industries that contribute to the economic development of a country. However, coal production usually causes serious damage to the environment, including impacts on groundwater quantity and quality, land subsidence, mining waste stockpiling, land occupation and other effects [2,3]. Take China as an example. The production of coal was 3.6 billion tonnes in 2013, accounting for up to 45.5% of global yields [1]. As a result, large quantities of mining waste were produced, including coal gangue, coal sludge, fly ash, coal mine drainage and coal bed methane (CBM) [4]. Statistics show that the total emissions of industrial waste water were 1.42 billion tonnes, waste gas reached 32.49 billion m^3 and solid wastes reached 385.37 million tonnes in 2012 [5]. Furthermore, the annual leaked emissions of CBM amounted to 15 billion m^3 [6]. It is generally argued that serious adverse environmental impacts and damages may be caused by coal mine waste, including interference with groundwater quantity and quality, land subsidence, creation of geological hazards, visible and esthetic issues, damage to infrastructure and potential ecological havoc [7,8]. An area of about 30 km^2 of subsidence is caused by underground coal mining every year [9]. And eventually these environmental damages will become constraints to economic development.

To protect the ecological environment of coal mining areas, the main coal-producing countries such as China, the United States, India and Australia issued a series of special laws and regulations

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http://dx.doi.org/10.1016/j.apenergy.2015.09.099
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for the coal industry. For example, the Chinese government released the *Emission Standard for Pollutants from the Coal Industry (GB 20426-2006).* In particular, in 2010, China's National Development and Reform Commission promulgated *The 12th Five-Year Development Plan for the Coal Industry* and *Opinions of Energy Conservation and Emissions Reduction Work in the Coal Industry*. The plan clearly states that by the end of 2015, China needs to reach the following targets: a national raw coal feed cleaning rate of more than 60%; a comprehensive utilization of solid wastes such as coal gangue rate of more than 75%; an extraction and utilization of methane rate of more than 55%; a mine water utilization rate of more than 80%; and a soil reclamation rate of more than 50%. The document also states that all large coal companies should meet the prescribed pollutant emission standards. If the emissions do not meet the requirements of the laws and regulations, the coal companies will be fined or forced to shut down. This loss may be called "penal costs." Clearly, coal mines should invest in pollution treatment projects, environmental technologies or waste recycling utilization procedures to avoid such penalties. However, if the treatment project is introduced too early, despite avoiding the fine, it will cause investment capital occupation loss as the pollutant generation rate is lower than the equipment treatment rate. The loss is then called "vacancy costs." Constrained by the amount and types of pollution, the treatment capacity of projects and capital limit, coal mines should make an appropriate decision to minimize the total investment cost of pollutant treatment projects. Obviously, this is a typical optimization problem of investment decision-making.

Different mathematical models or methods have been proposed to deal with the optimization problem of decision-making in environmental protection project investments. For example, Lin et al. applied the real option approach to evaluate the optimal environmental investment decisions under economic and ecological uncertainty [10]. Higgins et al. explored a multi-objective integer- programming model for environmental investment decision-making [11]. Myšková et al. discussed the decision-making in relation to environmental investments in waste water treatment plants using TOPSIS (the technique for order of preference by similarity to ideal solution) [12]. Kusi-Sarpong et al. introduced a multiple criteria evaluation of green supply programs using a novel multiple criteria approach that integrates rough set theory elements and fuzzy TOPSIS for the mining industry [13]. Moreover, Jaraite et al. developed a regression model identifying to investigate how environmental expenditure and investment of Swedish industrial firms responded to climate policies, such as the European Union's Emission Trading System (EU ETS) and the Swedish CO_2 tax, directed to mitigate air pollution [14]. These studies provided good solutions for the real decision-making in environmental project investments. However, decision-making is a multistage process aimed at finding a sequence of decisions that maximize (or minimize) an appropriately defined objective function such as costs, losses or risks. The dynamic programming (DP) procedure is a good candidate for handling this type of decision-making problem due to its dynamic nature, and is more effective than using linear programming or nonlinear programming alone. DP is a numerical algorithm based on Bellman's optimality principle [15] that finds the control law, which provides the global minimum value for the given objective function while satisfying the system constraints. In the modeling, DP converts a complex problem with multiple decision goals and limited resources into a sequence of interrelated subproblems arranged in stages, so that each subproblem is more tractable than the original problem.

The DP model has been widely applied to make optimal decisions on various decision-making problems, such as wastewater treatment system optimization [16], optimal well selection strategy [17], and the portfolio of IT projects' problem decision-making [18]. There are also several studies applying DP to find global optimum decision-making in energy systems. These studies can be divided into three broad categories: (1) DP optimization decision-making in electrical distribution systems. For example, Khalesi et al. applied dynamic programming to discover the optimal locations to place distributed generations (DGs) in a distribution system to minimize the power loss of the system and enhance the reliability and voltage profile [19]. Ganguly et al. presented a DP to solve the multi-objective optimization planning of electrical distribution systems [20]. Marano et al. applied the DP technique to the optimal management of a hybrid power plant, which consists of compressed air energy storage (CAES) coupled with a wind farm and photovoltaic panels, taking into account energy, economic and environmental aspects [21]. (2) DP optimization applications in energy storage systems management. This kind of study can be represented as follows. Liang et al. proposed a long-term operation optimization model of a Pumped-Hydro Power Storage (PHPS) station based on approximate DP [22]. For deriving the best configuration and energy split strategies, Song et al. utilized the DP approach to deal with the integrated optimization problem of a hybrid energy storage system that includes a battery and a supercapacitor for an electric city bus [23]. To achieve the optimal energy allocation for the engine-generator, battery and ultracapacitor of a plug-in hybrid electric vehicle, Zhang and Xiong employed a DP model to develop suboptimal control strategies for different driving blocks [24]. Furthermore, Fares et al. applied DP technique for optimizing fuel cell hybrid vehicles [25]. (3) DP optimal decision-making in oil stockpile strategy. Wu et al. presented a dynamic programming model to determine the optimal stockpiling and drawdown strategies for China's strategic petroleum reserve under various scenarios, focusing on minimizing the total cost of reserves [26]. Bai et al. applied DP to optimize a stockpile strategy for China's emergency oil reserve by minimizing stockpiling costs, including consumer surplus as well as crude acquisition and holding costs [27]. Besides these three categories, Škugor and Deur proposed a DP optimization method for aggregate battery charging for an electric vehicle fleet. They claimed that the DP method could lead to global optimal results for the applications [28]. Li et al. proposed a DP model for optimal control of a wave energy converter [29]. Although DP is very popular in many decision-making issues, less attention has been drawn towards dealing with environmental investment decision-making.

Therefore, our objective in this paper is to develop a multistage discrete dynamic programming procedure for investment decision-making in coal mine pollution treatment in China. There are two reasons for us using the DP method to solve the environmental investment decision-making problem in coal mining. First, the decision-making on investment in pollutant treatment projects has obvious dynamic stages, which decision of each stage constitutes entire decision-series of the problem. Second, it can always be guaranteed that DP will find the optimal global solution [21]. In the proposed procedure, the DP transforms the complex investment decision-making problem into a sequence of interrelated subproblems arranged in stages while considering the constraints of the amount and types of pollution as well as the treatment capacity of projects and capital limit. Furthermore, a case study of a pollution treatment project investment problem at the Laojuntang coal mine of Zhengzhou Coal Industry (Group) is implemented.

2. Problem statement

2.1. Pollutants and their treatment of coal production

The activities of coal production and utilization include mining, preparation and combustion of coal-fired boilers for heating.

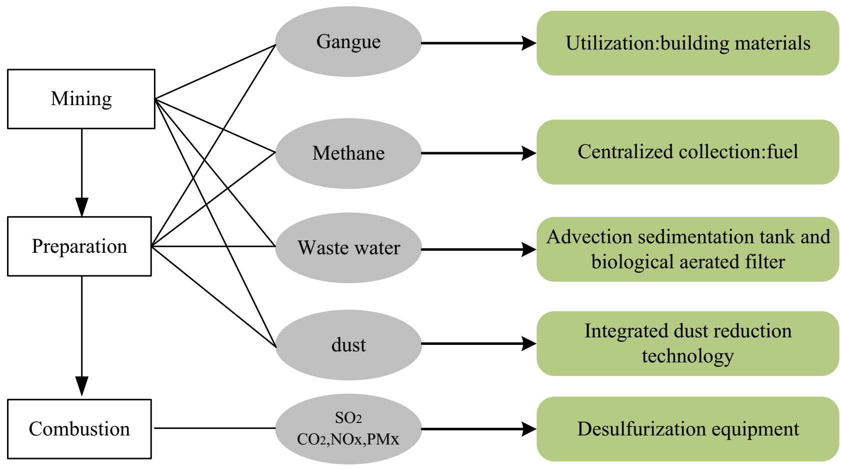

Fig. 1. Pollution emissions and treatment of coal production.

Different activities generate different pollutants, as shown in Fig. 1. Coal can be extracted either by opencast or underground mining techniques, depending on coal seam depth, geotechnical conditions, land use constraints and other factors [30]. However, the underground mining method is the most common in the world: for example, 96% of Chinese coal is produced from underground mines [31]. Different coal mining and using activities may generate various wastes. Pollutants in the mining process (including excavation and extraction) mainly include coal gangue, coal mine drainage and fly ash. Meanwhile, large amounts of coal bed methane escape in this process. The coal preparation process includes two sub-processes, namely coal washing and separation, which washes coal from soil and rock, crushes it into graded sized chunks (sorting), and stockpiles grades to prepare it for transportation by mechanical processing or chemical processing methods. Therefore, the main pollutants in the preparation are coal gangue, coal washing waste water, coal bed methane and fly ash. For heating in a mine tunnel and mining safety, coal-fired boilers are generally built in Chinese coal mining areas. Hazardous gases and greenhouse gases, such as SO_2, CO_2 and NO_x and fine particulate matter at sizes as low as 10 mm or even 2.5 mm (known as PM_{10} or $PM_{2.5}$) are emitted during coal combustion.

The main environmental damage from underground coal mining can be divided into two categories [32]. (1) Underground hazards. Safety hazards may be caused by the explosion of gas and coal dust and inundation with roof and side falls. The coal dust may lead to health hazards such as respiratory diseases. (2) The environmental impact on the surface. This includes land disturbance, water regime disturbance, air pollution, biological disturbance and societal disturbance, etc. Obviously, these pollutants from coal mines cause serious environmental problems that affect human health and the sustainable development of the region. Therefore, in accordance with relevant laws and regulations, coal mines must make the appropriate investment in pollutant treatment during coal production, so that the emissions meet the discharge or recycling utilization standards. Due to the fact that the physical and chemical compositions of different contaminants are not the same, the pollution treatment methods used are also different. For example, wastewater is mainly treated through sediment and biological aerated filters by building an advection sedimentation tank to eliminate harmful chemicals and sand grain. Through a building materials project, coal gangue can be transformed into bricks and paving materials to reduce the destruction of land leaching waste generation. Treatment of fly ash and dust can adopt integrated dust technology, which is mainly based on a dry bag filter. This technology can effectively control dust in the coal mining and preparation process. Coal bed methane can be centralized, collected and liquefied for electricity generation or used in a Combined Heat and Power (CHP) system as a residential fuel. SO_2, CO_2 and NO_x generated in coal-fired boilers are treated by installing desulfurization or capture equipment to meet the discharge standards.

2.2. The decision-making problem of pollutant treatment

Being an enterprise, coal mines should make appropriate decisions to minimize costs and maximize profits on investments in pollutant treatment projects. The decision-making depends on the amount and types of pollution, project treatment capacity and capital constraint, as well as legislative requirements in terms of environmental protection. This general optimizing problem of investment decision-making can be described as follows:

Let p_{tj} be the emission amount of pollutant j ($j = 1, 2, \ldots, M$) in the planning year of t ($t = 1, 2, \ldots, T$). s_{tj} is the treatment capacity of pollutant j in the tth year. However, existing pollution treatment capacity s_{0j} is not sufficient to meet the pollutant p_{tj} in the tth year. Therefore, coal mines have to invest in a related pollutant treatment project j to meet the legislative requirements. Assume that project j treats the corresponding pollutant j. The construction period and capital requirement for each project are different. The construction period of project j is N_{1j}. The investment amount is I_{jt} ($t = 1, 2, \ldots, N_{1j}$) at the beginning of year t for pollutant j during the construction period. Once a project has started the construction, the investment will be continuous in the construction period. The total investment of all projects at the beginning of each year should be lower than the investment constraint $MaxI$ and larger than 0. The newly added treatment capacity for pollutant j is PT_j after the completion of construction. PT_j can meet the treatment standard for a long period of time for pollutant j. In accordance with relevant environmental laws, the Department of Environmental Protection will punish the coal mine if pollutant does not meet the legislative requirement ($p_{tj} - s_{tj} > 0$) with pf_{tj} RMB yuan (¥) per unit of emission in the tth year. After the limited time period T, if the pollutants still cannot meet the emission standard, the coal mine will be forced to close by the government. Therefore, pollution treatment projects need to be completed early in the planning phase. However, if the project is completed too early, although not subject to the penalty, the coal mine will suffer from capital occupation loss when the pollutant generated is less than the treatment capacity of the equipment. Therefore, to minimize the total loss, including the penalty loss and the capital occupation loss, a coal mine should make a reasonable decision on project investment based on the yields of each pollutant, the construction period, the capital requirement of each project, and the capital available for environmental equipment investment.

Based on the above discussion, the total capital investment of j is $TI_j = \sum_{i=1}^{N_{1j}} I_{ij}(1+r)^{n_{1j}-i+1}$ by the end of the completed year, with r being the discount rate. The real investment per unit capacity of pollutant treatment is $CP_j = \frac{TI_j}{PT_j}$. Let $(s_{tj} - p_{tj}) > 0$ be the vacancy treatment capacity of project j, then the capital occupation loss for project j is $LO_{j1} = r \cdot (s_{1j} - p_{1j}) \cdot CP_j$ in the first year of vacancy, and the loss per unit vacancy capacity of treatment is $PL_{1j} = \frac{LO_{1j}}{s_{tj}-p_{tj}}$. If there is more than two years' vacancy, besides capital occupation losses $r \cdot (s_{tj} - p_{tj}) \cdot CP_j$ in the tth year, there are also regenerated capital benefits losses $r \cdot IC_{jt} \cdot (PL_{t-1} + PL_{t-2} + \ldots, PL_1)$ in the tth year for loss $(s_{tj} - p_{tj}) \cdot PL_{t-1,j}, (s_{tj} - p_{tj}) \cdot PL_{t-2,j}, \ldots, (s_{tj} - p_{tj}) \cdot PL_{1,j}$ in the previous years $t-1, t-2, \cdots, 1$.

3. The proposed dynamic programming model

Dynamic programming starts with a small portion of the original problem to find the optimal solution for this small problem. It then gradually enlarges the problem to find the current optimal solution from the previous stage, until the original problem is solved in its entirety. Based on the discussions in Section 2, in year t to year T, the model adapts to the project and capital constraints as well as the optimal investment policy, and is independent from previous decisions. In this particular application, the DP is designed to find the optimum investment strategy of treatment projects such that the emission standard of pollutants is met and the total costs (including vacancy costs and penalties) are minimal. Let each year be the state space that satisfies the Markov Property; we establish the following dynamic programming models based on the dynamic programming principle:

(1) **Stage** (k): the state variables represent the state of the system as it moves through the treatment levels. Since the interval of pollution treatment investment projects is on a yearly basis, the present paper divides the stage by years. Therefore, index k represents a given stage for each year, $k = 1, 2, \ldots, T$.

(2) **State** (S_k): The coal pollution investment loss is directly related to the capacity of pollution treatment in each stage. And the treatment capacity is influenced by whether project j is put into operation or not in a particular stage. Therefore, the state variable S_k is set to be the treatment capacity of pollutant j at stage k, namely,

$$S_k = [s_{k1}, s_{k2}, \ldots, s_{kj}, \ldots, s_{km}]^T \tag{1}$$

where s_{kj} is the treatment capacity of pollutant j in stage k.

(3) **Decision variables** (X_k): In this study, the decision-making problem is when to begin to construct pollution treatment projects, with the purpose of keeping coal pollution control investment losses to the minimum. If project j construction starts at the beginning of year h, then the treatment capacity of pollutant j is changed to PT_j for the year $h + N_{1j}$. Since the investment losses are determined by the treatment capacity and the pollution emissions, we set the newly added treatment capacity decision variable to be X_k at stage k.

$$X_k = [x_{k1}, x_{k2}, \ldots, x_{kj}, \ldots, x_{km}]^T \tag{2}$$

According to Section 2, if $x_{kj} \neq 0$, the coal mine should invest I_{ji} RMB yuan (¥) at the beginning of stage $k-i$ ($i = 1, 2, \ldots, N_{1j}$). Furthermore, the total investment of all projects should not exceed $MaxI$, namely $\sum_{j=1}^{M} I_{ji} \leqslant MaxI$.

(4) **Contribution function** ($D_k(S_k, X_k)$): This function provides the value at stage k given the decision variables X_k. According to the principle of dynamic programming, the contribution function $D_k(S_k, X_k)$ in the present study is represented by the total investment losses of pollution treatment in stage k, as shown in Eq. (3).

$$D_k(S_k, X_k) = \sum_{j=1}^{M} (LO_{kj} + PN_{kj}) \tag{3}$$

where LO_{kj} and PN_{kj} are capital occupation loss and penalty loss respectively, for project j at stage k, for substandard pollution emissions.

$$\begin{cases} LO_{kj} = r \cdot (s_{kj} - p_{kj}) \cdot (CP_j + PL'_{kj}) & \text{if } s_{kj} - p_{kj} \geqslant 0 \\ PN_{kj} = (p_{kj} - s_{kj}) \cdot PF_{kj} & \text{if } s_{kj} - p_{kj} < 0 \end{cases} \tag{4}$$

PL'_{kj} in Eq. (4) is calculated by Eq. (5)

$$PL'_{kj} = \begin{cases} 0 & \text{if } s_{k-i,j} - p_{k-i,j} \leqslant 0 \\ PL_{k-1,j} + PL_{k-2,j} + \ldots + PL_{k-i,j} & \text{if } s_{k-i,j} - p_{k-i,j} > 0 \end{cases}, \quad i = 1, 2, \ldots, N_{2j} \tag{5}$$

(5) **Transformation function** ($T_k(S_k, X_k)$): This function $T_k(S_k, X_k)$ shows how the treatment capacity of pollutants in stage k changes to the next stage $k+1$ based on the current state, stage and decision-making.

$$S_{k+1} = T_k(S_k, X_k) = S_k + X_k \tag{6}$$

(6) **Optimal value objective function** ($f_k(S)$): The minimum investment losses of pollution treatment from stage 1 to stage k are S_k, given the state at stage k.

(7) **Recursive equation**: In the DP model, there are two kinds of recurrent processes: backward formulation and forward formulation. Backward solution begins in the final instant T. The DP algorithm finds a set of optimal solutions for each value of discretized state vector in that instant, and continues the procedure backward in time for each time instant, and terminates in stage 1. This scheme ensures global optimality, but at the same time numerical inefficiency [24]. In the forward formulation, starting from the known initial state 1, the optimal input vector is successively reconstructed (forward in time) from the previously stored optimal solutions.

The main reason for us adopting a forward recursive solution as an optimization algorithm for investment decision-making in treating coal mine pollution treatment is that forward formulation can significantly reduce the online computational burden. In this study, all pollution treatment projects must be completed by the end of stage T, and there may be $C_M^1 + C_M^2 + \ldots + C_M^M$ possibilities at stage T.

Since it is very difficult to recursively compute from stage T to stage 1, forward formulation is used as the recursive equation in the study, represented by Eq. (7).

$$\begin{cases} f_k(S_k) = \min\limits_{x_k \in U} (D_k(S_k, X_k) + f_{k-1}(S_{k-1})) \\ f_0(S_0) = 0 \end{cases}, \quad k = 1, 2, \ldots, T \tag{7}$$

The above DP is described in Fig. 2.

It should be pointed out that the proposed DP model mainly focuses on the timing of the project investment in the planning

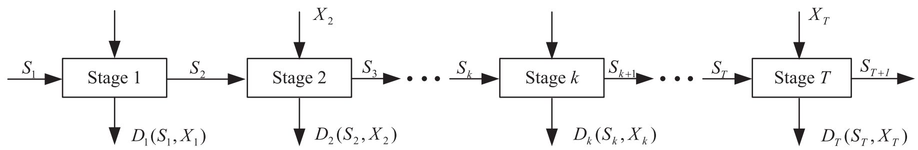

Fig. 2. Graphical illustration of the stages of the proposed DP formulation.

Table 1
Investment, construction period and pollution treatment capacity.

	Investment (million yuan)					Pollution treatment
	1st year	2nd year	3rd year	4th year	Total	Capacity (tonne)
Project 1	3.50	4.00			7.50	110
Project 2	5.10	3.20	1.80	1.80	12.00	350
Project 3	4.00	3.70	4.80		12.50	180
Project 4	2.50	2.50			5.00	90
Project 5	7.10	6.50	3.20	4.00	10.80	300

Table 2
All estimated pollution emissions in the future (unit: tonne).

	2016	2017	2018	2019	2020	2021
Coal-bed methane	47	63	76	85	90	105
Mine water	100	140	180	220	290	350
Fly-ash and dust	100	120	140	155	165	178
SO_2	30	41	50	63	75	88
Gangue	140	175	210	245	270	290

Table 3
Penalty per pollution emission.

Year	2016	2017	2018	2019	2020	2021
Penalty (Yuan/tonne)	1.0	1.5	3.0	4.7	5.5	6.5

periods. This determines the investment arrangement for all projects, but does not consider which project to invest in. Therefore, the daily operating costs of completed treatment projects and the pollutant recycling benefits are beyond the scope of the current study, and are considered to be exogenous factors. These factors do not directly impact the loss decision-making.

4. Case study

4.1. A brief introduction to the Laojuntang coal mine

Zhengzhou Coal Industry (Group) Co., Ltd. (ZCIG) was established in 1958. It later became a part of Zhengzhou Coal Industry & Electric Power CO., Ltd. in 1997, and was listed on the Shanghai Stock Exchange as "Zhenzhou Coal Industry & Electric Power," which was the first stock of a state-owned coal company. The coal recoverable reserves of ZCIG are 1.0 billion tonnes and the current coal production capacity is 27 million tonnes with about 54,000 employees in 2012. ZCIG ranks 30th in the "Top 100 coal mining companies in China" reported by the China Coal Industry Association and are one of the major companies in Henan province. Furthermore, it plays an important role in the Yuxi coal base, which is one of the 13 state-planned large-scale coal bases in China. There are 14 leading coal mines in ZCIG, among which the Laojuntang mine is the newest leading coal mine, having started construction in 2003. Phase III construction of the mine is planned for 2016, with the aim of gradually increasing annual coal production from 450,000 tonnes in 2014 to the maximum design production of 600,000 tonnes in 2021.

4.2. Data

The coal mine plans to invest in five pollutant treatment projects during the period from 2016 to 2021 in accordance with the five kinds of pollutant emissions. The capital investment at the beginning of each construction year and the completed treatment capacity for each project are listed in Table 1. The estimated emissions of each type of pollution during the period 2016–2021 are shown in Table 2. The penalty for substandard pollutant emission for each year is listed in Table 3. The model adapts to yearly penalty growth, from ¥1/tonne in 2015 to ¥6.5/tonne in 2021. The coal mine must make a decision on reasonable investment to minimize the investment cost of pollution treatment in the planned years from 2016 to 2021. Subject to mining capital, the total investment for all projects in each year cannot exceed 13.00 million yuan. The present treatment capacity of five types of pollutants is $S_0 = [0.40, 0.70, 0.80, 0.20, 1.00]^T$. According to the mines' accounting standards financial system, if the vacancy pollution treatment capacity of a project exceeds 5% of its rated capacity, the capital occupation loss for vacancy capacity will be calculated as 95% of the total vacancy capacity.

Based on the investment period, investment cost and completed construction capacity of pollution treatment shown in Table 1, the actual investment per newly added treatment capacity CP_j of five projects can be computed by $CP_j = \frac{TI_j}{PT_j}$. The results are listed in Table 4.

4.3. Solution procedure

Following the procedure in Section 4.2, the maximal stage is $T = 6$, the annual maximum investment is $MaxI = 13$ million yuan, the number of planning treatment projects is $M = 5$, and the discount rate is 6%. Table 1 shows that the construction periods (N_{1j}) of the five projects are not the same, therefore the completed construction stage possibility for each project is also different. For example, the construction of project 1 can be completed at any stage from 2 to 6, i.e. five possibilities. Therefore, there are in total $5 \times 3 \times 4 \times 5 \times 3 = 900$ combined possibilities of completed construction scenarios. However, subject to the maximum annual investment limit of $MaxI = 13$ million yuan, the feasible solutions

Table 4
Actual project investment per newly added treatment capacity (10^4 Yuan/tonne).

Project	1	2	3	4	5
Investment	11.68	5.25	12.74	7.80	12.27

can be greatly reduced. According to the proposed DP model in Section 3, the solution procedure of the Liaojuntang coal mine pollution treatment project is shown as follows.

(1) **Stage 1** ($k = 1$)

The capacity in stage 1 is the initial capacity, namely $S_1 = [0.40, 0.70, 0.80, 0.20, 1.00]^T$. Since the shortest construction period for the five projects is two years, no pollution treatment project can be completed in stage 1. There is no newly added treatment capacity in the present stage $X_1 = [0, 0, 0, 0, 0]^T$. The substandard pollution emission of the five projects is $p_{1j} - s_{1j} = [0.07, 0.20, 0.30, 0.10, 0.40]$ (million tonnes). The contribution function value and optimal objective function value of stage 1 are $D_1(S_1, X_1) = 1.07$ and $f_1(S_2) = 1.07$, respectively, according to Eqs. (3)–(5) and (7).

(2) **Stage 2** ($k = 2$)

Similar to stage 1 ($k = 1$), the state is $S_2 = S_1 + X_1 = [0.40, 0.70, 0.80, 0.20, 1.00]^T$. Although projects 1 and 4 can be completed at the end of this stage, the pollution treatment capacity has not increased. Therefore, the decision variable is $X_2 = [0, 0, 0, 0, 0]^T$. The substandard pollution emission is $p_{1j} - s_{1j} = [0.23, 0.60, 0.50, 0.21, 0.75]$ (million tonnes). The contribution function value is $D_2(S_2, X_2) = 3.44$, while the optimal objective function value is $f_2(S_2) = \min(D_2(S_2, X_2) + f_1(S_1)) = 4.51$.

(3) **Stage 3** ($k = 3$)

The state of stage 3 is $S_3 = S_2 + X_2 = [0.40, 0.70, 0.80, 0.20, 1.00]^T$. Since projects 1 and 4 can be completed at the end of stage 2, the treatment capacity of pollutants 1 and 4 can be increased in the present stage. Therefore, there are four feasible solutions depending on the newly added capacity, namely $X_3^{(1)} = [0, 0, 0, 0, 0]^T$, $X_3^{(2)} = [0.7, 0, 0, 0, 0]^T$, $X_3^{(3)} = [0, 0, 0, 0.7, 0]^T$ and $X_3^{(3)} = [0.7, 0, 0, 0.7, 0]^T$. Based on these four feasible solutions, the contribution function value and optimal objective value can be computed as shown in Table 5.

Table 5 shows that the optimal objective function is feasible 4 and the minimum total loss from stage 1 to the end of stage 3 is 13.31 million yuan. Feasible 4 indicates that the coal mine should invest in both projects 1 and 4 at the beginning of stage 1 for pollutant types 1 and 4, with construction of the two projects completed at the end of stage 2 and operation starting in early stage 3. This optimal strategy yields total losses of pollutant treatment of 13.31 million yuan from stage 1 to 3.

(4) **Stage 4** ($k = 4$)

In this stage, the state has four scenarios, namely $S_4 = S_3 + X_3 = \begin{Bmatrix} 0.40 & 1.10 & 0.40 & 1.10 \\ 0.70 & 0.70 & 0.70 & 0.70 \\ 0.80 & 0.80 & 0.80 & 0.80 \\ 0.20 & 0.20 & 0.90 & 0.90 \\ 1.00 & 1.00 & 1.00 & 1.00 \end{Bmatrix}$.

The construction periods for each project in Table 1 show that projects 1, 3 and 4 can be completed before the beginning of stage 4. And the treatment capacity of pollutants 1, 3 and 4 can be added later. Thus, the treatment capacity can increase at a combination of 0, 0.7, 0.7 and 1.10 million tonnes. However, subject to the maximum annual investment limit of 13.00 million yuan, there are eight feasible solutions in the present stage. Therefore, the feasible solution set of newly added treatment capacity in stage 4 is $U_4 = \begin{Bmatrix} 0 & 0.70 & 0 & 0 & 0 & 0 & 0.70 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.70 & 0 & 0.70 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}$. Similar to the computation procedure in Table 5, the contribution function values and optimal objective function values can be calculated by $D_4(S_4, X_4) = [14.89, 14.89, 14, 89, 14.03, 14, 03, 14.16, 14, 16, 13.31]$ and $f_4^*(S_4) = 30.77$, respectively. The optimal strategy from stage 1 to stage 4 is to put projects 1 and 4 into operation at the beginning of stage 3 and add no new pollution treatment capacity at the beginning of stage 4.

(5) **Stage 5** ($k = 5$)

Since the longest construction period is four years, construction of all projects will be completed at the end of stage four. Therefore, the newly added treatment capacity can be any combination of capacity from the five completed projects in stage five. In other words, the newly added treatment capacity can be any combination of 0, 2.00, 3.40, 4.70, 3.10, and 2.70 million tonnes, subject to the maximum annual investment of 13.00 million yuan. There are 29 feasible solutions in the present stage, as shown in Fig. 3. Fig. 3 shows that the optimal objective function value is $f_5^*(S_5) = 42.71$. The optimal strategy is the newly added pollution treatment capacity of 0 at the beginning of stages 1, 2 and 3, 0.70 million tonnes in stage 4, and 4.70 million tonnes for pollutants 2 and 5. With this strategy, projects 2, 4 and 5 have the vacancy treatment capacity

Table 5
The feasible solutions of stage 3.

Variables	Feasible 1	Feasible 2	Feasible 3	Feasible 4*
Vacancy project	–	1	4	1, 4
Vacancy capacity $\left(\sum_j (s_{3j} - p_{3j})\right)$	0	34	40	74
Vacancy loss $\left(\sum_j LO_{3j}\right)$	0	22.6264	14.1438	36.7702
Types of substandard emissions	1, 2, 3, 4, 5	2, 3, 4, 5	1, 2, 3, 5	2, 3, 5
Substandard emissions $\left(\sum_j (p_{3j} - s_{3j})\right)$	346	310	316	280
Penalty $\left(\sum_j PN_{3j}\right)$	10.38	9.30	9.48	8.40
$D_3(S_3, X_3)$	10.38	95.26	96.58	88.04
$f_2(S_2)$	45.1	45.1	45.1	45.1
$f_3(S_3)$	14.89	14.03	14.16	13.31

* Denotes the best solution at the present stage.

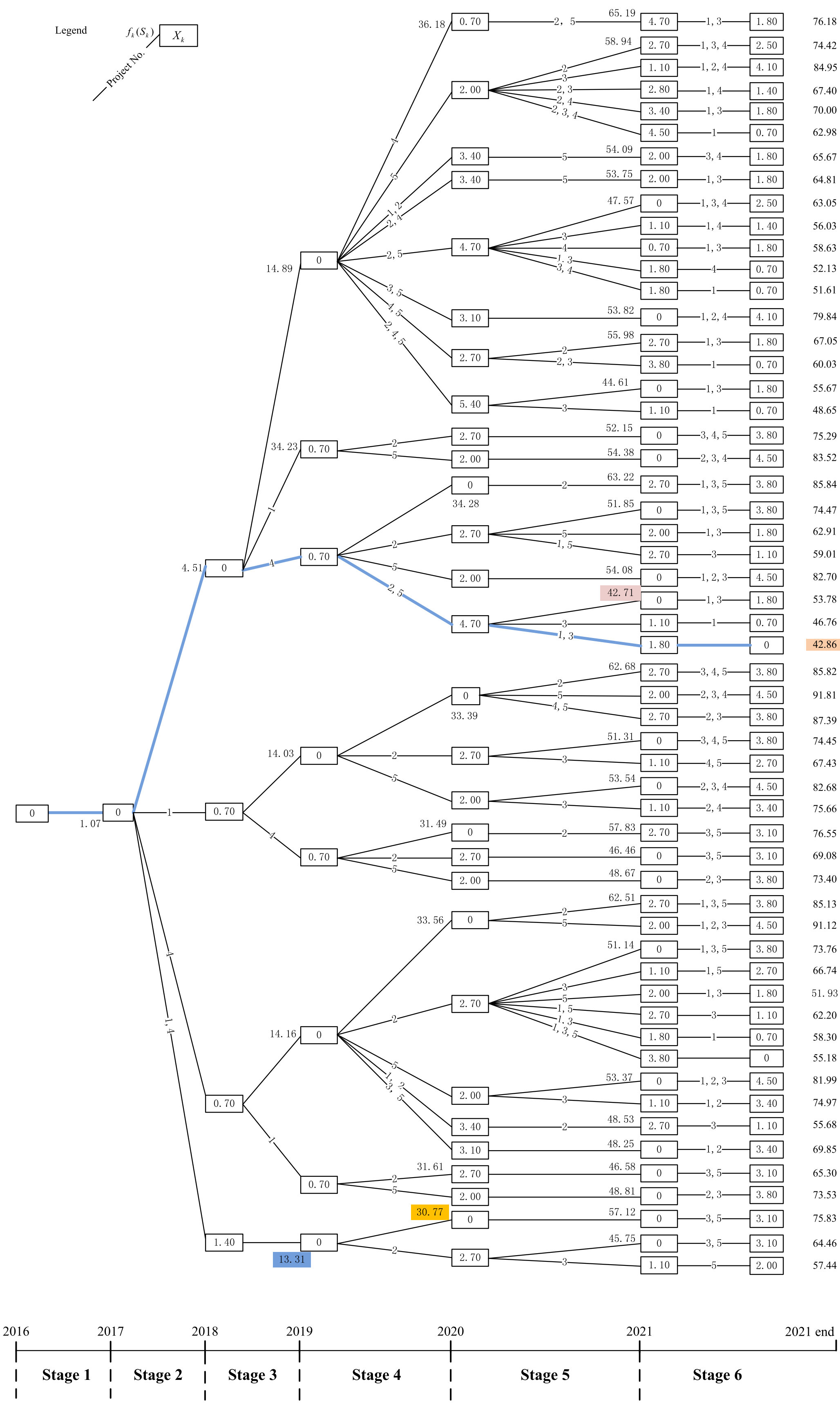

Fig. 3. Solution procedure of dynamic programming.

Table 6
The optimal investment decision-making.

	Investment (million yuan)					
	2016	2017	2018	2019	2020	2021
Project 1				3.50	4.00	
Project 2	5.10	3.20	1.80	1.80		
Project 3			4.00	3.70	4.80	
Project 4		2.50	2.50			
Project 5	7.10	6.50	3.20	4.00		
Total	12.2	12.2	11.5	13	8.8	0

with a total investment loss of 0.46 million yuan in the present stage. The total penalty for substandard pollution emissions is 7.95 million yuan.

(6) **Stage 6** ($k = 6$)

Similar to stage 5, construction of all projects can be completed at the beginning of stage 6. With the composition and financial constraints, there are 55 feasible solutions for stage 6 based on the combination of newly added capacity and investment capital constraint. The loss of each solution can be calculated by Eqs. (3)–(5), as shown in Fig. 3. Fig. 3 indicates that the minimal total loss is $f_6^*(S_7) = 42.86$ million yuan from stage 1 to stage 6. The vacancy loss is 0.73 million yuan while the penalty loss is 42.13 yuan. The optimal strategy of the present stage is to add a treatment capacity of 1.80 million tonnes for pollutants 2 and 6 in stage 6 based on the optimal policy in stage 5. In Fig. 3, the data on line or slash represents the project numbers of pollution disposal in the beginning of the present stage (project j); the data in the boxes is the new added treatment capacity at the end of the present stage (X_k); and the data beside the boxes gives the investment losses of pollution treatment in the present stage from the stage one ($f_k(S_k)$).

According to the optimal policy in stage 6, the optimal investment decision-making is listed in Table 6.

Table 6 indicates that coal mines should invest in project 1 in 2019, project 2 in 2016, project 3 in 2018, project 4 in 2017 and project 5 in 2016.

5. Conclusions

Investment in a pollution treatment project is a medium- to long-term strategic plan for coal mines. It involves many factors such as the amount of pollutants, the penalty cost for substandard emissions, projects' construction periods and capital constraints. How to make an optimal investment decision on pollution treatment projects is a very important issue in the clean-coal production process. The optimal strategy must minimize the economic losses caused by the mismatch between the pollutants and the treatment capacity of projects. Therefore, the present study proposed a dynamic programming model of pollution treatment project investment based on the pollutants in the coal production. The proposed model divided the complex multistage investment decision problem into a series of simple subproblems, and a forward recursive method was utilized to solve the model. A case study of the pollution treatment investment decision problem of the Laojuntang coal mine of Zhengzhou Coal Industry (Group) was implemented using the proposed model. The case study results show that the model is effective and is applicable for a typical Chinese coal mine environmental investment decision-making problem.

Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China under Grant (Nos. 71103016 and 71573236), the New Century Excellent Talents in University (No. NCET-12-0952), and the China University of Geosciences, Wuhan Takeoff Plan (No. CUG130505).

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