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Evaluating investment strategies for distribution networks based on yardstick competition and DEA

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ABSTRACT

The traditional investment for distribution networks is mainly evaluated and conducted from the static perspective. A dynamic comprehensive evaluation method is essential to obtain an efficient investment strategy. Firstly, a hierarchical evaluation index system is constructed to describe the overall performance of the distribution network, which includes six types of criteria such as information level, power supply capacity, asset utilization efficiency and economy, power supply quality and loss, power supply reliability, and sustainable development level. Each criterion is composed of input and output indicators. Then, using projection pursuit method considering subjective weight constraints, a combined weight optimization model is proposed to calculate the weight vector of each criterion. Furthermore, the data envelopment analysis (DEA) based dynamic evaluation approach is set up to compute the investment efficiency defined as ratio of output and input. The time degree theory is also introduced to realize dynamic evaluation. Via yardstick competition among multiple regions and "reward and punishment" rule, a precise investment planning strategy can be achieved while minimizing construction cost and maximizing efficiency of the resource allocation. The numerical results on a practical 10-region distribution system in four planning cycles verify the effectiveness of the proposed method.

1. Introduction

With the accelerating growth of electricity usage in modern times, the distribution network, playing a significant role in guaranteeing high quality and reliability of power supply for customers, has faced serious challenges. It is a sophisticated and enormous project for distribution networks to achieve precise investment planning [1]. Currently, it is a fact that automation reform of the distribution network is still in its infancy. Meanwhile, the investment scale of the distribution network is gigantic and shows an increasing trend year by year in China. Such being the case, there is no doubt that evaluating the overall investment efficiency comprehensively and scientifically is beneficial to efficaciously avoid deficiency of construction, to strike a balance between technology and economy in the distribution network [2].

In recent years, significant research efforts have been devoted to the optimal investment of modern power distribution systems. A multi-objective optimization considering reliability and costs as two objective functions has been presented in Ref. [3] to make investment strategy for multi-stage smart distribution network expansion planning. Although applying of the proposed model has shown a significant improvement in the area of distribution network planning, contemporary expansion of power system and information infrastructures weren't considered. Mokryani. G [4] proposed a probabilistic method for active distribution networks (ADN) investment planning with integration of demand response (DR), aiming at simultaneously minimizing the total investment cost and total energy losses of the lines from the point of view of distribution system operators (DSOs). In Ref. [5], regarding DR as virtual distributed resources to cover the effect of uncertain parameters, an aggregated model for planning and reconfiguration of ADN has been proposed, where a bi-level optimization procedure is developed to solve the proposed model. Zeng and Feng [6] presented an optimal integrated investment strategy for supporting growing penetration of electric vehicles in distribution systems. In Ref. [7], by minimizing the total investment and operational costs, a multi-stage expansion planning is proposed to consider dynamic behavior of the system parameters asset management and geographical constraints.

The designer of distribution networks, in the context of making investment strategies and planning schemes in distribution networks, has a primary goal to design the distribution system such as to timely meet the demand growth in the most economical, reliable, and safe way [8]. This is not straightforward, because of the very large extension of the power distribution system, as well as the fact that the evaluation of investment strategies for distribution networks is a complex and comprehensive problem, involving multiple objects, multiple indicators and

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multiple periods. As there exits many differences for diverse regional distribution networks in the aspects of structural characteristic, vulnerable segment and operational mode, construction goals of multiple regional distribution network actually are distinct. Therefore, how to effectively improve the fitness and flexibility of evaluation method is challenging for system operator (SO), particularly when the uncertainties of renewable energies and load demand are considered.

Currently, the evaluation method research of investment planning in distribution networks has been extensively investigated so far. In Ref. [9], the power grid construction investment strategy is evaluated from the low-carbon point of view, a comprehensive and refined index system is designed in consideration of different aspects of coverage, and the subjective and objective weights are determined by the G-1 method and the entropy weight method respectively. Combining with fuzzy analytical hierarchy process (AHP), Mu [10] has presented a multi-operator fuzzy analytical hierarchy evaluation model to evaluate power grid security and benefit. In Ref. [11], the combination of analytical hierarchy process and entropy weight, in which the subjective features and objective features are combined, is taken as the calculation method to evaluate the weights of the evaluation index system, the investment strategy of electric power and energy balance is synthetically evaluated. In addition, there are also studies to carry out valuable evaluation work for the actual operation of the power grid, such as real-time operation status evaluation of the power grid [12], evaluation of dispatch operation planning scheme [13], and daily dispatch operation evaluation [14].

As is mentioned above, a majority of existing research focuses on certain aspects of the power industry, but fails to establish a system that comprehensively evaluates the overall performance of power grid development from multiple perspectives; In terms of evaluation objects, most studies rely on the data of a certain region or a certain year for analysis and evaluation, the unified modeling of time and space factors cannot be realized, and the methods and conclusions cannot be applied to the evaluation of multiple spatial and temporal dimensions. Moreover, as for evaluation methods, although several researchers attempt to combine subjective and objective methods in order to circumvent their respective shortcomings, but the combined methods used are mostly simple weighting methods. These methods can avoid the evaluation results from relying too much on subjective factors or objective factors to some extent, but it will also obscure their respective characteristics and advantages.

Given that investment planning in distribution network is a dynamic rolling process and appears enormous regional difference, it is conceivable that the accuracy of investment strategy and planning scheme will directly affect reformation efficiency. Consequently, distinct from existing studies, this paper presents a dynamic yardstick evaluation method involving DEA of investment strategy in distribution networks. Hereinto, DEA is a technique for measuring the relative efficiency of a set of decision making units (DMUs) which apply multiple inputs to produce multiple outputs in a period of time. For the last two decades, the DEA analytical framework has been widely applied in the electricity distribution field (see Mardani et al. [15], Oskuee et al. [16], Gouveia [17], Aydın [18], Gustavo [19], Arcos-Vargas [20]). However, this research studies are usually devised to measure the technical and total efficiencies of DMUs over a certain period of time in a static manner. It is therefore worthwhile to build a dynamic DEA model to analyse investment efficiency.

Additionally, in the typical regulatory scheme, a franchised monopoly has little incentive to reduce costs. And since the regulator is unlikely to know what the appropriate cost level should be, he can rarely argue that the firm is run inefficiently. To assure cost control, prevent waste, and promote cost-reducing innovation, a regulatory scheme “yardstick competition” was proposed [21]. This scheme suggests comparing similar or identical regulated firms with each other. For any given firm, the regulator uses the costs of comparable firms to infer a firm's attainable cost level. At present, the yardstick regulation is prevalent in the aspects of electricity price regulation [22], frequency regulation services [23], and service quality regulation [24]. By the same token, the yardstick competition theory has also been applied in the investment for distribution networks around the world (see Tanure [25], Huang.Y [26], Emili [27], Ter-Martirosyan [28], Rondi [29], Zhang [30]). Distribution systems are inherent monopolies and therefore they have generally been regulated to protect customers and to ensure cost-effective operation. Yardstick competition works because it does decrease credibly the inefficient cost choices of distribution companies and achieve cost reduction. Taking approximate distribution companies in different regions as the research object, the proposed method judges the precision of investment strategy in distribution networks from spatial and temporal dimensions via comparative evaluation in the diverse regions. Afterwards, we regard high-efficient regions as benchmark, and then, investment efficiency of other regions will be determined with reference to benchmark regions. This pattern of benchmarking is generally considered superior to other regulatory regimes because it provides the regulated companies with strong efficiency improvement incentives and the regulator places fewer restrictions on the companies [27]. By this way, evaluation results can objectively reflect the investment efficiency of the distribution network so that it can scientifically provide guidance for accurate investment in the distribution network.

Specifically, the main contributions of this paper are detailed in the following:

1) A relatively complete and comprehensive “inputs-outputs” evaluation index system is established, covering the technical and economic characteristics of planning in distribution networks. Correspondingly, its investment efficiency is confirmed by the relationship between “actual inputs” and “effective outputs” for certain criterion.
2) In order to determine the weight vector of each criterion, an improved projection pursuit model considering subjective weight constraints is recommended. With the combination of subjective and objective evaluation, the decision makers can flexibly allocate the weight vector of each criterion according to the distribution network construction goals in different time and space dimensions.
3) Taking several similar regional distribution networks as the research objective and citing the concept of “yardstick competition”, this paper presents a yardstick evaluation model on the basis of DEA for investment strategy in distribution networks.
4) The time degree theory and least variance priority method are applied to calculate the dynamic weight vector, so as to achieve the dynamic weighted evaluation of static evaluation values in each planning cycle of distribution networks.

Since many schemes are applied within the algorithm, Fig. 1 is presented to visualize and classify the relevant modelling methods in spatial and time dimension. Furthermore, the remainder of the paper is organized as follows: Section 2 elaborates the hierarchical evaluation index system that is constructed to describe the overall performance of the distribution network. The detailed formulation of dynamic yardstick evaluation method for investment planning in distribution networks is presented in Section 3. Numerical computational results and analysis on a practical 10-region test system in 4 planning cycles (from year 2008 to 2016, the evaluation of investment strategies was executed at the end of every planning cycle such as year 2010, 2012, 2014, 2016) are carried out in Section 4. Finally, conclusions are drawn in Section 5, with the analysis of development characteristics and differences in several regional distribution networks, it is out of question to provide accurate reference for the regional distribution network investment.

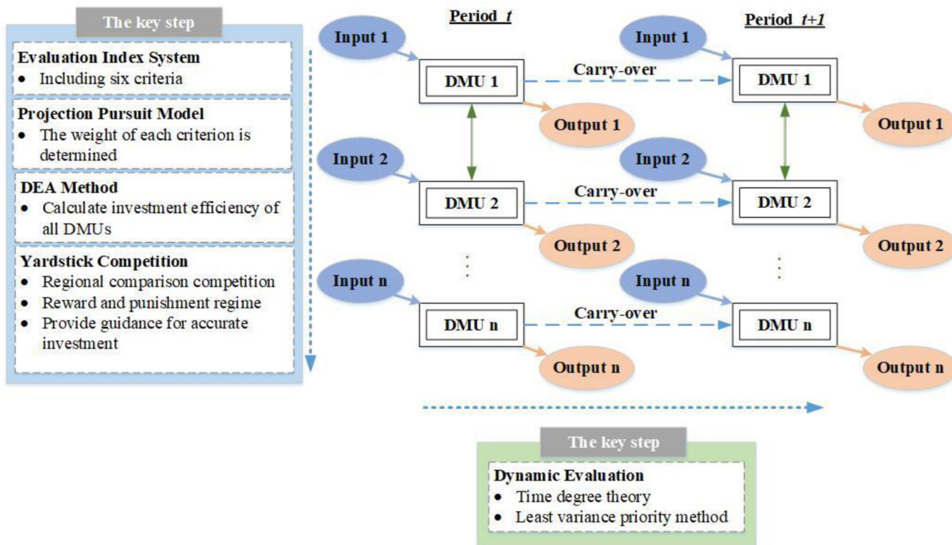

Fig. 1. A technical figure to visualise and classify the relevant modelling methods.

2. Hierarchical evaluation index system of investment strategies in distribution networks

In a broad sense, investment planning refers to an ex-ante and positive paradigm for the management of distribution network. Over the past decades, a variety of precise investment options have been deployed in the demonstration projects. Gradually, the key of investment strategy stands out and construction standard of distribution network comes into being.

Generally, the input indicators of investment mainly composed of various devices procurement and reformation such as smart electricity meter, remote terminal unit, transformer, fiber, cable and so on. The positive correlation holds in the output and input indicators correspondingly. In this regard, some practical data statistical analysis tools will be applied to acquire their relationship.

Given these idiosyncratic characters of investment planning in distribution networks, a comprehensive evaluation index system of investment strategies is summarized to assess the investment efficiency, including six types of criteria such as information level, power supply capacity, asset utilization efficiency and economy, power supply quality and loss, power supply reliability, and sustainable development.

Furthermore, we take the relative investment efficiency as overall objective, six criteria as the middle layer, and homologous indicators as the sublayer of each criterion, the hierarchical "object-criteria-indicator" model can be established to evaluate the precision of investment planning in distribution networks. Fig. 2 shows a hierarchical structure for assessing distribution investment.

To seize the relation in the indicator layer, this paper adopts the DEA method, whose basic idea is dividing the evaluation indicators into "input indicators" and "output indicators". Once the ratio between "output indicators" and "input indicators" has been identified, the DEA evaluation value is determined. It should be noted that the "input indicators" refer to the investment of distribution networks, the "output indicators" represent the effective outputs. Table 1 shows the inputs and outputs of each criterion.

3. Dynamic yardstick evaluation method for investment strategies in distribution networks

3.1. An improved projection pursuit model considering subjective weight constraints

Optimal investment strategy in distribution networks is currently conducted to achieve a large number of improvements such as upgrading the information level of distribution network, improving the power supply quality and capacity, optimizing asset utilization efficiency, enhancing the power supply reliability and promoting sustainable development level. Hence, it is apparent that the dynamic evaluation of investment strategies in distribution networks is a typical study involving multiple indicators and cross-disciplinary perspective. Particularly, one of the key issues in the evaluation method is how to confirm the weight of each criterion. To deal with this problem efficaciously, mathematical analysis methodology will be a favourable auxiliary tool.

At present, subjective decision making method is one of the most prevalent methods, but it may result in different decisions about the same object due to the dissimilarities of the decision experts in the aspects of knowledge backgrounds and experiences, causing inaccurate allocation of criteria weights. Notwithstanding this, subjective decision making does represent the common understanding and experience of human beings in a particular field. To a certain extent, it can reflect the relative importance of different criteria and the possible weights range of criteria. In contrast, despite that objective evaluation method effectively reduce the influence of subjective factors, its actual rationality is undetermined. Thus, this paper proposes a weighting allocation model combining subjective evaluation with objective evaluation. Firstly, the relative importance degree of each criterion that evaluates investment strategies for distribution networks is given by a classical subjective weighting method. The trapezoidal fuzzy number $\boldsymbol{F} = (l, m, g, h)$ is used to describe the judgment of experts. And the relative importance of different criteria is divided into five levels in Table 2. l, m, g and h represent the lower bound, left mean value, right mean value and upper bound.

By experts scoring, the value of fuzzy numbers can be obtained. Furthermore, with all fuzzy numbers weighed linearly and equally, the fuzzy evaluation results of all experts for specific criterion evaluating investment strategies are aggregated. The fuzzy number of the j th criterion is determined by formula (1):

$$F_j = \frac{1}{K}\sum_{k=1}^{K} F_{kj} \tag{1}$$

where, F_{kj}: fuzzy number corresponding to the result of the judgment of the k th expert on j th criterion,

K: number of experts involved in decision making,

F_j: fuzzy number of the j th criterion.

The value of fuzzy numbers can be compared according to the

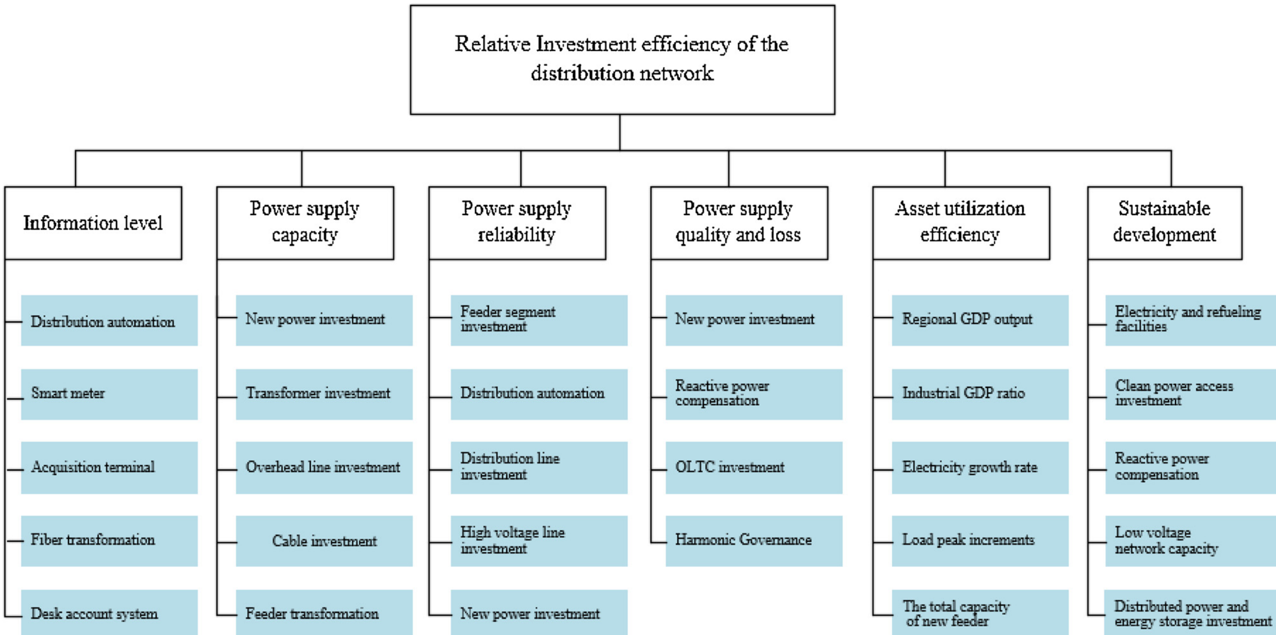

Fig. 2. Hierarchical evaluation index system for investment in the distribution network.

Table 1
The inputs and outputs of each criterion.

Criterion	Input indicators	Output indicators
Information level	(1) Distribution automation investment (2) Smart meter investment (3) Automatic acquisition terminal investment of low-voltage distribution transformers (4) Acquisition terminal investment of low-voltage distribution transformers (5) Optical fiber transformation investment in the Substation (35/110 kV) (6) Accounting information system investment	①Coverage rate increment of feeder automation ② Coverage rate of remote terminal units (RTU) ③ State estimation accuracy of distribution network ④ Fault isolation accuracy of feeder ⑤ The distribution transformers proportion that can measure synchronization line loss rate ⑥ Optical fiber communication bit error rate(BER)
Power supply capacity	(1) Newly added substations investment (2) Construction and reformation investment of high-voltage distribution lines (110/35 kV) (3) Capacity expansion investment of substations (4) Construction and reformation investment of Low-voltage distribution transformers (5) Renovation investment of 10 kV feeder (6) Newly added cable investment (7) Newly added overhead line investment	① The ratio of peak load and total Power supply capacity ② Average load rate of main transformers in 110 kV/35 kV substations ③ The ratio of capacity and load for 110/35 kV transformer ④ The average of maximum load rate for high-voltage distribution line ⑤ The proportion of 10 kV single-power-supply feeders ⑥ Average supply radius of 10 kV feeders ⑦ The average of 10 kV feeder maximum load rate ⑧ The proportion of heavy-load transformers ⑨ The average capacity of distribution transformer in each house
Power supply reliability	(1) Reformation investment cable and overhead line (2) Sectional reformation investment of medium -voltage feeder (3) Distribution automation investment (4) Newly added substations investment (5) Construction and reformation investment of high-voltage distribution lines (110/35 kV)	① Cable rate of 10 kV line ② Insulation rate of 10 kV overhead line ③ Average electricity outage time for users ④ Planned average electricity outage duration for users ⑤ N-1 qualification rate of high-voltage line (110/35 kV) ⑥ N-1 qualification rate of medium-voltage feeders (10 kV) ⑦ Average segments of mid - voltage overhead lines ⑧ Connection rate of 10 kV medium voltage feeders ⑨ Ratio of transferable load in distribution feeders
Power supply quality and loss	(1) Newly added substations investment (2) Reactive power compensation device investment (3) Reformation and maintenance investment of OLTC (4) Harmonic governance investment	① Overrun rate of power supply radius ② Qualified rate increments of feeder voltage ③ Capacity ratio of low voltage zone ④ Capacity percentage of low voltage feeders ⑤ Unbalance rate of three-phase voltage ⑥ Harmonic loss ⑦ Percentage of high loss zone ⑧ Average line loss rate of feeders
Asset utilization efficiency and economy	(1) Regional GDP output (2) Proportion of industrial GDP (3) Growth rate of electricity consumption (4) Increments of load peak (5) Expansion increments of total feeder capacity (6) Increments capacity of total main transformers (7) Total power supply capacity	① Average utilization time of feeder ② Average work hour of main transformer ③ Maximum load rate variance of feeders ④ The variance of maximum load rate for main transformers ⑤ Average price of electricity ⑥ The density power supply capacity ⑦ Unit capacity ⑧ Amount of selling electricity ⑨ Equipment utilization rate ⑩ Power supply capacity of unit asset
Sustainable development level	(1) Charging infrastructure investment (2) Integration investment of distributed clean energy resources (3) Reactive power compensation devices investment (4) Grid-connected PV capacity in low-voltage network (5) construction investment of distributed generations and energy storage devices	① Attainable scale of public electrical vehicles ② Attainable scale of private electrical vehicles ③ Attainable scale of Grid-connected PV ④ Grid-connected rate of DG ⑤ Reductions of carbon dioxide emission

Table 2
Delimitation of significance degree and corresponding trapezoidal fuzzy numbers.

Indicator importance degree	Trapezoidal fuzzy number
Not important	(0, 0.05, 0.15, 0.25)
Less important	(0.15, 0.25, 0.35, 0.45)
General	(0.35, 0.45, 0.55, 0.65)
More important	(0.55, 0.65, 0.75, 0.85)
Most important	(0.75, 0.85, 0.95, 1)

centre of gravity (COG) of the fuzzy set. The centroid of a trapezoidal fuzzy set presented by Ghorabaee et al. [31] is used for calculating possibility degree of a trapezoidal fuzzy set. Then the possibility degree is used for determining its ranking value. It is worth mentioning that the probability for the fuzzy number to lie in the higher importance degree will be improved with bigger COG. The COG of fuzzy numbers can be defined as [32]:

$$c(F) = \frac{\int x\mu(x)dx}{\int \mu(x)dx} = \frac{g^2 + h^2 + gh - m^2 - l^2 - ml}{3(g + h - m - l)} \tag{2}$$

$$\mu(x) = \begin{cases} \dfrac{x-l}{m-l}, x \in [l, m) \\ 1, x \in [m, g] \\ \dfrac{x-r}{g-r}, x \in (g, r] \\ 0, else \end{cases} \tag{3}$$

where, x: fuzzy decision value measuring the importance of each criterion,

$\mu(x)$: membership function corresponding to the trapezoidal fuzzy number F,

$c(F)$: COG of the fuzzy number F, which represents a weighted mean value of the variable x with the membership function $\mu(x)$ as weight and with the denominator as the sum of the weights.

By comparing the value of COG, we can obtain the importance degree ranking of each criterion in accordance with the weight of each criterion in the evaluation model of investment strategies.

Furthermore, since too large or small weights of some criteria may account for deviation of evaluation result, the "non-dictatorship" condition is introduced. The "non-dictatorship" condition of weight stands for that any criterion is non-dominated for the others that are less important than it. It should be noted that, $x \succ y$ represents that criterion x is more important than criterion y, $x = y$ represents that criterion x is as important as criterion y, respectively. In this paper, we assume that the importance of all criteria decreases in turn expressed as $x_1 \succ x_2 \succ \ldots \succ x_n$. Accordingly, the "non-dictatorship" condition of weight can be expressed as:

$$\begin{cases} \omega_j \le \omega_{j+1} + \cdots + \omega_n, j = 1, 2, \cdots, n-2 \\ \omega_1 + \omega_2 + \cdots + \omega_n = 1 \end{cases} \tag{4}$$

The projection pursuit algorithm is a novel statistical analysis method for multi-dimensional data as well as an effective data-driven objective weighting method [33]. The projection pursuit algorithm associates with each direction in the multidimensional space an index that measures its "usefulness" as a projection axis, and then varies the projection direction so as to maximize this index [34]. Namely, once finding out this optimal projection index of a certain evaluated object, the best projection direction revealing weight of each criterion in the evaluation model is confirmed.

Note that $\boldsymbol{\omega} = (\omega_1, \omega_2, \ldots, \omega_n)$ represents the projection direction that is equal to the weight of each criterion. Thus, the projection index of each evaluation object can be expressed as:

$$\theta_j^{(t)} = \sum_{i=1}^{n} \omega_i \theta_j^{i(t)} \tag{5}$$

The computational result of projection pursuit method hinges on projection function. In order to reflect objectively the weight of each criterion and realize the salient features of local concentrating and global expanding, a reasonable and classical function of projection indexes is presented [35].

$$S = \sqrt{\frac{\sum_{i=1}^{n} (\theta_j^{i(t)} - \bar{\theta}_j^{i(t)})^2}{n-1}} \tag{6}$$

$$D = \sum_{d=1}^{n} \sum_{e=1}^{n} (R - r_{de}) \delta (R - r_{de}) \tag{7}$$

$$\bar{\theta}_j^{(t)} = \frac{\sum_{i=1}^{n} \theta_j^{i(t)}}{n} \tag{8}$$

$$r_{de} = |\theta_j^{d(t)} - \theta_j^{e(t)}| \tag{9}$$

where, S: standard deviation of the projection value,

D: "local density" of the points after projection onto a projection axis,

r_{ds}: inter-point distance,

R: local density of the window radius related to the structure of the sample data. Usually, let $R = n$.

$\delta(t)$: unit step function.

Assuming that the weights of all indexes are always positive for the evaluation model of investment efficiency in distribution network planning, it is necessary to ameliorate traditional projection pursuit model as follows:

$$\begin{cases} \max Q = SD \\ \text{s.t.} \omega \in \boldsymbol{\Phi}_{\text{NDX}} \end{cases} \tag{10}$$

where, $\boldsymbol{\Phi}_{NDC}$ is a set of weights that satisfies the "non-dictatorship" condition of weights as is shown in formula (4) in detail.

Compared with the classical projection pursuit model, the model of the formula (10) can take the subjective opinion into the consideration in the form of constraint, which effectively overcomes the defects that the objective weighting methods can not reflect the subjective opinions and the conventional cognition. At the same time, the non-dictatorship condition can also balance the role of each criterion and moderate the polarize problem in the evaluation model. Owing that this model is a nonlinear constrained optimization problem with $\boldsymbol{\omega}$ as decision variables, it is difficult to solve this problem by implementing common deterministic optimization method. As a result, in this paper, the particle swarm optimization algorithm is implemented to obtain the global optimal weight of each criterion [36].

3.2. The theory and method of yardstick competition

3.2.1. Yardstick competition in distribution companies

The yardstick competition, also called regional comparison competition, was proposed by Shleifer in 1985. The basic idea of yardstick competition is that, via introducing a certain amount of the same-type regional distribution companies as a reference, the investment of any region will be determined by the other similar companies [37]. This method is applicable to the indirect competition of different regional monopoly enterprise and belongs to incentive regulation. The yardstick competition theoretically makes each region's construction investment not entirely dependent on its own cost, but also others, overcoming the shortcomings of traditional methods. In this paper, each observed region is considered as DMU, therefore, the construction cost subsidy of DMU_j in period t can be expressed as follows:

$$\alpha_j^{(t)} = L_j^{(t)}\{\varepsilon_j c_j^{(t)} + (1-\varepsilon_j)\sum_{i=1,i\neq j}^{n}(l_i^{(t)}c_i^{(t)})\} \tag{11}$$

where, $L_j^{(t)}$: construction amount of DMU_j in period t,

$c_j^{(t)}$: unit construction cost of DMU_j in period t,

ε_j : proportion of cost for DMU_j,

$l_i^{(t)}$: proportion of construction cost for DMU_i ($i = 1,2,\ldots,n,i \neq j$).

In the context of yardstick competition, by comparing similar regional distribution companies with analogical operating conditions and economic levels, regulators will create working groups comprising inefficient and benchmark companies, and regard high efficient regions as benchmarks to lead the investment of inefficient companies. This pattern of benchmarking is generally considered superior to other regulatory regimes because it provides the regulated companies with strong efficiency improvement incentives and the regulator places fewer restrictions on the companies.

The key to yardstick competition is contraposing a set of reasonable evaluation indicators, selecting a group of comparable companies as observed objects using effective methods to evaluate and rank them, in order to determine performance benchmarks, and motivate other companies. Alternatively, DEA is an effective research tool for this purpose.

3.2.2. Calculating investment efficiencies of different distribution companies

It is universally acknowledged that the evaluation of investment strategies in distribution networks is a typical multi-inputs and multi-outputs evaluation system. Since there exit conspicuous differences for diverse regional distribution network in the aspects of structural characteristic, vulnerable segment and operational mode, it is impossible to have a fair and objective grasp of the actual situation of the distribution network only by analysing a great deal of statistical data. On the contrary, the DEA method [38] is an effective tool to evaluate the efficiency of multi-inputs and multi-outputs systems. The evaluation results only depend on the actual inputs, the effective outputs and their relation, which overcomes the subjectivity of the traditional evaluation results, making the evaluation results can objectively reflect the actual investment efficiency of the distribution network. Accordingly, we introduce the "relatively effective idea" of DEA to the evaluation model of investment planning in distribution networks. The investment efficiency in the assessed region is determined jointly by its own and other participating regions. By analysing the relationships between inputs and outputs, we can understand the technical effectiveness and scale effectiveness of the distribution network planning. More importantly, DEA model possesses additional advantages of avoiding the subjective factors, simplifying the algorithm and mitigating deviation. Nowadays, it has been applied to the area of resource allocation and productivity improvement.

The traditional DEA model, in the evaluation of complex systems with multiple subsystems, usually regards the various subsystems as a whole "black box" so that it cannot fully reflect the efficiency of the system, and usually overestimate the investment efficiency [15]. Therefore, according to the actual situation of the investment planning in distribution networks, the conventional DEA model is improved. In detail, each DMU with "black box" system is divided into several parallel subsystems. In addition, the conventional DEA technique is devised to measure the performance of a DMU in a specified period of time in a static manner. When several periods with inter-relations are involved, the overall efficiency must be measured in a dynamic manner, considering the inter-relationship between consecutive periods. Otherwise, the resulting efficiency measures will be misleading. In this regard, this paper develops a dynamic DEA evaluation model. With the reference of relevant data reflecting the actual development level, the evaluation model will be frequently applied to investment strategies of actual distribution networks.

Supposing that there are n regional distribution networks involved in investment strategies. Each region is treated as a DMU. DMU_j ($j = 1,2,\ldots,n$) has p investment criteria in the period $t(t = 1,2,\ldots,T)$. Criterion $q(q = 1,2,\ldots,p)$ has $m(q)$ inputs expressed as $\boldsymbol{x_j}^{q(t)} = (x_{1j}{}^{q(t)}, x_{2j}{}^{q(t)},\ldots,x_{m(q)j}{}^{q(t)})^T > 0$ and $r(q)$ outputs expressed as $\boldsymbol{y_j q} = (y_{1j}{}^{q(t)}, y_{2j}{}^{q(t)},\ldots,y_{r(q)j}{}^{q(t)})^T > 0$, respectively. For the sake of eliminating the differences of magnitude among different indicators, it is essential to standardize the whole data firstly. The larger positive indicators denote a better investment performance of distribution network, where it can be standardized by formula (12) and (13). By contrast, the larger negative indicators represent a worse performance of distribution network, standardized by formula (14) and (15), analogously.

$$f_{ij}^{q(t)} = \frac{x_{ij}^{q(t)} - \min_i x_{ij}^{q(t)}}{\max_i x_{ij}^{q(t)} - \min_i x_{ij}^{q(t)}} \tag{12}$$

$$s_{rj}^{q(t)} = \frac{y_{rj}^{q(t)} - \min_r y_{rj}^{q(t)}}{\max_r y_{rj}^{q(t)} - \min_r y_{rj}^{q(t)}} \tag{13}$$

$$f_{ij}^{q(t)} = \frac{\max_i x_{ij}^{q(t)} - x_{ij}^{q(t)}}{\max_i x_{ij}^{q(t)} - \min_i x_{ij}^{q(t)}} \tag{14}$$

$$s_{rj}^{q(t)} = \frac{\max_r y_{rj}^{q(t)} - y_{rj}^{q(t)}}{\max_r y_{rj}^{q(t)} - \min_r y_{rj}^{q(t)}} \tag{15}$$

where, $f_{ij}{}^{q(t)}$: standardized input of indicator i from criterion q for region j in period t,

$s_{rj}{}^{q(t)}$: standardized output of indicator r from criterion q for region j in period t.

Hypothesizing that v_i and u_r denote the weights of i-th input and r-th output, we can define the ratio of output and input as the investment efficiency index of criterion q for region j in period t.

$$\theta_j^{q(t)} = \frac{\sum_{r\in r(q)} u_r s_{rj}^{q(t)}}{\sum_{i\in m(q)} v_i f_{ij}^{q(t)}} \tag{16}$$

To maximize the investment efficiency index of DMU_{j0}, which is subject to the overall investment efficiency index, a model for analysing investment efficiency of distribution network can be established:

$$\begin{cases} \max_{\mathbf{U},\mathbf{V}} \theta_{j0}^{q(t)} = \sum_{r\in r(q)} u_r s_{rj0}^{q(t)} / \sum_{r\in r(q)} v_i f_{ij0}^{q(t)} \\ s.\ t.\ \sum_{r\in r(q)} v_i f_{ij0}^{q(t)} = 1 \\ \sum_{r\in r(q)} u_r s_{rj0}^{q(t)} - \sum_{i\in i(q)} v_i f_{ij0}^{q(t)} \leq 0 \\ \mathbf{V} = [v_1, v_2, \cdots, v_{r(q)}] \geq 0 \\ \mathbf{U} = [u_1, u_2, \cdots, u_{r(q)}] \geq 0 \end{cases} \tag{17}$$

Whether investment efficiency index of DMU_{j0} is satisfying or not is relative to other DMUs. If $\theta_{j0}^{q(t)} = 1$, the distribution network investment efficiency of DMU_{j0} will be relatively higher. Likewise, If $\theta_{j0}^{q(t)} < 1$, the investment efficiency of DMU_{j0} will be relatively lower.

3.3. Dynamic evaluation of investment efficiency in distribution network

There is no doubt that the investment planning in distribution networks is a durative and propulsive process. When several periods with inter-relations are involved, the overall efficiency must be measured in a dynamic manner, taking into account the inter-relationship between consecutive periods. Only by evaluating the investment efficiency several former planning cycles, can decision makers master the actual level of distribution network comprehensively and adjust investment strategy in the later periods. In this paper, the concept of "time degree" [39] and the Least Variance Priority Method [40] are

Table 3
The detailed description of different time degree.

Time degree	Description
0.1	The recent data are very important
0.3	The recent data are important
0.5	The same to all data
0.7	The forward data are important
0.9	The forward data are very important

Table 4
The Evaluation Result at the end of every planning cycle.

DMU	2010	2012	2014	2016	Overall	Coefficient	Rank
1	0.538	0.613	0.794	0.833	0.733	−0.667	10
2	0.646	0.682	0.766	0.879	0.770	−0.528	9
3	0.815	0.875	0.916	0.954	0.906	−0.019	7
4	1	1	1	1	1	0.333	1
5	0.900	0.929	0.987	1	0.967	0.209	5
6	0.924	0.962	1	1	0.981	0.262	4
7	0.891	0.883	0.934	0.948	0.922	0.041	6
8	1	1	1	1	1	0.333	1
9	0.940	0.966	1	1	0.984	0.274	3
10	0.780	0.803	0.849	0.901	0.848	−0.238	8
avg	0.844	0.871	0.925	0.951	0.911	0	

introduced to calculate the dynamic weight vector of each planning cycle, so as to establish the periodic dynamic evaluation model.

The time degree and dynamic weight vector are defined as follows:

$$\lambda = \sum_{t=1}^{T} \frac{T-t}{t-1}\tau_t \tag{18}$$

$$\sum_{t=1}^{T} \tau_t = 1 \tag{19}$$

where, τ: dynamic weighted vector reflecting the contribution differences of the different planning cycles for dynamic evaluation, $\tau_t \in [0,1]$.

λ: time degree reflecting the attention degree of decision makers for different cycles. The detailed description for different value of time degree is given in Table 3.

The variance of the dynamic weight vector is defined as follows:

$$D(\tau) = \sum_{t\in T} \frac{1}{T}[\tau_t - E(\tau)]^2 = \frac{1}{T}\sum_{t\in T}\tau_t^2 - \frac{1}{T^2} \tag{20}$$

$$E(\tau) = \frac{1}{T}\sum_{t\in T}\tau_t \tag{21}$$

Based on Least Variance Priority Method, the model of computing dynamic weighted vector can be demonstrated as formula (22), which belongs to a nonlinear constrained optimization problem. As the interior-point method is becoming more widespread as an alternative to solve this type of problem, this paper implements it to calculate the proposed dynamic model.

$$\begin{cases} \min_{\tau} \frac{1}{T}\sum_{t\in T}\tau_t^2 - \frac{1}{T^2} \\ s.\ t.\ \lambda = \sum_{t\in T}\frac{T-t}{T-1}\tau_t \\ \sum_{t\in T}\tau_t = 1,\ \tau_t \in [0,1],\ t = 0, 1, \cdots, T \end{cases} \tag{22}$$

3.4. Reward and punishment regime

It has been proved that reward and punishment regime is conductive to enhance the efficiency of investment strategies in distribution networks in pioneering studies. Intuitively, the regulators will give the DMUs with high investment efficiency appropriate reward incentives. On the contrary, the DMUs with lower investment efficiency will be given punishment [41].

The reward and punishment are determined by yardstick competition among multiple regions, depending on the dynamic evaluation result of DEA. The static investment efficiency index $\theta_j^{q(t)}$ will be calculated by formula (20), the dynamic weighted vector τ_t will be calculated by formula (23), and then, via weighed linearly, the dynamic investment efficiency index of criterion q for region j in period t can be acquired, as shown in the formula (24).

$$\theta_j^{dynamic} = \tau_1\theta_j^{q(1)} + \tau_2\theta_j^{q(2)} + \cdots + \tau_t\theta_j^{q(t)} \tag{23}$$

The coefficient of reward and punishment of DMU_j in period t can be defined as follow [42]:

$$\xi_j^{(t)} = \frac{\theta_j^{dynamic} - \frac{1}{n}\sum_{i=1}^{n}\theta_i^{dynamic}}{\max(\theta_j^{dynamic}) - \min(\theta_j^{dynamic})} \tag{24}$$

Moreover, the reward and punishment can be calculated as follows:

$$\rho_j^{(t)} = \begin{cases} \Delta P_t\xi_j^{(t)},\ \Delta P_t > 0 \\ 0,\ \Delta P_t < 0,\ \xi_j^{(t)} > 0 \\ -|\Delta P_t\xi_j^{(t)}|,\ \Delta P_t < 0,\ \xi_j^{(t)} < 0 \end{cases} \tag{25}$$

where, ΔP_t denotes the increment of investment in period t compared to the period t-1.

4. Case study

A practical 10-region real distribution system in China is carried out to verify the proposed method in this paper. It should be noted that the cycle of distribution network planning is generally two years in China. Thus, 4 planning cycles are chosen as study periods from year 2008 to 2016.

4.1. Dynamic yardstick evaluation model

4.1.1. Weight of each criterion

Initially, by the form of expert scoring, we can obtain the trapezoidal fuzzy number. According to the COG comparison of involved criteria, the importance of six types of criteria can be sorted as follows:

$\omega_3 \succ \omega_2 \succ \omega_4 \succ \omega_1 \succ \omega_5 \succ \omega_6$

where, $\omega_1, \omega_2, \ldots, \omega_6$ represent the weights of information level, power supply capacity, power supply reliability, power supply quality and loss, asset utilization efficiency and economy and sustainable development, respectively.

And then, with the improvement of conventional projection pursuit model, combing objective evaluation with subjective evaluation, the weight of each criterion in the evaluation model of investment planning can be ultimately confirmed. The detailed computational result is summarized as follows:

$$\theta_j^{(t)} = 0.1765\theta_j^{1(t)} + 0.1932\theta_j^{2(t)} + 0.2105\theta_j^{3(t)} + 0.1801\theta_j^{4(t)} + 0.1383\theta_j^{5(t)} + 0.1014\theta_j^{6(t)}$$

4.1.2. Dynamic evaluation model

Furthermore, according to the attention degree of decision makers for different cycles, the dynamic weight vector can be calculated by formula (22). The dynamic evaluation model is shown as follows:

$$\theta_j^{dynamic} = 0.138\theta_j^{(2010)} + 0.215\theta_j^{(2012)} + 0.301\theta_j^{(2014)} + 0.346\theta_j^{(2016)}$$

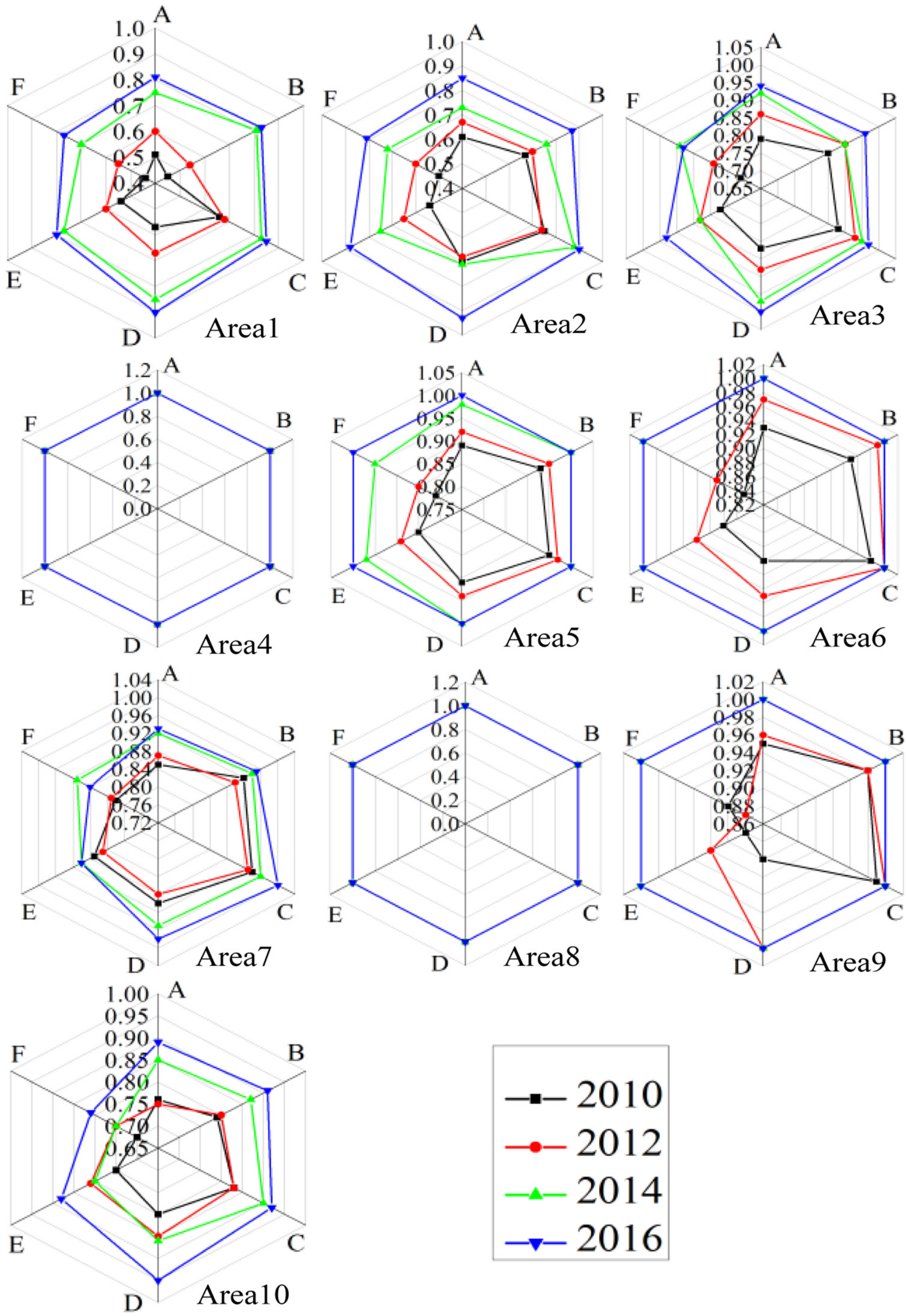

Fig. 3. Each criterion's distribution investment evaluation value from 2010 to 2016.

4.2. Analysis of evaluation results

According to the inputs and outputs data for 10 regions in four planning cycles, we can calculate the investment efficiency of distribution network in every cycle based on DEA model. Afterwards, the overall investment efficiency of each region will be attained in a complete research period from 2008 to 2016 by the dynamic evaluation model. On a basis of yardstick competition, regulators will create working groups comprising inefficient and benchmark companies. An assessment in 10 regions is carried out in accordance with the reward and punishment regime, which motivates the improvement of investment efficiency in regional distribution networks. Due to the limited space of this paper, the computational progress is no longer listed in detail. Table 4 shows the evaluation result at the end of every planning cycle.

From the evaluation result shown in Table 4, it is clear that the average overall investment efficiency is 0.911 during the complete research period from 2010 to 2016 and the average investment efficiency keeps in stable increasing year by year. Particularly, regulators will create working groups comprising inefficient and benchmark companies. Thereinto, the investment efficiency index of six DMUs (4, 5, 6, 7, 8, 9) are above the average scores, which can be regard as benchmark companies.

More intuitively, taking the evaluation value of six types of criteria into account. Each criterion's investment evaluation value from 2010 to 2016 is comprehensively depicted in Fig. 3. Hereinto, A, B, C, D, E, F

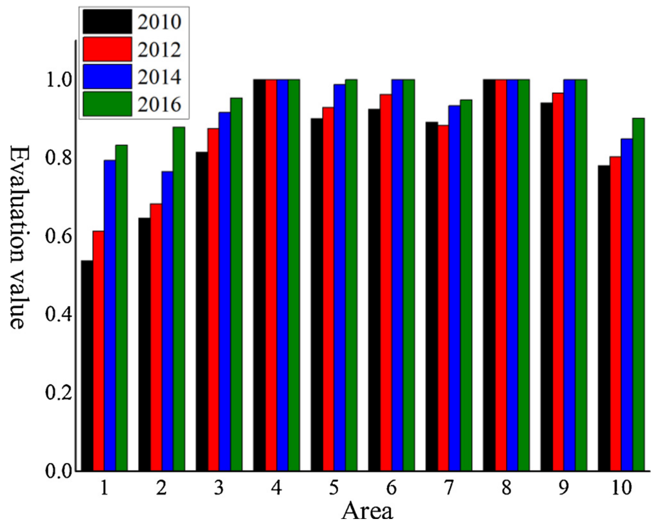

Fig. 4. Distribution investment evaluation value of each area from 2010 to 2016.

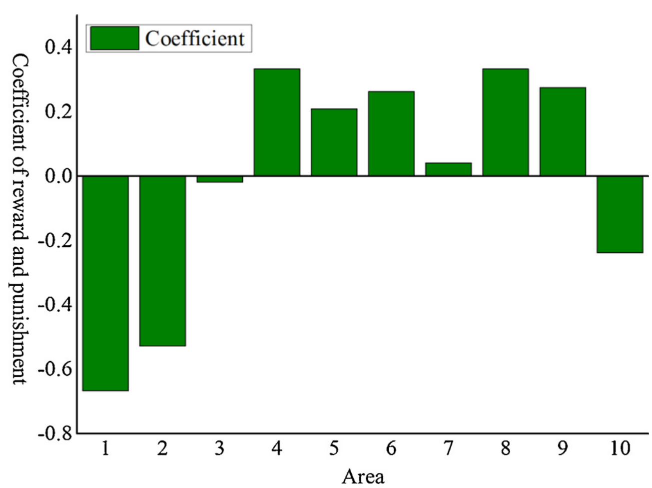

Fig. 5. The coefficient of reward and punishment.

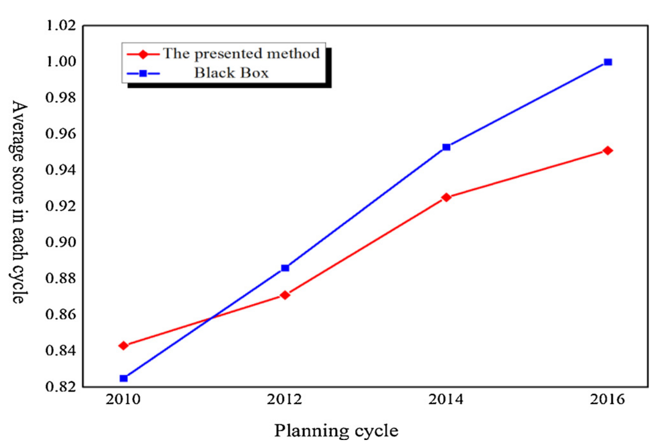

Fig. 6. Comparison of presented method with "black box" model.

represent information level, power supply capacity, asset utilization efficiency and economy, power supply quality and loss, power supply reliability and sustainable development level, respectively.

As shown in Fig. 3, the investment efficiency of the observed regional distribution networks appear a growing trend without exception all the time for some areas owning complete data from 2008 to 2016 such as area 1,2,3,5,7,10. Especially, the efficiency of some areas even increased by 40% compared the ahead planning cycle. Afterwards, it is worth mentioning that the investment data of a few areas is difficult to attain completely due to several irresistible factors. However, the overall trend is sufficient to prove that the proposed method is beneficial to adjust investment strategies for improving the investment efficiency and reducing construction cost in the next planning cycle.

In addition, the effect of regional economic development level on the investment efficiency in distribution networks has been succinctly analysed in this research. It is a fact that the economic development level of western areas is lower than the eastern in China. The observed areas in this paper mainly compose of two parts: the eastern (e.g., area 4,5,6,7,8,9) and the western (e.g., area 1,2,3,10). Fig. 4 shows investment evaluation value of each area at the end of four planning cycles. It is obvious that the investment efficiency in distribution networks will be enhanced with higher level of economic development. Under this premise that the eastern areas' economic level is higher than the western areas, eastern investment efficiency (i.e., area 4, 8, 9) are higher than western areas (i.e., area 1, 2, 3).

In order to improve the investment efficiency, assessment incentive regime has been extensively studied in many exiting works. In this study, the reward and punishment rules are applied. The reward and punishment are determined by yardstick competition among multiple regions, depending on the dynamic evaluation result of DEA. Fig. 5 shows the reward and punishment coefficient, calculated by formula (25). Numerical results in Fig. 3 have powerfully demonstrated that reward and punishment regime applied to the dynamic yardstick evaluation model is conductive to enhance the investment efficiency in distribution networks. As depicted in the Fig. 5, the reward and punishment coefficients of all observed areas differ from one another, including the positive and the negative. Intuitively, the regulators will give the DMUs (i.e., 4, 5, 6, 7, 8, 9) with high investment efficiency appropriate reward incentives. On the contrary, the DMUs (i.e., 1, 2, 3, 10) with lower investment efficiency will be punished. This pattern of reward and punishment regime is generally considered superior to other regulatory regimes because it provides the regulated distribution companies with strong efficiency improvement incentives.

4.3. Comparison of the prosed model and "black box" model

As mentioned in Section 3.2.2, the traditional DEA model, in the evaluation of complex systems with multiple subsystems, usually regards the various subsystems as a whole "black box", which has been confirmed that it cannot fully reflect the efficiency of the system, and usually overestimate the investment efficiency. Nevertheless, the traditional DEA model has been improved in this paper. Each DMU with multiple indicators is divided into several parallel subsystems according to six types of criteria. Namely, each criterion is an evaluation subsystem.

As is shown in Fig. 6, in comparison with the traditional "black box" model, the evaluation values calculated by the presented method are lower in most cases, which avoids overestimating the investment efficiency. Definitely, it is possible that although some DMUs are efficient for overall system by the traditional "black box" model, shows badly inefficient performance for certain criteria (subsystems). The overall efficient production system can also be improved in technical or scalar efficiency with the aid of information derived from other DMUs, which is just the shortcoming of "black box" model in efficiency-measuring of multi-criteria. In another word, the methodology that proposed in this study can be relevant for real application and evaluate investment strategies for distribution networks more truly and accurately. Besides, its discriminate ability is also better than the black box model since it involves multiple specific criteria in detail.

5. Conclusions

This paper explores the evaluation of multi-timescale dynamic investment strategy in distribution networks, the dynamic yardstick evaluation model over the planning horizon is developed from spatial and temporal dimensions with the analysis of distribution network planning and construction in a 10-region test system, the most important observations may be summarized as follows:

a. The evaluation index system mentioned in this paper covers the significant aspects of the current development of distribution networks. It comprehensively considers several essential factors including the performance of the distribution network, information level, regional economic level, the market environment, and so on. The "input and output indicators" was explicitly considered by the precise indicators analysis, rather than using unilaterally effective output indicators presenting performance to characterize the investment efficiency of distribution networks as before. Data of each planning cycle is obtained via historical statistical data and data mining methods. Clearly, the proposed hierarchical evaluation index system has prominent advantage for systematization and comprehensiveness compared with traditional evaluation methods.
b. The evaluation method proposed in this paper adopts a multi-dimensional hierarchical DEA. While reducing the amount of calculation, it can effectively reveal more problems in the planning and construction of distribution networks and make more accurate investment strategies for distribution networks in the later period. It is worth mentioning that DEA is creatively used to guide the planning investment in distribution networks and has a good effect.
c. The evaluation model is developed from spatial and temporal dimensions, which can efficaciously present the dynamic development benefits of distribution networks in different regions during a certain planning cycle. Moreover, the dynamic yardstick evaluation method involving yardstick competition and the reward and punishment regimes, is generally considered superior to other regulatory regimes because it provides the regulated distribution companies with strong efficiency improvement incentives and gradually guides the precision investment in the distribution network.
d. In our future work, the evaluation indicators for "punishment" on the basis of the existing distribution network evaluation index system will be enriched, the consideration of the impact of distribution network planning on various types of losses (such as power outage, insufficient power capacity, DG consumption, etc.) also will be strengthened. In addition, we will adjust the input-output relation and the calculation method of weights according to the relationship of various indicators, to make a more scientific and comprehensive assessment of investment strategies in distribution networks, and further improve the accuracy of investment strategies for distribution networks.

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References

[1] R.C. Lotero, J. Contreras, Distribution system planning with reliability, IEEE Trans. Power Deliv. 26 (4) (2011) 2552–2562.
[2] J. Aghaei, K.M. Muttaqi, A. Azizivahed, et al., Distribution expansion planning considering reliability and security of energy using modified PSO algorithm, Energy 65 (2) (2014) 398–411.
[3] S. Nejadfard-Jahromi, M. Rashidinejad, A. Abdollahi, Multistage distribution network expansion planning under smart grids environment, Int. J. Electr. Power Energy Syst. 71 (2) (2015) 222–230.
[4] G. Mokryani, Active distribution networks planning with integration of demand response, Sol. Energy 122 (3) (2015) 1362–1370.
[5] H. Arasteh, M.S. Sepasian, V. Vahidinasab, An aggregated model for coordinated planning and reconfiguration of electric distribution networks, Energy 94 (2016) 786–798.
[6] B. Zeng, J. Feng, J. Zhang, et al., An optimal integrated planning method for supporting growing penetration of electric vehicles in distribution systems, Energy 126 (2017) 273–284.
[7] N. Ravadanegh, G. Roshanagh, On optimal multistage electric power distribution networks expansion planning, Int. J. Electr. Power Energy Syst. 54 (1) (2014) 487–497.
[8] B. Zou, J. Wang, F. Wen, Optimal investment strategies for distributed generation in distribution networks with real option analysis, IET Gener. Transm. Distrib. 11 (3) (2017) 804–813.
[9] Y. Sun, C. Kang, S. Chen, et al., Low-carbon power grid index system and evaluation method, Automation Electr. Power Syst. 38 (17) (2014) 157–162.
[10] Y.Z. Mu, Z.X. Lu, Y. Qiao, et al., A comprehensive evaluation index system of power grid security and benefit based on multi-operator fuzzy hierarchy evaluation method, Power Syst. Technol. 39 (01) (2015) 23–28.
[11] T.J. Pu, N.S. Chen, X.J. Ge, et al., Research on evaluation index system and synthetically evaluation method for balance of electric power and energy, Power Syst. Technol. 39 (01) (2015) 250–256.
[12] Z. Shang, W. Tao, X.P. Gu, Synthetic evaluation of power grid operating states based on intuitionistic fuzzy analytic hierarchy process, Automation Electr. Power Syst. 40 (4) (2016) 41–49.
[13] L. Yang, H. Wu, K. Men, An energy saving and economy operation evaluation method for China Southern power grid, Automation Electr. Power Syst. 38 (17) (2014) 31–38.
[14] Y.H. Dai, L. Chen, Y. Min, T. Chen, Study on the daily operation assessment system of power grid, Power Syst. Technol. 39 (06) (2015) 1611–1616.
[15] A. Mardani, E.K. Zavadskas, D. Streimikiene, et al., A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency, Renew. Sustain. Energy Rev. 70 (2017) (2017) 1298–1322.
[16] M.R.J. Oskuee, E. Babazadeh, S. Najafi-Ravadanegh, et al., Multi-stage planning of distribution networks with application of multi-objective algorithm accompanied by DEA considering economical, environmental and technical improvements, J. Circuits Syst. Comput. 2015 (2015) 1650025.
[17] M.C. Gouveia, L.C. Dias, C.H. Antunes, et al., Benchmarking of maintenance and outage repair in an electricity distribution company using the Value-Based DEA method, Omega 53 (2015) 104–114.
[18] Aydın Çelen, Neşe Yalçın, Performance assessment of Turkish electricity distribution utilities: an application of combined FAHP/TOPSIS/DEA methodology to incorporate quality of service, Util. Policy 23 (4) (2012) 59–71.
[19] N.D.A. Gustavo, L. Araujo Alves, R.F.D.S.C. Eduardo, et al., Evaluating electricity distributors efficiency using self-organizing map and data envelopment analysis, IEEE Lat. Am. Trans. 12 (8) (2014) 1464–1472.
[20] A. Arcos-Vargas, F. Núez-Hernández, G. Villa-Caro, A DEA analysis of electricity distribution in Spain: an industrial policy recommendation, Energy Policy 102 (2017) 583–592.
[21] P.T. Dijkstra, M.A. Haan, M. Mulder, Industry structure and collusion with uniform yardstick competition: theory and experiments, Int. J. Ind. Organ. 50 (7) (2016) S141–S151.
[22] E. Chong, Huet F. Yardstick, Competition, franchise bidding and firms' incentives to collude, Rev. Ind. Organ. 35 (1-2) (2009) 149–169.
[23] Z. Wang, J. Zhong, Procuring and pricing performance-based frequency regulation services in the electricity market, IET Gener. Transm. Distrib. 11 (10) (2017) 2633–2642.
[24] P.J. Agrell, Humberto Brea-Solís, Capturing heterogeneity in electricity distribution operations: a critical review of latent class modelling, Energy Policy 104 (2017) 361–372.
[25] J.E.P.S. Tanure, C.M.V. Tahan, J.W. Marangon Lima, Establishing quality performance of distribution companies based on yardstick regulation, IEEE Trans. Power Syst. 21 (3) (2006) 1148–1153.
[26] Y. Huang, L. SiDer, Assessing the impact of incentive regulation on distribution network investment considering distributed generation integration, Int. J. Electr. Power Energy Syst. 89 (Complete) (2017) 126–135.
[27] Emili GrifellTatjé, K. Kerstens, Incentive regulation and the role of convexity in benchmarking electricity distribution: economists versus engineers, Ann. Public Coop. Econ. 79 (2) (2010) 227–248.
[28] A. Ter-Martirosyan, J. Kwoka, Incentive regulation, service quality, and standards in U.S. Electricity distribution, J. Regul. Econ. 38 (3) (2010) 258–273.
[29] L. Rondi, Incentives to quality and investment: evidence from electricity distribution in Italy, J. Regul. Econ. 49 (1) (2016) 1–32.
[30] T. Zhang, S.X. Chen, H.B. Gooi, et al., A hierarchical EMS for aggregated BESSs in energy and performance-based regulation markets, IEEE Trans. Power Syst. 2016 (2016) 1–1.
[31] M.K. Ghorabaee, M. Amiri, J.S. Sadaghiani, et al., Multiple criteria group decision-making for supplier selection based on COPRAS method with interval type-2 fuzzy sets, Int. J. Adv. Manuf. Technol. 75 (5–8) (2014) 1115–1130.
[32] S.M. Chen, L.W. Lee, Fuzzy multiple attributes group decision-making based on the ranking values and the arithmetic operations of interval type-2 fuzzy sets, Expert

Syst. Appl. 37 (1) (2010) 824–833.

[33] J.H. Friedman, J.W. Tukey, A projection pursuit algorithm for exploratory data analysis, IEEE Trans. Comput. C-23 (9) (2006) 881–890.

[34] Y.C. Gong, Z.Y. Ren, F. Ding, et al., Grey relation-projection pursuit dynamic cluster method for multi-attribute decision making assessment with trapezoidal intuitionistic fuzzy numbers, Proc. IEEE Conf. Decis. Control 2015 (7) (2015) 1333–1339.

[35] Y. Jiahang, L. Cunbin, Intuitionistic trapezoidal fuzzy group decision-making based on prospect choquet integral operator and grey projection pursuit dynamic cluster, Math. Probl. Eng. 2017 (2017) 1–13.

[36] T. Jiang, H. Jia, H. Yuan, et al., Projection pursuit: a general methodology of wide-area coherency detection in bulk power grid, IEEE Trans. Power Syst. 31 (4) (2016) 2776–2786.

[37] P.T. Dijkstra, M.A. Haan, M. Mulder, The effect of industry structure and yardstick design on strategic behavior with yardstick competition: an experimental study, Res. Rep. (2013) 13008-eef.

[38] A. Hadi-Vencheh, A. Mohamadghasemi, A fuzzy AHP-DEA approach for multiple criteria ABC inventory classification, Expert Syst. Appl. 38 (4) (2011) 3346–3352.

[39] F.M. Ma, Y.J. Guo, Density-induced ordered weighted averaging operators, IEEE Transactions on Systems Man & Cybernetics Part B Cybernetics : a Publication of the IEEE Systems Man & Cybernetics Society 26 (9) (2011) 866–886.

[40] H. Liao, Z. Xu, Priorities of intuitionistic fuzzy preference relation based on multiplicative consistency, IEEE Trans. Fuzzy Syst. 22 (6) (2014) 1669–1681.

[41] Leticia Blázquez-Gómez, Emili Grifell-Tatjé, Evaluating the regulator: winners and losers in the regulation of Spanish electricity distribution, Energy Econ. 33 (5) (2011) 807–815.

[42] Yalin Huang, Lennart Soder, Evaluation of economic regulation in distribution systems with distributed generation, Energy 126 (2017) (2017) 192–201.