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POWER DISTRIBUTION GRID INVESTMENT DECISION MAKING BASED ON MULTI-OBJECTIVE FLEXIBLE DECISION MAKING MODEL (MOFDMM)

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Abstract. *Power distribution grid (PDG) has the characters of small scale, short construction cycle, small independent investment, scatted location, etc., which makes the investment of PDG more risky and uncertain. Flexibility theory mainly focuses on uncertain problems, and the uncertain environment can be adjusted via the interference of decision-makers. Based on flexibility theory, this study builds a multi-objective flexible decision making model and builds an evaluation indicator system of PDG investment decision making, which contains economic indicators, technical indicators and social indicators. The model can measure the satisfaction of decision-makers by using two indicators: all schemes comprehensive degree (ASCD) and each scheme accomplishment degree (ESAD). On the premise that both ASCD and ESAD reach the satisfaction of decision-makers, then the schemes are ranked according to the score of another indicator: each scheme comprehensive degree (ESCD). Finally, the optimal scheme with the highest score of ESCD can simultaneously satisfy the economic benefit, technical performance, social benefit, as well as the satisfaction of decision-makers.*
Keywords: Power distribution grid, Multi-objective flexible decision making model, Investment decision making, Evaluation indicator system

1. **Introduction.** Power distribution grid plays an important part in connecting power generation sides, transmission and distribution sides, and the consumption sides. In recent years, the investment in PDG in China has been increasing, and the development of PDG has achieved remarkable effect. According to Action Plan of Construction and Renovation in Power Distribution Grid (2015-2020) issued by the National Energy Administration, the accumulated investment in PDG construction will not be less than 1.7 trillion CNY during 2015 to 2020 [1]. As large amounts of capital flowing into PDG construction, it is an urgent problem of how to make scientific decisions on PDG investment to achieve the desired objectives, and good economic and social benefits after putting the project into operation. However, PDG has the characters of small scale, short construction cycle, small independent investment, scatted location, etc., which makes the investment management not easier than the main power grid.

Currently, many scholars have studied the investment decision making of PDG and have made some achievements. Dong and Jiang [2] fully considered the positive and negative external benefits of PDG on the residents living, working and urban environment, and then established the investment benefit evaluation indicator system of urban PDG from the perspective of program whole-life cycle. Range index pretreatment method and combined weight method were used in their study to determine the weight of indicators. Based on the overall goal of investment benefits and the basic calculation model of benefit-cost ratio, Liu et al. [3] have evaluated the investment benefit of PDG by comprehensively considering electricity revenue, loss reduction benefit and invisible benefit. Liu et al. [4] have taken the overall investment returns, single project investment benefit and investment decisions into consideration and established investment benefit evaluation and decision making model for PDG of 35kV and under. Georgilakis and Hatziargyriou [5] have presented an overview of the art models and methods applied to the modern power distribution planning problem, analyzing and classifying current and future research trends in this field. Wallnerström et al. [6] have proposed a framework for more detailed quantitative risk analysis methods, aiming to allocate resources more cost-effectively for power distribution systems. As can be seen, the existing researches on PDG investment decisions mainly depend on the economic benefits, but ignore the experiences and preferences of decision-makers. Besides, the exclusive characters of PDG presented in investment decision making evaluation indicator system are not obvious. So the help they provide for investment decision-makers is very limited. Therefore, present paper introduces the flexible theory and builds a multi-objective flexible decision making model, which considers the complexity and the uncertainty in the process of investment decision making. Besides, this paper establishes an evaluation indicator system of investment decision making, which is more PDG characteristic, more scientific and more rational. This study provides strong theoretical support to the investment decision making of PDG.

The layout of this paper is outlined as follows. In the second section, the model basis of flexibility theory and flexible decision making are detailed, and a multi-objective flexible decision making model is established. In the third section, an evaluation indicator system of PDG investment decision making is built from two aspects, namely inflexible indicators and flexible indicators. Lastly, the model proposed is applied in the empirical analysis to test the decision making effect and draw a conclusion.

2. Model Basis.

2.1. Flexibility theory and flexible decision making.

Most decision making problems in reality need to consider many factors and balance them, and make investment plans from the overall comprehensively. These problems are called multi-objective decision making problems. If decision-makers are considered bounded rational, and the aspirations and preferences of the decision-makers are vague, semi-quantitative and expressed by language, and the constraints and objectives of decision making problems can be adjusted within a certain range [7], this type of decision making is called flexible decision making. Flexibility is an ability of the system itself that is able to deal with the uncertain and changing environment through self-adjustment, and to rapidly improve its efficiency by taking full advantage of the uncertainty and changes [8]. Generally, the higher the flexibility of the system is, the wider the range can be. Besides, less time and cost will be spent on making changes.

2.2. MOFDMM.

Suppose there are m alternative PDG investment schemes, namely $B = \{b_1, b_2, \ldots, b_m\}$. Decision making group which contains t decision-makers will select an optimal scheme. For each investment scheme, there are s evaluation indicators which compose the indicator set E, and $E = \{e_1, e_2, \ldots, e_s\}$. Due to the influence of random factors, there exist kinds of uncertain statuses in practice. The possibility of the statuses varies along with the difference of the indicators. Suppose the variable r represents the number of statuses for e_k $(k = 1, 2, \ldots, s)$ and the status set for e_k is Φ_k, and $\Phi_k = \{\varphi_{1k}, \varphi_{2k}, \ldots, \varphi_{rk}\}$. The occurring probability for φ_{jk} $(j = 1, 2, \ldots, r)$ is p_{jk}, which meets the following conditions as presented in Equation (1):

$$\sum_{j=1}^{r} p_{jk} = 1, \quad 0 < p_{jk} < 1 \tag{1}$$

For the scheme b_i $(i = 1, 2, \ldots, m)$, x_{ijk} represents the value of e_k under the status of φ_j. The three-dimensional matrix $C = (x_{ijk})_{m\times r\times s}$ is called flexible decision making matrix.

(1) Data normalization

Indicators are generally classified into two types: benefit type (E_1) and cost type (E_2). The incommensurability between different indicators makes the operation difficult. Normalization can transfer the values of different indicators into $[0, 1]$, which provides convenience for the following process. Set $\overline{x_{ijk}} = \max\{x_{ijk}\}$, $\underline{x_{ijk}} = \min\{x_{ijk}\}$, then:

For the indicators belonging to E_1, the data are normalized as Equation (2).

$$x'_{ijk} = \begin{cases} \frac{\left(x_{ijk}-\underline{x_{ijk}}\right)}{\left(\overline{x_{ijk}}-\underline{x_{ijk}}\right)}, & x_{ijk} > x_1^0 \\ 0, & x_{ijk} \le x_1^0 \end{cases} \tag{2}$$

where x_1^0 is the critical value of e_k, and $e_k \in E_1$. When x_{ijk} is small to a certain degree, the value does not have practical significance anymore. Therefore, x'_{ijk} is regarded as zero.

For the indicators belonging to E_2, the data are normalized as Equation (3) [9].

$$x'_{ijk} = \begin{cases} \frac{\left(\overline{x_{ijk}}-x_{ijk}\right)}{\left(\overline{x_{ijk}}-\underline{x_{ijk}}\right)}, & x_{ijk} < x_2^0 \\ 0, & x_{ijk} \ge x_2^0 \end{cases} \tag{3}$$

where x_2^0 is the critical value of e_k, and $e_k \in E_1$. When x_{ijk} is large to a certain degree, the value does not have practical significance anymore. Therefore, x'_{ijk} is regarded as zero.

(2) Combination weight determination

Suppose w_k is the combination weight of e_k. Three factors should be considered in the determination of w_k: ① The attention paid by decision-makers to each indicators, which can be represented by w_{k1}. w_{k1} reflects the aspiration and preference of decision-makers, and the value of w_{k1} is given by decision-makers in advance. In present study, Delphic method is used to determine w_{k1}. ② The decision making information transmitted to decision-makers, which can be represented by w_{k2}. w_{k2} is sensitive to evaluation matrix and scheme set. Entropy is a good tool to measure w_{k2}. Thus, entropy evaluation method is applied in this study to determine w_{k2}. ③ The reliability of evaluation result for each indicator, which contains uncertainty, randomness, fuzziness, and even the psychological factors of decision-makers. It is represented by w_{k3}, and present study uses set-valued statistic analysis to determine w_{k3}. w_k can be determined according to Equation (4):

$$w_k = f\left(w_{k1}, w_{k2}, w_{k3}\right) = \frac{w_{k1}\cdot w_{k2}\cdot w_{k3}}{\sum_{k=1}^{s} w_{k1}\cdot w_{k2}\cdot w_{k3}} \quad (k = 1, 2, \ldots, s) \tag{4}$$

(3) MOFDMM establishment

$W = (w_1, w_2, \ldots, w_s)$ is the weight vector of E. Because of the existing of uncertainty, the weight information for each indicator is partly known. Suppose that the known information forms the weight set τ, and $W \in \tau$. Establish the multi-objective flexible decision making model to maximize $z(W)$ as shown in Equation (5) and Equation (6):

$$\begin{aligned} &Max\ \ z(W) = (z_1(W), z_2(W), \ldots, z_m(W)) \\ &\text{s.t.}\ \begin{cases} W \in \tau \\ w_k = f\left(w_{k1}, w_{k2}, w_{k3}\right) \\ k = 1, 2, \ldots, s \end{cases} \end{aligned} \tag{5}$$

$$Min\ \ z_i(W) = \sum_{k=1}^{s} x_{ijk}\overline{w_k},\ i \in m$$

$$\text{s.t.} \quad \begin{cases} W \in \tau \\ \overline{w_k} = f\left(\overline{w_{k1}}, \overline{w_{k2}}, \overline{w_{k3}}\right) \\ k = 1, 2, \ldots, s \end{cases} \tag{6}$$

where, $\overline{w_{k1}}$, $\overline{w_{k2}}$ and $\overline{w_{k3}}$ are the maximum weight of e_k. $z_i^{\min}$, which is equal to $\sum_{k=1}^{s} x_{ijk}\overline{w_k}$, is called the negative ideal value of $ESCD$ for b_i.

In this study, the satisfaction of decision-makers is defined that the value of $ASCD$ $(Z(W))$ and the value of $ESAD$ $(\eta(z_i(W)))$ simultaneously satisfy the limit value set by decision-makers [10]. That is, $Z(W)$ should be greater than the lower limit value Z_0 and $\eta(z_i(W))$ should surpass the initial accomplishment degree η_i^0.

$Z(W)$ is defined as the sum of the distance between $z_i(W)$ and $z_i^{\min}$, which can be calculated as Equation (7):

$$Z(W) = \sum_{j=1}^{m} \left(z_i(W) - z_i^{\min}\right) \tag{7}$$

where $Z(W)$ is a strict monotone increasing function about $z_i(W)$. Establish single-objective optimal model as presented in Equation (8):

$$\begin{array}{ll} Max & Z(W) \\ \text{s.t.} & W \in \tau \end{array} \tag{8}$$

$\eta(z_i(W))$ can measure the implementation of each scheme. Taking the $z_i^{\min}$ as a reference point, $\eta(z_i(W))$ can be defined as the ratio between $z_i(W)$ and $\overline{z_i}$ as detailed in Equation (9).

$$\eta\left(z_i(W)\right) = \frac{z_i\left(W\right) - z_i^{\min}}{\overline{z_i} - z_i^{\min}} \tag{9}$$

For the equation above, $\overline{z_i}$ is the expectation level of decision-makers. $\eta(z_i(W))$ is a strict monotone increasing function about $z_i(W)$. The further away $z_i(W)$ is from $z_i^{\min}$, the higher accomplishment degree can be achieved.

Depending on $z_i(W)$, $\eta(z_i(W))$ and $Z(W)$ obtained above, decision-makers determine η_i^0 and Z_0. Taking overall consideration of the comprehensive degree and accomplishment degree, the model detailed in Equation (10) is established as follows.

$$Max \;\; J = \sum_{i=1}^{m} \eta_i \tag{10}$$

$$\text{s.t.} \quad \begin{cases} Z(W) \geq Z_0 \\ \eta\left(z_i(W)\right) \geq \eta_i \geq \eta_i^0 \\ W \in \tau \end{cases}$$

If Equation (10) is solvable, the optimal solution is the efficient solution of multi-objective optimal model presented in Equation (4). If Equation (10) is unsolvable, the decision-makers should reset η_i^0 and Z_0, and calculate $z_i(W)$, $\eta z_i(W)$ and $Z(W)$ for the second time. If the result satisfies the request of decision-makers, then rank the schemes according to the score of $z_i(W)$. The scheme with the highest score is the most satisfactory one. Otherwise, decision-makers should make appropriate adjustment of η_i^0 and Z_0. Solve the model again until the decisionmakers are satisfied with the result.

3. **Evaluation Indicator System of PDG Investment Decision Making.** A number of factors need to be considered when making investment decision of PDG. The establishment of evaluation indicator system of investment decision making should follow the principles such as scientificity, comprehensiveness, hierarchy, practicability, and quantitative and qualitative analysis. In order to make scientific and rational investment decisions of PDG, this paper digs the main factors affecting the PDG investment decisions, and then establishes the evaluation indicator system of PDG investment decision

TABLE 1. Evaluation indicator system of PDG investment decision making

First class	Second class	Processing	Unit	Type
Economic benefit	IRR (Internal Rate of Return)	$\sum(CI - CO)_t \times (1 + IRR)^{-t} = 0$ where CI is cash inflow, and CO is cash outflow.	%	Benefit
	PP	$\sum_{t=0}^{pp} NB_t = K$ where K is total investment, and NB_t is net income in the year of t.	Year	Cost
	Revenue growth per unit of reduced line loss	Revenue growth per unit of reduced line loss = Rate of reduced line loss × Electricity price where Rate of reduced line loss = (Line loss of the current year–Line loss of the last year)/Line loss of the last year	100 × kWh/CNY	Benefit
	Revenue growth per unit of increased power supply	Revenue growth per unit of increased power supply = Rate of increased power supply × Electricity price where Rate of increased power supply = (Electricity sale of the current year–Electricity sale of the last year)/Electricity sale of the last year	100 × kWh/CNY	Benefit
Technical performance	Cabling rate	Cable length/Total line length × 100%	%	Benefit
	Number of line fault	The number of line fault per hundred thousand meters per year	Times/100km/year	Cost
	Qualified rate of line loading	Qualified rate of line loading = The number of the lines meeting the load requirements/The total number of the lines × 100%	%	Benefit
	Rate of loop network	Rate of loop network = The number of loop network/The total number of the lines × 100%	%	Benefit
Social benefit	Coordination between new construction and reconstruction	Qualitative indicators, which can be quantified by expert scoring	1	Benefit
	THDu	THDu = $\sqrt{U_2 \times U_2 + U_3 \times U_3 + \cdots + U_n \times U_n}$ $/U_1 \times 100\%$ where U_n is the harmonic voltage effective value for the Nth time, and U_1 is the fundamental voltage effective value	%	Cost
	Public satisfaction	Public satisfaction = The number of questionnaires with the score $\geq$ 90/The number of questionnaires recovered	%	Benefit

making. The factors are decided according to previous studies and the experience of the writers. The evaluation indicator system of PDG investment decision making is presented in Table 1.

4. **Empirical Analysis.** In this part, an 110KV PDN program is taken as an example. There are six alternative schemes for this program, and the aim of investment decision

TABLE 2. Original and normalized data for the alternative schemes

Indicators		Original data						Normalized data					
		b_1	b_2	b_3	b_4	b_5	b_6	b_1	b_2	b_3	b_4	b_5	b_6
IRR	e_1	14.2	11.7	10.8	13.7	15	13.3	0.81	0.21	0.00	0.69	1.00	0.60
PP	e_2	9	8	10	11	9	11	0.67	1.00	0.33	0.00	0.67	0.00
Benefit growth per unit of reduced line loss	e_3	0.54	0.46	0.56	0.49	0.51	0.49	0.82	0.00	1.00	0.30	0.52	0.32
Benefit growth per unit of increased power supply	e_4	2.44	1.15	1.23	2.07	1.99	1.76	1.00	0.00	0.06	0.71	0.65	0.47
Cabling rate	e_5	74	76	65	78	59	70	0.79	0.89	0.32	1.00	0.00	0.58
Number of line fault	e_6	5	11	6	3	0	2	0.55	0.00	0.45	0.73	1.00	0.82
Qualified rate of line loading	e_7	99	91	94	95	99	97	1.00	0.00	0.38	0.50	1.00	0.75
Rate of loop network	e_8	83	81	79	82	77	77	1.00	0.67	0.33	0.83	0.00	0.00
Coordination between new construction and reconstruction	e_9	9	7	8	8	9	9	1.00	0.00	0.50	0.50	1.00	1.00
THDu	e_{10}	0.5	1.4	1.1	0.9	0.8	1	1.00	0.00	0.33	0.56	0.67	0.44
Public satisfaction	e_{11}	89	82	79	90	91	88	0.83	0.25	0.00	0.92	1.00	0.75

making is to select the optimal scheme. According the market survey and analysis, the market in near future may be in three statuses: good, general and poor. Therefore, the value of r is 3. The relevant data of the six schemes and 11 indicators are detailed in Table 2.

Due to the impact of uncertainty, the weight vector information of the 11 indicators is partly known. Thus, the weight set τ is represented as follows:

$\tau = \{W = (w_1, w_2, \ldots, w_{11}) | 0.2 \leq w_1 \leq 0.41,\ 0.1 \leq w_2 \leq 0.15,\ 0.5 \leq w_3 \leq 0.72,\ w_4 \leq 0.03,\ 0.21 \leq w_5 \leq 0.45,\ w_6 \leq 0.31,\ 0.06 \leq w_7 \leq 0.09,\ 0.4 \leq w_8 \leq 1.8,\ w_9 \leq 0.06,\ 0.55 \leq w_{10} \leq 0.67,\ 0.31 \leq w_{11} \leq 0.65,\ \sum_{k=1}^{11} W_k = 1, W_k \geq 0, k = 1, 2, \ldots, 11\}$

Negative ideal value $z_i^{\min}$ for each scheme b_i $(i = 1, 2, \ldots, 6)$ can be obtained according to Equation (6):

$z_1^{\min} = 0.516;\ z_2^{\min} = 0.120;\ z_3^{\min} = 0.134;\ z_4^{\min} = 0.445;\ z_5^{\min} = 0.485;\ z_6^{\min} = 0.325$

The decision-makers put forward the expectation level $\overline{z_i}$ for each scheme:

$\overline{z_1} = 0.71;\ \overline{z_2} = 0.2;\ \overline{z_3} = 0.2;\ \overline{z_4} = 0.54;\ \overline{z_5} = 0.65;\ \overline{z_6} = 0.42$

According to single-objective optimal model as shown in Equation (8), each scheme comprehensive degree $z_i(W)$ can be obtained.

$z_1(W) = 0.618;\ z_2(W) = 0.315;\ z_3(W) = 0.219;\ z_4(W) = 0.484;\ z_5(W) = 0.521;\ z_6(W) = 0.378$

All scheme comprehensive degree $Z(W)$ and each scheme accomplishment degree η $(z_i(W))$ can be gotten by Equation (7) and Equation (9):

$Z(W) = 0.4764$

$\eta(z_1(W)) = 0.5105 \quad \eta(z_2(W)) = 2.4375 \quad \eta(z_3(W)) = 1.2812$

$\eta(z_4(W)) = 0.4099 \quad \eta(z_5(W)) = 0.2202 \quad \eta(z_6(W)) = 0.5616$

The decision-makers put forward the lower limit value Z_1 and the initial value η_i^1 as shown below:

$Z_1 = 0.45;\ \eta_1^1 = 0.40;\ \eta_2^1 = 2.1;\ \eta_3^1 = 1.5;\ \eta_4^1 = 0.47;\ \eta_5^1 = 0.32;\ \eta_6^1 = 0.5$

Solve Equation (10) and obtain each scheme comprehensive degree $z_i(W^1)$, all scheme comprehensive degree $Z(W^1)$ and each scheme accomplishment degree $\eta(z_i(W^1))$:

$z_1(W^1) = 0.615;\ z_2(W^1) = 0.316;\ z_3(W^1) = 0.219;\ z_4(W^1) = 0.489;\ z_5(W^1) = 0.520;\ z_6(W^1) = 0.378$

$Z(W^1) = 0.5124$

$\eta(z_1(W^1)) = 0.5116 \quad \eta(z_2(W^1)) = 2.4500 \quad \eta(z_3(W^1)) = 1.2888$

$\eta(z_4(W^1)) = 0.4626 \quad \eta(z_5(W^1)) = 0.2136 \quad \eta(z_6(W^1)) = 0.5574$

From the above results we can see, the value of $Z(W^1)$ is 0.5124, which is greater than the lower limit. However, the accomplishment degrees of b_3, b_4 and b_5 are lower than the initial values. Therefore, decision-makers are not satisfied with the result. According to the need of decision-makers, η_1^1 is increased to 0.45 and η_5^1 is decreased to 0.26. The value of Z_1 remains unchanged. Solve Equation (10) once again and obtain the second decision result as shown below.

$z_1(W^2) = 0.604$; $z_2(W^2) = 0.321$; $z_3(W^2) = 0.255$; $z_4(W^2) = 0.501$; $z_5(W^2) = 0.534$; $z_6(W^2) = 0.384$

$Z(W^2) = 0.5744$

$\eta(z_1(W^2)) = 0.4550 \quad \eta(z_2(W^2)) = 2.5125 \quad \eta(z_3(W^2)) = 1.8359$

$\eta(z_4(W^2)) = 0.5890 \quad \eta(z_5(W^2)) = 0.2982 \quad \eta(z_6(W^2)) = 0.6207$

For the second result of decision making, all the value of $Z(W^2)$ and $\eta(z_i(W^2))$ can satisfy the request of decision-makers. Then rank the six schemes according to the sort of $z_i(W^2)$:

$$b_1 \succ b_5 \succ b_4 \succ b_6 \succ b_3 \succ b_2$$

The ranking shows that: though the IRR of b_5 is better than b_1, the technical performance indicators of b_5 are obviously inferior to b_1. The technical performance of b_4 and b_5 are about the same, but b_5 possesses better economic benefit. Therefore, b_4 is placed behind b_5. b_2, b_3 and b_6 do not have significant advantage comparing to the first three schemes. Finally, b_1 is the best decision, which can satisfy the decision-makers, and at the same time reaches the economic, technical and social request.

5. **Conclusions.** The flexibility theory is a good tool to solve uncertain problems of investment decision making. Present study combines the flexibility theory and multi-objective decision making theory, and builds a multi-objective flexible decision making model. MOFDMM can deal with PDG investment decision making problems with great complexity and uncertainty. In addition, this study establishes PDG investment decision making evaluation indicator system, which contains four economic benefit indicators, four technical performance indicators and three social benefit indicators. This model is applied in an empirical case and gets the conclusion that MOFDMM built in present paper can take a full consideration of decision-makers' rational thinking and preference, and simultaneously satisfy the request of economic benefit, technical performance and social benefit. Though this research is applicable and feasible in theory and practice, the indicator system still needs to be completed and modified in investment practice. In addition, the model also is improved by adding more constructions such as financing cost and environmental cost. This is what we will work on in the near future.

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