Effectiveness evaluation method on construction of active distribution network based on public service value model

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Abstract. Evaluating the construction effectiveness of active distribution network is the key point of coordinated development of distribution network. At present, effectiveness evaluation on the distribution network in domestic only focuses on output performance while leaves out of consideration of utilization efficiency of investment. Therefore, this paper presents a kind of effectiveness evaluation method for construction and updating of the active distribution network based on public service value model which could make an overall evaluation in two dimensions of output performance and cost efficiency. The evaluation results are comprehensively analyzed on the four quadrant diagram, and the evaluation conclusions and suggestions are put forward according to the quadrant of the evaluation objects. Finally, it verifies this evaluation method is scientific, reasonable and feasible in guiding construction investment of the power grid by applying the method in evaluating construction effectiveness of distribution networks in some areas of Hubei Province in China.

1. Introduction
In recent years, China's construction standard of distribution network has been upgraded in an all-round way to meet the needs of large-scale access of electric vehicles, distributed energy sources, micro-grid, energy storage devices and other facilities. The investment in active distribution network construction has been steadily increasing. Therefore, it is of great practical significance to comprehensively evaluate the development effect and benefit of construction and upgrading of active distribution network by adopting scientific evaluation method.

The main effectiveness evaluation methods on construction of power grid projects [1-9] include analytic hierarchy process, fuzzy comprehensive evaluation method, success degree analysis method, grey correlation analysis method, data envelopment analysis method and so on. Literature [10] proposes a comprehensive post evaluation model for power grid reconstruction projects based on analytic hierarchy process (AHP). Considering various qualitative and quantitative factors, and the uncertainty of information, the interval number theory is added to the fuzzy AHP, which reduces the subjectivity in determining the weights of evaluation factors. The literature [11] establishes 16 evaluation indexes from three aspects: social efficiency evaluation, power grid performance evaluation and economic evaluation, and evaluates the investment effect of rural power network upgrading projects in three typical counties by using fuzzy evaluation method. The literature [12,13] evaluates the distribution network planning scheme based on the saving theory and the grey correlation analysis method respectively. The literature [14] is an assessment of the grid planning scheme using the public service value model, rather than an assessment of the effectiveness of the grid construction, and lacks
a comprehensive analysis of the assessment results in two dimensions.

As a public utility, the power grid company undertakes the important mission of ensuring a safer, cleaner and sustainable power supply, and on the other hand, it also needs to ensure the development of the enterprise itself. Therefore, the evaluation of the effectiveness of the transformation and upgrading of distribution network should focus on output performance as well as input costs. For the first time, this paper applies the public service value model [15] to the effectiveness evaluation of distribution network construction, and evaluates the effectiveness of power grid construction from the two dimensions of output performance and cost effectiveness. The four-quadrant diagram is used to analyze the evaluation results, and according to the different quadrants of each regional power grid company, efficient and reasonable investment suggestions are proposed.

2. Effectiveness evaluation method on construction of active distribution network based on public service value model

2.1. Public service value model and its evaluation process

The previous effectiveness evaluation system only evaluates the output performance of the object. The public service value model (shown in figure 1) evaluates the value created by public service from two dimensions: output performance and cost effectiveness. The output performance is obtained by weighting and summing the evaluation results of the evaluation targets, which reflects the comprehensive benefits of investment. Cost effectiveness measures the degree to which output performance and input costs match, which is the ratio of output performance divided by input costs.

![Figure 1. Public service value model.](image-url)

The calculation part of output performance in figure 1 is equivalent to the traditional effectiveness evaluation method. Its process is generally as follows: index selection→index weighting→single index scoring→all indicators weighted and summed to obtain total score→give evaluation conclusion according to the score.

The public service value model added the calculation of input cost and cost effectiveness. Cost effectiveness refers to the ratio of output performance divided by input costs, which effectively reflects the efficiency of the organization who uses the investment. A comparison of the two effectiveness evaluation processes is shown in figure 2.
2.2. Index selection
Effectiveness evaluation indicators mainly include output indicators and input indicators. The selection of output indicators takes these factors into account, such as the necessity of project establishment, the evaluation index of development level of active distribution network and the development goal of active distribution network. In designing and selecting the indicators, the basic requirements of objectivity, scientificity, operability and integrity are followed, the level of construction of active distribution network is reflected comprehensively and truly. In the “Action Plan for Reconstruction of Distribution Network Construction (2015-2020)”, the National Energy Administration has proposed six key tasks for strengthening distribution network construction. According to these six key tasks, the first-level index output indicators of this paper are divided into six second-level indicators: power supply quality, power grid structure, equipment level, power supply capacity, intelligent level, and grid efficiency. Later, the State Grid Corporation has formulated the “Action Plan for Distribution Network Construction and Renovation of the State Grid Corporation” (2015-2020), based on the National Energy Administration version. The reliability rate of power supply, the qualified rate of comprehensive voltage, the line loss rate of 110kV and below voltage levels, the capacity-load ratio of high-voltage distribution network, the average distribution capacity of households, distribution automation coverage rate and smart meter coverage rate are proposed as the guiding objectives of distribution network construction and transformation. Take all the above contents into account, six second-level indicators are further decomposed into 17 third-level indicators. The input indicators include the total assets of the active distribution network at the end of last year and the investment of the active distribution network in that year. Detailed indicators are shown in table 1.

| First level index  | Second level index      | Third level index            |
|--------------------|-------------------------|------------------------------|
| output indicators  | Power supply quality    | Power supply reliability rate|
|                    |                         | voltage qualification rate   |

Figure 2. Comparison of two effectiveness evaluation flowcharts.
Household average blackout time per year
Power supply capability
- Capacity-load Ratio of High Voltage Distribution Network
- Ratio of heavy load lines
- Ratio of Heavy load transformer
- average household distribution capacity

Power network structure
- "N-1" Pass Rate of High Voltage Distribution Network
- distribution line connection Rate

Equipment level
- Cabling Rate of 10 kV Line
- Overhead line Insulation rate

Power grid efficiency
- Average Load Rate of Distribution Line
- line loss rate

Intelligent level of power grid
- Distribution automation coverage
- Smart meter coverage
- New energy penetration
- Density of Charging Facilities for Electric Vehicles

Input indicators:
- total assets of the distribution network up to the end of last year
- investment amount of the distribution network in the current year

2.3. Index scoring

- Step 1: Output performance scoring

The evaluation indicators for construction of distribution network can be divided into benefit type, cost type and interval type. Benefit type indicators are positive indicators, that is, the greater the index value, the better; cost type indicators are inverse indicators, that is, the smaller the index value, the better; interval type indicators are moderate indicators, that is, the index value is better in a certain range. For each individual index score, this paper uses the trapezoidal distribution linear membership function method, calculated according to the following formula.

For benefit type indicators,

\[ y = \frac{x-a}{b-a}, \quad x \leq b. \]  \hspace{1cm} (1)

For cost type indicators,

\[ y = \frac{a-x}{a-b}, \quad x \geq b. \]  \hspace{1cm} (2)

For interval type indicators,

\[ y = \begin{cases} \frac{x - b + a}{a} & x \leq b \\ \frac{a + b - x}{a} & x > b \end{cases} \]  \hspace{1cm} (3)

Formulas (1) to (3): x is the index value; y is the index score; a and b are the parameters of membership function, which are set individually according to the development goals of distribution network [22] and the relevant provisions of power industry. Taking "power supply reliability rate" as an example, this index belongs to benefit index, and its scoring formula is as follows:
According to the scoring formula, the scores of power supply reliability is shown in table 2.

Table 2. Scores of power supply reliability rate index.

| Power supply reliability rate | 0 | 20 | 40 | 60 | 80 | 100 |
|------------------------------|---|----|----|----|----|-----|
| Index scores                 | 99.799 | 7499 | 7799 | 8199 | 9199 | 965 |

Output performance is equal to the score of weighted summation of all individual indicators, using a linear model, i.e.

\[ y = \sum_{i=1}^{n} \omega_i x_i. \]  

In the formula: \( n \) is the number of indicators, \( x_i \) is the score of single indicators, \( \omega_i \) is the weight of indicator \( i \).

- Step 2: Input cost indicator scoring

In the effectiveness evaluation of the construction of the distribution network, the input cost index is the investment in per unit electricity sales, which is obtained by dividing the sum of the investment amount of the distribution network in the current year and the total assets of the distribution network up to the end of last year by the electricity sales in the current year, and then standardizing the result, i.e.

\[ C_{in} = \left( C_t + C_c \right) / E_s, \]  

In the formula: \( C_t \) is the total assets of the distribution network at the end of the previous year, \( C_c \) is the investment amount of the distribution network in the current year, \( E_s \) is the electricity sales of the current year, \( C_{in} \) is the input cost of the unit electricity sales.

- Step 3: Cost Effectiveness scoring

Cost performance is equal to the output performance score divided by the input cost score, i.e.

\[ C_{E} = I_{out} / C_{in}, \]  

In the formula: \( I_{out} \) is output performance, \( C_{E} \) is cost effectiveness.

2.4. Determining the weight of indicators by analytic hierarchy process

The weight of evaluation indicators reflects the relationship between indicators, which is assigned by analytic hierarchy process in this paper.

After comparing the indicators in pairs, the relative order of the evaluation indicators is determined by the 1-9 scale method, and the judgment matrix \( A \) of the evaluation indicators is constructed in turn.

\[
A = \begin{bmatrix}
1 & a_{12} & \cdots & a_{1n} \\
a_{21} & 1 & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & 1
\end{bmatrix}
\]

Where \( a_{ij} \) (\( i, j = 1, 2, \ldots, n \), \( n \) is the order of matrix \( A \)) represents the comparison results of the elements \( a_i \) and \( a_j \). The definition of scale 1-9 is shown in table 3.
Judgment scale

| Definition | Elements $a_i$ and $a_j$ are equally important |
|------------|-----------------------------------------------|
| 1          | $a_i$ is slightly more important than $a_j$   |
| 3          | $a_i$ is more important than $a_j$            |
| 5          | $a_i$ is much more important than $a_j$       |
| 7          | $a_i$ is obviously more important than $a_j$  |
| 9          | The elements lie between the two adjacent judgements mentioned above. |

The eigenvector corresponding to the maximum eigenvalue $\lambda_{\text{max}}$ of the matrix $A$ is the relative weight of each evaluation index, which is normalized as below,

$$ W_i = \frac{\sum_{i=1}^{n} w_i}{\sum_{i=1}^{n} w_i} $$

Obtain the weight vector $W' = (w'_1, w'_2, \ldots, w'_n)$. Where: $w_i$ is the relative weight of the $i$-th evaluation index, $n$ is the order of the matrix $A$.

Next, check the consistency of the judgment matrix. Introducing Compatibility Index,

$$ I_C = \left( \lambda_{\text{max}} - n \right) / (n - 1). $$

After calculating the IC value, look up the corresponding average consistency index IR value according to table 4.

| Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|
| $I_R$ | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

Finally, the consistency ratio is calculated.

$$ R_C = I_C / I_R. $$

If $R_C < 0.1$, the consistency of the judgment matrix is acceptable. If $R_C \geq 0.1$, the judgment matrix should be modified appropriately, and then the weight of the modified matrix and the consistency test should be recalculated.

Taking four third indicators (high voltage capacity-load ratio, heavy-load line ratio, heavy-load transformer ratio, average household distribution capacity) of power supply capacity as examples, judgment matrix is as below,

$$ A = \begin{bmatrix} 1 & 3 & 3 & 1 \\ 1/3 & 1 & 1 & 1/3 \\ 1/3 & 1 & 1 & 1/3 \\ 1 & 3 & 3 & 1 \end{bmatrix} $$

The maximum eigenvalue $\lambda_{\text{max}}$ of the matrix $A$ is 4, the corresponding eigenvector is $[0.6708 \ 0.2236 \ 0.2236 \ 0.6708]^T$, and the consistency check result $R_C = 0$, which satisfies the consistency requirement, and the weight matrix is normalized to $[0.375 \ 0.125 \ 0.125 \ 0.375]^T$, and the weight is $[0.4 \ 0.1 \ 0.1 \ 0.4]^T$ after rounding adjustment.

Based on the above analysis, the weight assignment of each indicator in this paper is shown in table 5.

| Table 5. Output Index weights. |
### 2.5. Analysis of evaluation results

| Second level index                  | Third level index                                                                 | Third level index weight |
|-------------------------------------|-----------------------------------------------------------------------------------|--------------------------|
| Power supply quality                | Power supply reliability rate                                                     | 0.3                      |
|                                     | voltage qualification rate                                                        | 0.4                      |
|                                     | Household average blackout time per year                                           | 0.3                      |
| Power supply capability             | Capacity-load Ratio of High Voltage Distribution Network                          | 0.4                      |
|                                     | Ratio of heavy load lines                                                         | 0.1                      |
|                                     | Ratio of Heavy load transformer                                                   | 0.1                      |
|                                     | average household distribution capacity                                           | 0.4                      |
| Power network structure             | "N-1" Pass Rate of High Voltage Distribution Network                              | 0.6                      |
|                                     | distribution line connection Rate                                                 | 0.4                      |
| Equipment level                     | Cabling Rate of 10 kV Line                                                         | 0.5                      |
|                                     | Overhead line Insulation rate                                                     | 0.5                      |
| Power grid efficiency               | Average Load Rate of Distribution Line                                            | 0.5                      |
|                                     | line loss rate                                                                   | 0.5                      |
| Intelligent level of power grid     | Distribution automation coverage                                                 | 0.3                      |
|                                     | Smart meter coverage                                                             | 0.3                      |
|                                     | New energy penetration                                                           | 0.2                      |
|                                     | Density of Charging Facilities for Electric Vehicles                             | 0.2                      |

![Four quadrant diagram](image)

**Figure 3.** Four quadrants diagram.

Four quadrant diagram is used to analyze the evaluation results, as shown in figure 3. Taking output performance as the ordinate and cost performance as the abscissa, the average value of a set of output performance and cost performance scores is evaluated as the origin, and the space is divided into four quadrants. Different scores determine its distribution position in the four quadrant diagram. The first quadrant represents both output and cost effectiveness above average, and is a value growth interval that can be built and invested in as previous years. The third quadrant represents that the output and cost performance are lower than the average level. It is an operational inefficiency interval. It is necessary to analyze the reasons for the low investment efficiency and optimize the planning plan and construction strategy. The second quadrant represents that the output is higher than average level, but the cost performance is lower, which is the output focus interval. The investment in the region can be
appropriately reduced, and the indicators with lower scores will be upgraded. The fourth quadrant represents the output is lower than average, but the cost performance is high, which is the cost efficiency focus interval. We can continue to implement the current planning and construction plan and increase investment in the region.

3. Case analysis and results
This section takes the construction of distribution network in some regions as an example, and carries out assessment work based on the public service value model.

3.1. Input indicators
The input cost index is obtained by standardizing the sum of the investment amount of the distribution network in 2017 and the total assets of the agricultural distribution network up to the end of 2016 divided by the electricity sales in 2017. The input cost indicators are shown in table 6.

| Region | Input cost index |
|--------|-----------------|
| A      | 0.68            |
| B      | 0.69            |
| C      | 0.67            |
| D      | 0.67            |
| E      | 0.71            |
| F      | 0.68            |
| G      | 0.69            |
| H      | 0.74            |
| I      | 0.7             |
| J      | 0.69            |
| K      | 0.72            |
| L      | 0.89            |
| M      | 0.98            |
| N      | 0.65            |

3.2. Output indicators
According to the above scoring method and weight assignment, the output performance of ural distribution network in these areas is calculated. Take Area A as an example, the initial data and score of each indicator is shown in table 7. The overall output performance in Area A was excellent, scoring 83.6 points. Among them, the indexes of power supply quality, power grid structure and power supply capability are excellent, with scores above 90. The equipment level and grid efficiency indicators are good, while the intelligent level indicators are not good, for the distribution automation coverage and distributed generation coverage need to be improved urgently.

| Second level index | Third level index | Third level index value | Third level index score | Third level index weight | Second level index score | Total score |
|--------------------|-------------------|-------------------------|-------------------------|--------------------------|--------------------------|-------------|
| Power supply quality | Power supply reliability rate % | 99.93 | 85 | 0.3 | 91.0 | 83.6 |
|                    | Voltage qualification rate % | 99.79 | 100 | 0.4 |     |     |
|                    | Household average blackout time per year/hour | 6.1 | 85 | 0.3 |     |     |
| Power supply capability | Capacity-load Ratio of High Voltage Distribution Network | 2.26 | 100 | 0.4 | 97.6 |
|                    | Ratio of Heavy load transformer % | 8.9 | 85 | 0.1 |     |     |
|                    | Average household | 9.57 | 91 | 0.1 |     |     |
|                    | Average household | 3.4 | 100 | 0.4 |     |     |
distribution capacity/kVA

| Power network structure | "N-1" Pass Rate of High Voltage Distribution Network/% | 9.09 | 100 | 0.6 | 96.6 |
|-------------------------|-------------------------------------------------|------|-----|-----|------|
|                         | distribution line connection Rate/%             | 83.08| 92  | 0.4 |
| Equipment level         | Cabling Rate of 10 kV Line/%                    | 21.4 | 87  | 0.5 | 78.0 |
|                         | Overhead line Insulation rate/%                 | 59.17| 69  | 0.5 |
| Power grid efficiency   | Average Load Rate of Distribution Line/%        | 40.7 | 69  | 0.5 | 77.2 |
|                         | line loss rate/%                                | 4.28 | 86  | 0.5 |
| Intelligent level of power grid | Distribution automation coverage/% | 1.6  | 30  | 0.3 | 61.0 |
|                         | Smart meter coverage/%                          | 100  | 100 | 0.3 |
|                         | New energy penetration/%                        | 0.21 | 60  | 0.2 |
|                         | Density of Charging Facilities for Electric Vehicles/(MVA/100·km²) | 0.76 | 50  | 0.2 |

The results of output performance of different regions are shown in table 8.

**Table 8. Output performance of active distribution network in each area.**

| Region | output performance | Region | output performance |
|--------|--------------------|--------|--------------------|
| A      | 83.6               | H      | 57.48              |
| B      | 68.49              | I      | 60.3               |
| C      | 72.19              | J      | 61.22              |
| D      | 70.34              | K      | 75.98              |
| E      | 71.48              | L      | 57.58              |
| F      | 70.81              | M      | 63.49              |
| G      | 59.34              | N      | 82.82              |

3.3. Analysis of evaluation results

According to the public service value model, taking output performance as ordinate and cost effectiveness as abscissa, and taking average output performance and average cost effectiveness as origin, the space is divided into four quadrants. The distribution of the scores in four quadrants diagram is shown in figure 4. 7 regions are in the value growth quadrant, accounting for 50%; 6 regions are in the operating inefficient quadrant, accounting for 42.86%, and one region is in the cost-effective focus quadrant, accounting for 7.14%.

Take Area A as an example, this area is located in the value growth area. The output index of this area is higher than the average value, and the grid effect is good. The investment efficiency is higher than the average value and the cost effectiveness is high. It is suggested that the investment strategy and the construction plan of previous years can be continued.

Take Area M as an example, this area is located in the operation inefficiency area, the output index of this area is lower than the average, the power grid effect is not good; the investment efficiency is lower than the average, the cost effectiveness is low; it is necessary to analyze the reasons of the low investment efficiency, and optimize the planning and construction plan and strategy.
Figure 4. Example of four-quadrant analysis of public service value model.

Take area B as an example, this area is located in the cost effectiveness focus area. The output index of this area is lower than the average value, and the power grid effect is not good. The investment efficiency is higher than the average value, and the cost effectiveness is high. It is suggested to increase investment and improve the output performance of this area.

Each region did not fall in the second quadrant, the output focus area. The output index of this region is higher than the average value, and the effect of power grid is good; the investment efficiency is lower than the average value, and the cost effectiveness is low. It is suggested that the total investment can be reduced appropriately, and the weak points of the third indicators should be focused on.

4. Discussion
The method is to analyze the distribution of a set of scoring data on the four-quadrant diagram, which can be used in two situations. One is to compare the difference of output performance and cost effectiveness scores of similar units in the same year, so as to compare the development and investment efficiency of different units. Another situation is to track the changes of output performance and cost effectiveness scores of a unit in different historical periods, and then to make performance prediction. The case study in this paper belongs to the former.

5. Conclusions
This paper takes the overall construction effect of distribution network as the research object, and studies the evaluation method of its transformation and upgrading effect, which is summarized as follows:

The existing effectiveness evaluation mainly focuses on the output performance evaluation, but cannot evaluate the difference of investment utilization efficiency between different units. Therefore, this paper studies a method of evaluating both the output performance of the grid and the cost effectiveness based on public service value model. Taking cost effectiveness as abscissa and output performance as ordinate, and taking the average value of output performance and cost effectiveness of regional distribution network as origin, the space is divided into four quadrants, and the evaluation conclusions and suggestions are put forward according to the quadrant of the evaluation object.

The output performance and cost effectiveness are calculated based on the data of the related indicators of the transformation and upgrading of distribution network in some areas of Hubei Province in China, and the evaluation conclusions and suggestions are given for the areas in different quadrants, which confirm the feasibility and effectiveness of the method.
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