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Efficiency evaluation of emergency resource allocation for urban gas pipeline leakage accidents based on DEA

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In the daily operation of city gas pipelines, due to the characteristics of the gas itself and the influence of the environment in which the pipeline is located, leakage accidents are prone to occur and cause serious consequences. When the gas pipeline leaks, the accident is handled according to the emergency plan, and the emergency resources are an important part of the emergency plan, and the complete emergency resources can well reduce the maintenance time, thereby reducing the economic losses caused by the leakage accident. In order to improve the utilization rate of emergency resources for urban gas pipeline leakage accidents, reduce their redundancy, and improve the efficiency of emergency repair. The purpose of this study is to evaluate the efficiency of emergency resource allocation for third-party damage leakage accidents in city gas pipelines by combining DEA models. Through the analysis of the efficiency values, the under-investment or redundancy of each gas company's resource allocation is found, and corresponding suggestions are made to improve the gas company's emergency response capability for gas leakage accidents and to provide a reference basis for the emergency resource allocation for urban gas pipeline leakage accidents.

Keywords: gas leakage accident, emergency repair, resource allocation, digital envelope analysis, efficiency evaluation, Configuration optimization.

1. Introduction

Gas pipelines are in a complex environment all year round, and the combination of multiple factors such as hidden gas facilities, urban construction interference, and threats of geological hazards, as well as the flammable and explosive nature of gas and its easy proliferation, can easily lead to major safety accidents. In China, for example, according to gas company statistics, there were 43 incidents in June 2022, and third-party damage caused 44% of the leaks where the cause of the leak was confirmed. A reasonable allocation of emergency resources not only supports emergency repairs after a gas pipeline leak, but also allows emergency equipment to be used without waste.

In the past, in terms of emergency resource allocation preparation for gas pipeline leaks, emergency resource allocation always resulted in the over allocation of a single piece of equipment that was idle or failed to replace in order to guarantee response to various causes of gas pipeline leaks. It causes waste of resources and increases the consumption of resource allocation. Sometimes the final maintenance and repair time is extended due to equipment damage or lack of necessary maintenance and repair equipment. In a community where the timeliness of gas incident response is extremely high, the inability to deploy the appropriate repair equipment in a timely manner will cause inconvenience to residents' schedules and even lead to leaks that turn into explosions that cause incalculable harm to community residents. Therefore, a reasonable allocation of emergency resources can bring greater economic benefits.

In 2012, the first evaluation of water emergency resource allocation efficiency using DEA method.HE D(2012). Iribarren(2015) developed a method for selecting building components based on eco-efficiency by calculating the efficiency of each building component's environmental impact through a DEA model in the process of selecting specific building components. Goksen(2015) used the DEA method to determine the performance levels of the university's faculties, discussed the skill scores and size scores of each department, and analyzed the causes of inefficiencies. López and Cacheda (2018) used the DEA approach to evaluate the efficiency of toll roads using the BBC model and the CCR model, respectively, to identify the causes of inefficiencies and thus increase efficiency. Miao et al. (2020) used DEA model to evaluate the safety management efficiency of 14 listed coal companies, analyzed the reasons that hinder the improvement of safety management efficiency, and provided suggestions for improving safety management efficiency. Li and Ran(2018) conclude that the safety efficiency of coal companies is generally low by assessing 19 coal companies in 2016. Liu et al.(2023) construct a hybrid DEA-BP neural network driven model considering safety management efficiency for coal company evaluation and prediction

However, there is a lack of research on emergency repair resource allocation for gas leakage accidents caused by third-party damage, so this paper evaluates the efficiency of emergency resource allocation for gas companies by pre-processing output indicators combined with an efficiency evaluation model (DEA model) to solve the problem of not being able to use sample data directly for efficiency evaluation. Optimization recommendations are made based on the evaluation results, thus optimizing resource allocation.

2. Research Methodology

2.1.*The DEA Model*

Charnes et al (1978) proposed the data envelopment analysis method (DEA model), which is commonly used to measure the relative efficiency of a given set of operational entities. DEA model is a nonparametric model to evaluate the technical efficiency of multiple input and multiple output decision-making units. It includes CCR model and BCC model. WEI G W and WANG J M.(2017).

A pool of n gas leak repair emergency resources of the same nature is provided, called n decision units.

Each decision unit D_j ($1 \leqslant j \leqslant n$) consists of m input indicators and s output indicators. The vectors of input and output indicators for any decision cell D_j are denoted as x_j, y_j, respectively. (see Eq(1) and Eq(2)) .

$$\boldsymbol{x}_j = \left(x_{1j}, x_{2j}, \cdots, x_{ij}, \cdots x_{mj}\right)^{\mathrm{T}} 1 \leqslant j \leqslant n, 1 \leqslant i \leqslant m \tag{1}$$

$$\boldsymbol{y}_j = \left(y_{1j}, y_{2j}, \cdots, y_{rj}, \cdots y_{sj}\right)^{\mathrm{T}} 1 \leqslant j \leqslant n, 1 \leqslant r \leqslant s \tag{2}$$

$$h_j = \frac{u_1 y_{1j} + u_2 y_{2j} + \cdots + u_s y_{sj}}{v_1 x_{1j} + v_2 x_{2j} + \cdots + v_m x_{mj}} = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} j = 1,2,\cdots,n \quad (3)$$

where x_j and y_j denote the input and output indicator vectors of the j-th decision unit, respectively, and x_{ij} and y_{rj} denote the i-th input and r-th output of the j-th decision unit, respectively.

For each decision unit j, the expression for calculating its efficiency is h_j.. v_m and u_s are the weights of the input and output indicators, respectively. Taking v and u such that $hj \leq 1$. (see Eq(3)).

If the efficiency of any one decision unit j is the target and the efficiency of all decision units is the constraint,The following CCR fractional planning model can be developed. (see Eq(4)). López and Cacheda (2018).

To facilitate the solution, the Charness-Coomer transformation is applied,and introduce the relaxation variable s^+,the residual variable s^- and a non-Archimedean infinitesimal,convert the CCR fractional planning to the following equivalent pairwise planning model. (see Eq(5)).Jiang et al. (2022).

θ is the resource allocation efficiency of gas leak repair emergency,λj is the weighting factor. x_0 and y_0 are the input and output index values of the evaluated DMU, respectively. Let the optimal solution of the above pairwise programming model be θ^*、s^{+*}、s^{-*}、λ^*， then there are 3 cases as follows:

i）If $\theta^*=1$ and $s^{+*}=s^{-*}=0$， then the decision cell D_j is valid under the DEA model. That is, the resource allocation is reasonable and there is no need to optimize emergency resource allocation;

ii）If $\theta^*=1$， but at least 1 of s^{+*} and s^{-*} is greater than 0, then the decision cell D_j is weakly valid under the DEA model. Represents that although the resources are well allocated, there are still some resources that can be optimized for suggestions.

iii）If $\theta^*<1$， then the decision unit D_j non-DEA is valid. It means that the resource allocation in this case is not reasonable, and the resource allocation plan should be adjusted according to the calculation results.

$$(C^2\mathrm{R}) \begin{cases} max h_j = \dfrac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \\ \text{s. t. } \dfrac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leqslant 1, \ j = 1,2,\cdots,n \\ u_r \geqslant 0, \ r = 1,2,\cdots,s \\ v_i \geqslant 0, \ i = 1,2,\cdots,m \end{cases} \quad (4)$$

$$
(D)\begin{cases} min\left[\theta-\varepsilon\left(\sum_{i=1}^{m} s^{+}+\sum_{r=1}^{s} s^{-}\right)\right] \\ \text{s.t.} \sum_{j=1}^{n} x_{ij}\lambda_j + s^{+} = \theta x_0, \ i=1,2,\cdots,m \\ \sum_{j=1}^{n} y_{rj}\lambda_j - s^{-} = y_{0,} \ r=1,2,\cdots,s \\ \lambda_j \geqslant 0, \ j=1,2,\cdots,n \\ s^{+}\geqslant 0, s^{-}\geqslant 0 \\ \theta \text{ Unbound} \end{cases} \tag{5}
$$

Table 1. Evaluation index system of resource allocation efficiency for emergency repair of gas leakage accidents.

Classification of indicators	Tier 1 Indicator	Secondary indicators
Input Indicators	Emergency repair equipment	Number of base equipment
		Number of personal protective equipment
		Number of emergency repair equipment
Output Indicators	Repair remaining time	Maintenance time(h)
	Maintenance completion	Maintenance completion rate

2.2.Gas leak repair emergency resource evaluation system construction

Emergency resources is the general term for all resources that can be dispatched quickly in a short period of time in the disposal of emergencies, and the guaranteed resources necessary for the effective control of the development of emergencies and their reduction. The types of materials included in emergency resources often vary depending on the type of emergency, and in a broad sense, they are mainly divided into various forms of existence such as personnel, materials, funds and information. The emergency resources evaluated here mainly include all tools to support the repair of gas pipeline leaks in the community.

Due to the complexity of gas repair equipment, emergency repair equipment is divided into basic equipment, personal protective equipment, and repair equipment according to the characteristics of the repair equipment. Basic equipment is mainly used for basic technical security, including command vehicles, warning equipment, lighting equipment, etc. ; personal protection equipment mainly includes helmets, safety belts, safety undershirts and other equipment used to protect the personal safety of construction personnel; emergency repair equipment is generally used directly for the repair of leaking pipelines, mainly including leak detection equipment, operating equipment, etc. The number of emergency repair equipment is used as an input indicator. The remaining repair time is the difference between 24 hours and the repair time, and the remaining repair time and the repair equipment integrity rate are used as output indicators. The remaining time of repair and the rate of repair equipment integrity are used as output indicators. (see Table 1).

3. Model Applications

3.1.*Data Selection*

Taking the emergency repair equipment of a Beijing gas company as an example, the emergency repair resources owned by its head office and four branches are used as input indicators, while the output indicators are mainly obtained by means of on-site research and expert consultation. Decision-making units D1-D5 represent the head office and the first branch, the second branch, the third branch, and the fourth branch, respectively. (see Table 2).

3.2. *Data Processing*

In the output indicator, the longer maintenance time represents the more inadequate emergency resource allocation, so the maintenance length cannot directly represent the maintenance effectiveness. The length of maintenance in the output indicator is reverse intervalized. Make its range belongs to [1, 24]. (see Eq(6)).

$$Y = a + (b - a) * \frac{Y_{max} - Y_i}{Y_{max} - Y_{min}} \quad (6)$$

Y_{max} is the maximum value of maintenance hours in each decision unit and Y_{min} is the minimum value of total hours in each decision unit. a has a value of 1 and b has a value of 24.

The repair completion rate is estimated by a combination of expert scoring and repair reports, resulting in a repair rate value (%). The more emergency resources missing from the repair process and the less effective the repair, the lower the corresponding repair rate value will be. The effect of maintenance is mainly reflected in the timeliness and completeness of maintenance, so in the model, the repair time and maintenance effect are used as the first-level indicators, and the output secondary indicators are set as the total repair time and repair completion rate after processing, which are recorded as y_i. Use the number of hours of maintenance after treatment as an output indicator. (see Table 3).

3.3.*Evaluation results*

With the efficiency of the first decision unit D1 as the objective and the efficiency of all decision units as the constraint, the raw data of inputs and outputs in Table 2 are substituted into Eq(4) and a linear programming dyadic model as in Eq (5) is established. (see Eq(7) and Eq(8)).

Table 2. Input-output raw data.

DMU	Input Indicators			Output Indicators	
	Number of base equipment	Number of personal protective equipment	Number of emergency repair equipment	Repair time (h)	Repair efficiency (%)
D1	182	70	357	10	100
D2	231	60	131	17	95
D3	150	70	194	14	90
D4	126	30	119	16	90
D5	129	60	236	20	80

Table 3. Results for output indicator Y1 after reverse intervalization.

DMU	Raw data	Processed data
D1	10	24
D2	17	7.9
D3	14	14.8
D4	16	10.2
D5	20	1

$$min[\theta - 0.000001(s_1^- + s_2^- + s_3^- + s_1^+ + s_2^+)] \quad (7)$$

$$
\text{s.t.}\begin{cases}182\lambda_1+231\lambda_2+150\lambda_3+126\lambda_4+129\lambda_5+s_1^-=182\theta\\ 70\lambda_1+60\lambda_2+70\lambda_3+30\lambda_4+60\lambda_5+s_2^-=70\theta\\ 357\lambda_1+131\lambda_2+194\lambda_3+119\lambda_4+236\lambda_5+s_3^-=357\theta\\ 24\lambda_1+7.9\lambda_2+14.8\lambda_3+10.2\lambda_4+\lambda_5-s_1^+=24\\ 100\lambda_1+95\lambda_2+90\lambda_3+90\lambda_4+80\lambda_5-s_2^+=100\\ \lambda_j\geq 0,\ j=1,\ 2\ldots,\ 5;\ s_1^-,\ s_2^-,\ s_3^-,\ s_1^+,\ s_2^+\geq 0\end{cases} \quad (8)
$$

The combined efficiency θ of D1, as well as the input redundancy s_1^-、s_2^-、s_3^- and the output deficiency s_1^+、s_2^+, were calculated by LINGO auxiliary software, and the results are shown in Table 4. (see Table 4).

According to the above method, the original data of the remaining decision units are substituted to obtain the resource allocation efficiency θ of the remaining four gas leak rescue emergency resource pools, as well as the input redundancy s_1^-、s_2^-、s_3^- and output deficiency s_1^+、s_2^+, and the results are shown in Table 5. (see Table 5).

3.4. *Analysis of results*

According to the calculation results of DEA model, the minimum value of emergency repair resource allocation efficiency of all companies is 0.868 and the maximum value is 1. And θ(D1)=θ(D3)=θ(D4)>θ(D2)>θ(D5). The θ=1 for D1, D3 and D4 decision units indicates that the emergency repair resource allocation of the head office and the second and third branch companies is at a reasonable level and has reached DEA validity, and no change is needed in the existing resource allocation.

Table 4. D1's resource allocation efficiency for emergency repair of gas leaks

Decision-making unit	s_1^-	s_2^-	s_3^-	s_1^+	s_2^+	θ
D1	0	0	0	0	0	1

Table 5. Efficiency of resource allocation for emergency repair of gas leaks

DMU	θ	s1-	s2-	s3-	s1+	s2+
D1	1	0	0	0	0	0
D2	0.959	88.497	25.865	0	2.867	0
D3	1	0	0	0	0	0
D4	1	0	0	0	0	0
D5	0.868	0	25.426	99.121	8.067	0

Decision units D2 and D5 are DEA non-effective, and the main reason is still the existence of both input redundancy or output insufficiency, which requires optimization of resource allocation.

Inputs:The s_1^- value of D2 is 88.497,which means that the number of infrastructure inputs in the first branch is too much or the utilization rate is low ; The s_2^- values of D2, and D5 are 25.865 and 25.426, representing the excessive number of personal protective equipment input or low utilization rate of the first branch and the fourth branch; The s_3^- value of D5 is 99.121 , representing the excessive quantity or low utilization rate of the emergency repair equipment of the fourth branch. The resource input should be reduced appropriately according to the situation, or the resource utilization rate should be improved by improving the emergency repair plan to reduce the redundancy of emergency resources.

Outputs: Outputs: s_1^+ values of 2.867 and 8.067 for D2 and D5, i.e., representing inadequate resource allocation or failure of emergency repair personnel to carry out the correct repair plan during the repair process in the first and fourth branches, resulting in the extension of the repair time.

4. Conclusion

By constructing a gas leak resource evaluation system, pre-processing the data of output indicators, and calculating the branch emergency resource allocation efficiency of gas companies in combination with the DEA model, it solves the problem that the data extracted directly from the database cannot be directly applied in the evaluation of the DEA model, and can obtain the reasonable situation of resource allocation efficiency, input redundancy and output deficiency of each company, and make corresponding suggestions to the emergency resource allocation of gas companies according to the results, so as to improve the utilization rate of emergency repair resources, reduce the economic loss caused by excess resources, increase the efficiency of gas leak accident repair, and guarantee the normal operation of the gas system.

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