Survey of a Dynamic Programming Model for Environmental Investment Decision-Making in Coal Mining
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This survey relates to using dynamic optimization to solve for optimal capacity investment planning regarding the problem in the academic journal presented "A dynamic programming model for environmental investment decision-making in coal mining" by Siwei Gao, published in Applied Energy. Additionally, it should be acknowledged this survey report was produced for ISE 3210 (Nonlinear and Dynamic Optimization) at Ohio State University and is not meant for reproduction or publication.

Introduction

To protect the environments of coal mining areas, major coal producing countries such as China have issued law and regulations for the coal mining industry. Specifically, the Chinese government released al industry. For example, the Chinese government released the Emission Standard for Pollutants from the Coal Industry (GB 20426-2006) guidelines for coal miners to abide by. The major pollutants addressed are coal-bed methane, mine-water, fly-ash and dust, SO2, and coal gangue, as these present both safety hazards and severe environmental impact. The guidelines state all large coal companies should invest in prescribed pollution emission control projects to meet standards or coal companies will be fined or forced to shut down. These fines are called "penalty costs." Coal mines are needing to invest monetary capital in current pollution treatment projects such as environmental technologies or waste recycling utilization procedures through expanding pollution treatment capacity to avoid such penalties. Coal mines seek to make annual pollution treatment capacity expansion investments to minimize the total investment capital cost of these undertakings. Dynamic programming procedure can aid in finding a sequence of decisions regarding how much a coal mining company should increase pollution treatment capacity on an annual basis while minimizing investment capital cost and pollution penalty cost.

Optimal Annual Pollution Treatment Capacity: Dynamic Optimization Model Formulation

Zhengzhou Coal Industry (ZCI) is a coal mining company based in China; whose objective is considering optimal investment decision making in annual coal mine pollution treatment expansion over the next six years starting in 2016 while minimizing capital investment capital occupation and penalty costs on a present value basis. The decision also considers constraints regarding treatment capacity expansion limits and value constraints. Hence, a simplified discrete and deterministic dynamic programming procedure is implemented to find the optimal minimized costs and optimal decision-sequence of the pollution treatment investment problem using data form Laojuntang coal mine of Zhengzhou Coal Industry. Being a for-profit enterprise, coal miners such as ZCI must make appropriate decisions to minimize total costs on investments in pollution treatment projects. Additionally, the pollutants will be defined by index $\boldsymbol{j}$, where pollutant $\boldsymbol{j}$=1 for methane, $\boldsymbol{j}$=2 for mine-water, $\boldsymbol{j}$=3 for fly-ash and dust, $\boldsymbol{j}$=4 SO2, and $\boldsymbol{j}$=5 for coal gangue.

(1) Decision Stages:

The decision-making on investment in pollutant treatment capacity expansion has dynamic stages that the decisions, and state variables are represented by. The intervals of pollution treatment capacity expansion projects are on an annual basis, which divides the stages by years. The investment timeline is considered over six years from 2016 to 2021, so index $\boldsymbol{t}$ is represents a given stage for each given year, where:

$$\boldsymbol{t = 1, 2, 3, 4, 5, 6}$$

(2) State Variables:

The coal pollution investment cost is directly related to capacity of pollution $\boldsymbol{j}$ treatment in each stage which is an endogenous state variable. State variables concerning the estimated pollution emissions of pollutant $\boldsymbol{j}$ in metric tons in state $\boldsymbol{t}$ and penalty cost in USD ($) per metric tons of any pollutant $\boldsymbol{j}$ emission in metric tons at state $\boldsymbol{t}$ are exogenous information processes. Hence, the decision treatment capacity increase is influenced by state variables where: State variable, S_{tj} is the treatment capacity of pollutant j in metric tons at beginning of state t; State variable, E_{tj} is the estimated pollution emissions of pollutant j in metric tons in state t; State variable, P_t is the penalty cost in USD ($) per metric tons of any pollutant j emission in at state t.

(3) Parameters:

Within this specific simplified problem, concerning the ZCI coal plant, there are two parameters in consideration. First, as cost is being evaluated in present state, r, is the discount rate which is held constant for all the stages or years in consideration. Thereafter, the total investment cost in each stage or specified year is based off the pollutant in consideration, j ,investment cost per newly added treatment capacity in metric tons, denoted as I_j Table 1 conveys this information for each pollutant type in USD.

Table 1

Actual project investment per newly added treatment capacity (thousands of $/metric ton).

Polluntant (j)	1	2	3	4	5
Investment	$16,492.98	$7,413.37	$17,989.78	$11,014.15	$17,326.10

(4) Decision:

The decision to be made for each stage or year in consideration is the value of increase in pollutant j 's treatment capacity in metric tons. This decision is made with the purpose of keeping coal pollution penalty and treatment capacity expansion costs to the minimum. The newly added treatment capacity decision variable is denoted as X_{tj} or the increase in treatment capacity of pollutant j in metric tons for each state t.

(5) State-Transition Functions:

The primary transformation applied to the state variables is to state variable, S_{tj} is the treatment capacity of pollutant j in metric tons at beginning of state t, as the state variable is classified as endogenous information. The state-transition function is represented by Eq. (1).

$$S_{t+1,j} = S_{t,j} + X_{t,j} \qquad (1)$$

Additionally, the state variable S_{tj}, values for stage 1 or the present treatment capacity in metric tons of the five types of pollutants is $S_{11} = 0.40$, $S_{12} = 0.70$, $S_{13} = 0.80$, $S_{14} = 0.20$, $S_{15} = 1.00$. The exogenous state variable, E_{tj} , value changes according to Table 2, while state variable, P_t , value changes according to Table 3.

Table 2

All estimated pollution emissions in the future (unit: metric ton)).

	2016 (t=1)	2017 (t=2)	2018 (t=3)	2019 (t=4)	2020 (t=5)	2021 (t=6)
Coal-bed methane (j=1)	0.47	0.63	0.76	0.85	0.9	1.05
Mine Water (j=2)	1	1.4	1.8	2.2	2.9	3.5
Fly-ash and dust (j=3)	1	1.2	1.4	1.55	1.65	1.78
SO_2 (j=4)	0.3	0.41	0.5	0.63	0.75	0.88
Gangue (j=5)	1.4	1.75	2.1	2.45	2.7	2.9

Table 3

Penalty per pollution emission.

	2016 (t=1)	2017 (t=2)	2018 (t=3)	2019 (t=4)	2020 (t=5)	2021 (t=6)
Penaty (thousands of $/metric tons	$ 1,412.09	$ 2,118.14	$ 4,236.27	$ 6,636.82	$ 7,766.50	$9,178.59

(6) Objective Contribution Function:

The objective contribution function provides the total investment cost value at stage t given the pollutant, state variable, parameters, decision variables, and current stage values. The total investment cost value is represented by $\boldsymbol{D_{tj}(S_{tj}, X_{tj}, P_t, E_{tj}, r, I_j)}$, as shown in Eq. (2).

$$D_{tj}(S_{tj}, X_{tj}, P_t, E_{tj}, r, I_j) = \frac{LO_{tj}+PN_{tj}}{(1+r)^t} \quad (2)$$

Where $\mathbf{LO_{tj}}$ and $\mathbf{PN_{tj}}$ are present value of the pollutant capacity expansion investment or capital occupation cost and penalty cost of pollution, respectively.

$$LO_{tj}(X_{tj}, I_j) = I_j * X_{t,j} \quad (3)$$

$$P_{tj}(S_{tj}, P_t, E_{tj}) = (E_{t,j} - S_{tj}) * P_{tj} \quad (4)$$

(7) Constraints:

Specially, due to annual construction capabilities and cash flow requirements, maximum pollution treatment capacity expansion can only increase by 25% from previous year to build in time. Additionally, the decision for each stage or the value of increase in pollutant j 's treatment capacity in metric tons can only be changed in units of 0.05 metric tons to simply the model for discrete decisions. Finally, as state variable, S_{tj} or the treatment capacity of pollutant j in metric tons at beginning of state t, can only increase stage to stage. This would imply X_{tj} is always non-negative. These constraints are represented by the following series of statements:

$$\frac{X_{t,j}}{0.05} \in \{0, 1\}, \ S_{t,j} + X_{t,j} \geq S_{t,j}, \ (0.25) * S_{t,j} \leq X_{t,j}$$

Solution

The above formulation of the coal mining pollutant treatment capacity expansion at the ZCI coal plant was solved using the dynamic programming backwards-then-forward recursion algorithm. This algorithm was developed with the above dynamic optimization application in a MATLAB procedure. The solution was solved five time for each pollutant j and its corresponding data. Table 4 conveys the optimal decision sequence per the solution to the formulation, while Table 5 show the associated costs.

Table 4

Pollutant treatment capacity expansion amount (unit: metric ton)).

	2016 (t=1)	2017 (t=2)	2018 (t=3)	2019 (t=4)	2020 (t=5)	2021 (t=6)
Coal-bed methane (j=1)	0.1	0.1	0.15	0	0	0
Mine Water (j=2)	0.15	0.2	0.25	0.3	0.4	0
Fly-ash and dust (j=3)	0.2	0.25	0.3	0	0	0
SO_2 (j=4)	0.05	0.05	0.05	0.05	0	0
Gangue (j=5)	0.25	0.3	0.35	0	0	0

Table 5

Pollutant treatment capacity expansion investment costs (unit: thousands of USD/$)).

	2016 (t=1)	2017 (t=2)	2018 (t=3)	2019 (t=4)	2020 (t=5)	2021 (t=6)	TOTAL
Coal-bed methane (j=1)	$ 1,672.86	$ 1,762.47	$ 2,761.87	$ 556.54	$ 934.84	$ 2,114.46	$ 9,803.03
Mine Water (j=2)	$ 1,469.50	$ 2,424.53	$ 4,408.25	$ 6,873.81	$ 10,481.45	$ 10,572.30	$ 36,229.85
Fly-ash and dust (j=3)	$ 3,713.28	$ 4,506.37	$ 5,286.15	$ -	$ 623.22	$ 1,621.09	$ 15,750.11
SO_2 (j=4)	$ 662.12	$ 814.64	$ 1,225.03	$ 2,020.11	$ 2,181.28	$ 3,383.14	$ 10,286.32
Gangue (j=5)	$ 4,685.51	$ 5,729.63	$ 7,355.71	$ 3,060.96	$ 4,985.79	$ 7,048.20	$ 32,865.80
TOTAL	$ 12,203.28	$ 15,237.65	$ 21,037.00	$ 12,511.42	$ 19,206.58	$ 24,739.18	***$ 104,935.11***

Conclusion

Investment in a pollution treatment capacity is a medium-to long-term plan for coal mines, involving many factors such as the amount of pollutants, the penalty cost for emissions, and capital development costs. Through the above case-study, the overall optimal objective function value of the formulation or total investment cost to expand pollution treatment capacity is $104.93511 million dollars. With the optimal decision policy made according to Table 4.

References

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Furthermore, the MATLAB dynamic programming model of the problem described is attached to the submission for solving the solution of the dynamic optimization problem formulation.

About Author

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