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Optimization Method for Distribution Network Investment Projects on the Basis of Brittle Link Entropy and Cumulative Prospect Theory

Jianzhou Wen[1,*], Huiyang Wang[1], Xiaoxu Li[1], Gelin Zhang[1] and Fen Cheng[1]

[1]*State Grid Shanxi Electric Power Company Yuncheng Power Supply Company, Yuncheng 044000, China*

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Abstract

An optimization method for distribution network investment projects on the basis of brittle link entropy and cumulative prospect theory was proposed to address the problem of single time scale and insufficient consideration of the correlation between projects in traditional distribution network investment. First, brittle link entropy was applied to analyze the correlation between projects and calculate the project implementation risks. Second, projects were divided into three levels in accordance with their implementation purposes, and the relationship between them and the distribution network indexes was established to determine the contributions of the distribution network projects to the power grid. On this basis, an evaluation index system for projects was created. Last, the projects were comprehensively evaluated using cumulative prospect theory containing the time discount function, and the scores of all the projects were given based on the project implementation risks and prospect values. With the total score of the project group being the highest, an investment optimization model was established, and the optimal investment scheme was obtained by the hybrid bat algorithm. Analyses of numerous examples show that the risks of project investment can be measured by brittle link entropy, and the necessity of project implementation can be scored using the project evaluation method based on cumulative prospect theory containing the time discount function.

Keywords: Distribution network investment, Brittle link entropy, Time discount function, Cumulative prospect theory, Hybrid bat algorithm

1. Introduction

To meet the stringent requirements of the whole society regarding the total amount and quality of electricity supply in China, the power industry, as the basis of the national economy, is continuously increasing its investment in various aspects. With the strengthening of the transmission grid structure, the input–output ratio shows a decreasing marginal effect trend. In addition, the requirement of achieving precise investment and solving the weak and unbalanced development at both ends of the power grid proposed by power system reform has gradually tilted the investment of power grid enterprises toward distribution networks [1, 2]. Although relevant policies and measures have achieved good results, decisions to invest in distribution networks are difficult to make because of China's vast territory, relatively unbalanced economic development, considerable urban–rural differences in distribution network construction, need for further improvement in power supply level and quality, regional differences in distribution network development, and economic imbalances. Aside from fulfilling its power supply responsibilities, the power grid also needs to ensure the economic benefits of enterprises to achieve the maximization of economic and social benefits in the established investment plan. Moreover, with the integration of distributed energy, the deepening of the supply–demand interaction, the opening up of incremental distribution businesses, and the implementation of energy substitution strategies, the distribution network, as an important link that ensures high-quality, high-reliability electricity for users, can no longer adapt to the development needs of power supply reliability and distribution intelligence [3, 4]. Traditional investment methods for distribution networks often rely on empirical judgment and historical data and lack precise forecasts for future load changes, technological innovations, and market trends. Thus, these methods cannot effectively address the challenges posed by the contradictions between power supply and demand and uneven resource allocation.

Precise investment has become a popular topic in studies because it is a means to make distribution network investments refined and intelligent and resource allocation optimal. As a critical aspect of the construction and optimization of modern power infrastructures, precise investment in distribution networks, given its efficient resource allocation, precise demand response, and sustainable development strategies, demonstrates immense potential and value in various fields such as smart grid construction, urban grid renovation, rural grid upgrading, and renewable energy integration [5]. However, the complexity of distribution network structures and the numerous factors that need to be considered during planning and construction pose substantial challenges in accurately assessing the vulnerable points of distribution networks, thereby affecting the precision of investments.

On this basis, researchers have conducted extensive research on distribution network investment methods [6]. However, issues, such as the weak correlation between investment projects and distribution network indexes and unclear investment optimization objectives, still exist. Meanwhile, as the number of distribution network projects increases and the investment scale expands, the current

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*E-mail address: 18935061133@163.com

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strategy for precise investment in distribution networks needs to solve problems concerning the relationships between projects, the prioritization of project investments, and targeted investments in the vulnerable points of distribution networks. Therefore, methods for the accurate evaluation of distribution network projects and precise investment in them need to be developed to effectively guide the planning, construction, and renovation of distribution networks and maximize the benefits.

To this end, this study analyzed the correlation between projects by using brittle link entropy, considered the correspondence between project objectives and distribution network evaluation indexes, established a project evaluation index system, and combined the time discount function and cumulative prospect theory to comprehensively evaluate projects. Then, an investment optimization model was established to obtain an investment scheme for maximizing investment benefits and achieving precise investment in distribution networks. This work provides a reference for power grid planning and construction.

2. State of the Art

Precise investment is an investment strategy for achieving optimal resource allocation, aiming at targeted investment in vulnerable points on the basis of the accurate evaluation of distribution networks and in consideration of regional characteristics, policy requirements, and project rationality. Scientific and reasonable evaluation of a distribution network is required to ensure investment precision, and this process encompasses multiple aspects, such as economic operation, intelligent development, and investment benefits. After a comprehensive evaluation index system is established for a distribution network, the weight of each index needs to be measured. Commonly used weighting methods include the analytic hierarchy process method [7, 8], order relation analysis [9], Delphi method [10], entropy weight method [11, 12], and the criteria importance through intercriteria correlation method [13]. Jia et al. [14] proposed a combined weighting method on the basis of game theory. In terms of evaluation, scholars frequently used gray relational analysis [15] and the technique for order of preference by similarity to the ideal solution (TOPSIS) [16]. Xu et al. [17] improved the calculation of the closeness between the actual value and the optimal value of indexes in the traditional TOPSIS method, making the results increasingly accurate and clear. After a distribution network is accurately evaluated, the evaluation results need to be correlated with projects to select the optimal scheme for investment in projects. The methods for selecting distribution network investment projects can be broadly divided into multiattribute decision-making and optimization models for distribution network investment decisions.

Extensive research has been conducted on the multiattribute decision-making model. With this method, an evaluation index system is established, and weights are assigned to the indexes related to project selection, thereby allowing alternative projects to be ranked based on factors, such as investment benefits. Then, projects with high rankings are selected based on investment amounts. In terms of establishing an evaluation index system, current studies mainly consider factors, such as project risks and degree of improvement in power supply reliability [18]. Li et al. [19] combined project attributes with distribution network evaluation indexes and built an optimal index system for projects on the basis of the established distribution network evaluation indexes. Yang et al. [20] created a double-layer evaluation index system for investment benefits and selected projects with the maximum investment returns by considering the relationships between projects. Wang et al. [21] proposed the prospect theory of “rewarding the good and punishing the bad” to calculate the comprehensive optimal prospect value of all investment projects and ranked them accordingly. Liu [22] divided the project selection process into two steps: project selection focusing on the key planning indexes and project selection focusing on common planning indexes.

With the improvement of distribution network construction, integration of distributed power sources, and increase in user participation, the content of project evaluation has been enriched. Zhang et al. [23] considered interactive source–grid–load–storage effects and established an index system for making investment decisions from the perspectives of power supply, grid, and load. Commonly adopted comprehensive evaluation models include the TOPSIS method, fuzzy theory [24], and prospect theory [25]. The evaluation results of projects are prioritized in the multiattribute decision-making model, and they are effective when the number of projects is limited or no correlation exists between alternative projects. However, they are inapplicable when the number of alternative projects is large or when the correlation between projects is high.

An optimization model for investment decision-making in distribution networks can be obtained by setting corresponding investment objective functions and constraints, such as investment amounts, and the optimal investment scheme can be derived by solving the model via optimization algorithms. With the ever-increasing scale of investment in distribution networks and the diversification of construction objectives, optimization models of investment decision-making have considerable advantages over multiattribute decision-making models [26–28]. In terms of model establishment, Yang et al. [29] built a multiobjective investment optimization model for maximizing economic benefits, development potential, and grid reliability. Pan et al. [30] established an optimization model by using the decrease in annual average outage time for users, economy, and reliability as the objective functions. Jin et al. [31] built a project investment evaluation system that included economic, reliability, and environmental benefits and an investment time series optimization model with maximum overall benefits by using the planning period as the objective function. Yang et al. [32] utilized deep transfer learning to establish an investment optimization model with optimal economy, performance improvement, and optimization of comprehensive indexes. Gao et al. [33] introduced an index system for the risks and benefits of grid investment, and an investment optimization model with constraints, such as investment amount, power demand, and low-carbon requirement. Liu et al. [34] established a multiobjective optimization model for investment schemes with the goal of maximizing economic, social, and security benefits within the annual investment amount and used the multistep iterative ranking learning method to solve the model. Javadi et al. [35] built and solved an optimization model, with investment costs, operating costs, and system reliability during the planning period as objective functions.

In terms of model solution, the application of intelligent algorithms makes the obtainment of an optimal or near-optimal investment solution within a complex decision space possible, thereby effectively enhancing the scientificity and rationality of investment schemes for distribution networks. Thus, researchers have begun to use advanced intelligent algorithms to solve optimization models. Gao et al. [36] utilized the non-dominated sorting genetic algorithm II to solve the multiobjective optimization model for a grid investment scheme. Ma et al. [37] proposed a method for solving the investment optimization model on the basis of deep learning. Compared with the multiattribute decision-making model, the optimization model for investment decision-making can use multiple specific performance indexes as objective functions with multiple constraints, such as investment amount and project correlation. However, with the increase in project numbers, the diversification of project types, and the complication of relationships between projects, how to effectively improve the performance of distribution networks, coordinate the relationships between projects, consider the risks existing in an investment scheme, and optimize investment directions, scales, and structures have become urgent problems that need to be solved.

To address these problems, this study proposed a method to optimize investments in distribution network projects on the basis of brittle link entropy and cumulative prospect theory. The main steps in this study were as follows:

(1) Brittle link entropy was introduced to analyze the correlation between projects, and the brittle risks of the projects were calculated.

(2) The projects were divided into three levels in accordance with the implementation purposes. The corresponding relationship between the project purposes and distribution network indexes was established, and the contributions of the distribution network projects to the power grids were determined. On this basis, an evaluation index system for projects was built.

(3) An evaluation method for distribution network projects was proposed based on cumulative prospect theory containing the time discount function. An investment optimization model was then established, and project optimization was realized.

The remainder of this study is organized as follows. The third section introduces the analysis of project relevance and the evaluation of distribution network projects. A project optimization model is established and solved using the hybrid bat algorithm. The fourth section analyzes the advantages and effectiveness of the proposed method through numerical examples. The final section summarizes the study and indicates that the risks of project investment can be measured by brittle link entropy, and the necessity of project implementation can be scored using a project evaluation method based on cumulative prospect theory containing the time discount function. The method here can serve as a reference in distribution network investment planning.

3. Methodology

3.1 Analysis of project correlation

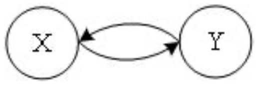
In practical situations, projects influence and restrict each other. Therefore, whether the implementation of a project meets relevant standards directly or indirectly affects the benefits of other projects and the total benefit of project investment. Therefore, the correlation between projects must be considered. In this study, brittle link entropy [38] is used to reveal the effect of the implementation of other projects on another project. The higher brittle link entropy is, the greater the effect is and the higher the risk of the project is.

(1) Brittle link entropy of projects

If the expected goal of a project is not achieved because of the influence of internal or external factors, this failure may have a direct or indirect effect on the benefits of other projects. This property is called brittleness.

The basic brittle link between two projects, X and Y, is divided into unilateral and complete brittle links, as shown in Fig. 1. In the former, when the intended goal of Project X is not achieved, Project Y is affected; however, when the intended goal of Project Y is not achieved, Project X is not affected. In the latter, failure to implement one project affects the other project. Fig. 1 shows that a complete brittle link is equivalent to two unilateral brittle links.

(a) Unilateral brittle link



(b) Complete brittle link

Fig. 1. Basic brittle link diagram

The link between projects is represented by state vector $S = (s_1, s_2, \cdots)$, a set of characterizing state parameters for a project. If Project X is not successfully implemented, that is, the values of all the parameters in the state vector for Project X deviate from the normal range, and if parameter value s_i ($i = 1, 2, \cdots$) in the state vector for Project Y exceeds the normal range, then the same link exists between Y and X. If value s_i is within the normal range, then an opposite link exists between Y and X. If value s_i fluctuates between normal and abnormal values, then a fluctuating link exists between Y and X. The brittle link between Y and X can be defined as:

$$u = a + bI + cJ \tag{1}$$

where a, b, and c are ratios of the number of state parameters for the same, opposite, and fluctuating links between Y and X, respectively, to the total number of state parameters. I and J are the coefficients for opposite and fluctuating measures, respectively.

The brittle link between Y and X can be expressed as brittle link entropy $H^{r_{XY}}$:

$$H^{r_{XY}} = w_a H_a^{r_{XY}} + w_b H_b^{r_{XY}} + w_c H_c^{r_{XY}} \tag{2}$$

where $H_a^{r_{XY}}$, $H_b^{r_{XY}}$, and $H_c^{r_{XY}}$ denote brittle similar, brittle opposite, and brittle fluctuating entropy, respectively. w_a, w_b, and w_c are the weight coefficients of $H_a^{r_{XY}}$, $H_b^{r_{XY}}$, and $H_c^{r_{XY}}$, respectively. $H_a^{r_{XY}}$, $H_b^{r_{XY}}$, and $H_c^{r_{XY}}$ are obtained as:

$$H_a^{r_{XY}} = -p_a(Y|X) \ln p_a(Y|X) \tag{3}$$

$$H_b^{r_{XY}} = -p_b(Y|X) \ln p_b(Y|X) \tag{4}$$

$$H_c^{r_{XY}} = -p_c(Y|X)\ln p_c(Y|X) \tag{5}$$

where p_a , p_b , and p_c are the probability of the brittle similar, brittle opposite, and brittle fluctuating links between Y and X, respectively.

The expected cost, expected profit, and expected risk of a project are selected to be state vector $S=(s_1,s_2,s_3)$ in this study.

(2) Interaction effects of projects

The correlation between projects originates from their interaction effects, that is, all projects affect and restrict each other in terms of resources, profits, or results. Therefore, the interaction effect can be divided into resource, profit, and result interaction effects. The resource interaction effect refers to the sharing of some resources among projects to improve investment efficiency. The profit interaction effect refers to the direct or indirect influence of the profits from the successful implementation of some projects on the profits from other projects, and the result interaction effect refers to the probability of successful implementation of a project depending on whether another project is successfully implemented or not. The brittle link between the state parameters of projects under the above-mentioned interaction effects are shown in Table 1, where $+$, $-$, and $+/-$ stand for the same, opposite, and fluctuating links, respectively.

Table. 1. Brittle link between the state parameters of projects under all interaction effects [39]

interaction effects	expected cost	expected profit	expected risk
resource	+/-	-	-
profit	-	-	-
result	-	+/-	+
result & profit	-	+/-	+
resource & profit	+/-	-	-
resource & result	+/-	+/-	+
resource& profit &result	+/-	+/-	+

(3) Calculation of the brittle risk of projects

The brittle risks of a project can be calculated by the brittle link entropy between the project and other projects. The steps are as follows:

Step 1: Establish a set of interactions between projects for a given project group, denoted by:

$$R=\{r_{ij} | i \neq j; i,j=1,2,\cdots\} \tag{6}$$

where r_{ij} represents unilateral brittle link $i \rightarrow j$ between Projects i and j.

Step 2: Compare the type of r_{ij} with that in Table 1 and calculate $H_a^{r_{ij}}$, $H_b^{r_{ij}}$, and $H_c^{r_{ij}}$ of all the unilateral brittle links, by applying Eqs. (3)-(5).

Step 3: Use the catastrophe progression method to calculate the weight coefficients as:

$$\begin{cases} |w_a| = \sqrt{-p_a \ln p_a} \\ |w_b| = \sqrt[3]{-p_b \ln p_b} \\ |w_c| = \sqrt[4]{-p_c \ln p_c} \end{cases} \tag{7}$$

where $w_a \geq 0$, $w_b \leq 0$, and $w_c \geq 0$.

Step 4: Use the brittle link entropy between Project i and other projects to calculate the brittle risk of Project i as follows:

$$h_i = \sum_j H^{r_{ij}} \tag{8}$$

3.2 Evaluation of the distribution network projects

(1) Contribution of a project

The level of improvement in power grid performance due to the implementation of a project is an important index to evaluate the necessity of investing in the project, which is called the contribution of the project. Given that different distribution network projects have different purposes and contributions, they are divided into three categories on the basis of their purposes. The first one (top priority) is responsible for solving the problems that threaten the safe and stable operation of power grids. The second one is mainly used to optimize power grids or solve potential problems that threaten them. The third one (bottom priority) is responsible for power grid renovations. The project purposes and the corresponding distribution network indexes are shown in Table 2.

The scoring function $f(x_1,x_2,\cdots,x_q)$ for the comprehensive evaluation of a distribution network originates from the extension model. In scoring function *f*, q is the number of evaluation indexes of the distribution network. The score of the indexes of the distribution network is denoted by $z=\{z_1(x_1),z_2(x_2),\cdots,z_q(x_q)\}$, and the contribution of the unit growth of index i to the total score is:

$$e_i = \frac{\partial f}{\partial x_i}\Big|_z \tag{9}$$

The contribution of a project under project purpose k can be calculated using Eq. (9) as follows:

$$E_k = \sigma_k \sum_i e_i, i \in \phi_k \tag{10}$$

where σ_k is the importance of the project under project purpose k (1, 0.3, and 0.1 stand for project categories 1, 2, and 3, respectively) and ϕ_k is the set of indexes corresponding to project purpose k.

(2) Index system for project evaluation

Project evaluation indexes reflect the project's attributes and can be used to evaluate the risks and profits of project investment. The index system for project evaluation in this study is shown in Fig. 2, where technical maturity reflects the level of project implementation risks, gross domestic product (GDP) growth and total tax payment denote the direct economic profits from the implementation of the projects, and urgency reflects the urgency of project implementation.

Table 2. Project purposes and the corresponding distribution network evaluation indexes

Category	number	Project purpose	Distribution network evaluation index
1	A1	Solve the overload of medium voltage lines	Power supply reliability rate Heavy overload rate of 10-kV lines
	A2	Improve the typical connection rate, contact rate, reasonable segmentation level in power supply areas of class B and C ; Rectify and reform lines whose tripping rates rank top 25％ in various cities	Power supply reliability rate Transferable power supply rate of medium voltage line Line loss rate of ultra-long and weak 10-kV lines
	A3	New outgoing lines (renovated medium voltage lines)of substations can supply new loads with power	Line loss rate Transferable power supply rate of medium voltage line Heavy overload rate of 10-kV lines Number of ultra-long and weak 10-kV lines
	A4	Renovation of distribution areas with low-voltage inventory problems that can not be solved by maintenance and load transfer	Comprehensive voltage qualification rate The number of distribution areas with low voltage
	A5	Solve the problem of distribution transformer overload	Power supply reliability rate Overload distribution ratio
	A6	Solve the problem of unqualified terminal voltage of medium voltage transmission lines (below 9.3kV)	Comprehensive voltage qualification rate Number of low-voltage lines
	A7	Improve the medium voltage grid structure (increase in typical connection rate, contact rate, reasonable segmentation, etc.)	Power supply reliability rate Transferable power supply rate of medium voltage line Proportion of light load medium voltage lines Proportion of Light load distribution
	A8	Improve the typical wire rate, contact rate, reasonable segmentation, and distribution automation level of central urban areas (Class A+, A power supply areas of class A+, A) and "1-hour power supply areas"	Power supply reliability rate Transferable power supply rate of medium voltage lines Effective coverage rate of feeder automation
2	B1	Solve the problem of annual power outages exceeding 100 hours for a single customer (excluding the impact of major events)	Power supply reliability rate Number of ultra-long and weak 10-kV lines
	B2	Solve the heavy load of the distribution transformer that is expected to be overloaded within two years)	Power supply reliability rate
	B3	Solve the problem that lines do not meet N-1 requirements (areas of class A+,C)	The ' N-1 ' passing rate of 10-kV lines
	B4	Solve the problem of low voltage that is expected to occur within two years and cannot be resolved through maintenance and load transfer in the distribution areas	Comprehensive voltage qualification rate Number of distribution areas of low-voltage
	B5	Solve the problem of low voltage that is expected to occur within two years and cannot be resolved through maintenance and load transfer on medium voltage lines	Comprehensive voltage qualification rate Number of low-voltage lines
	B6	Solve the problem of overload of medium-voltage lines that is expected to be overloaded within two years	Power supply reliability rate Heavy overload rate of 10-kV lines Number of ultra-long and weak 10-kV lines
	B7	Solve the problems that customers have a lot of complaint on power supply	12398 / 95598 Complaint
	B8	Ensure that the rural power grid's rural distribution transformer capacity, power supply reliability, and voltage pass rate indexes are not less than the state requirements	Power supply reliability rate Comprehensive voltage qualification rate
	B9	Wind-resistant and ice-	Power supply reliability rate

		resistant reinforcement to Improve the ability to withstand natural disasters	
	B10	Newly build and renovate various terminal equipment for power distribution automation, distribution transformer, metering, etc, and distribution network communication	Effective coverage rate of feeder automation
	B11	Comprehensive treatment of low voltage, implementation of rural power grids in remote poverty-stricken areas, including Tibetan areas.	Comprehensive voltage qualification rate The number of low voltage area
3	C1	Solve the problem that lines do not meet ‘N-1‘requirements(areas of class D and E)	The ' N-1 ' passing rate of 10-kV lines
	C2	Solve the problem that distribution transformers do not meet N-1 requirements (areas of class D and E)	The 'N-1'passing rate of 10-kV distribution transformers

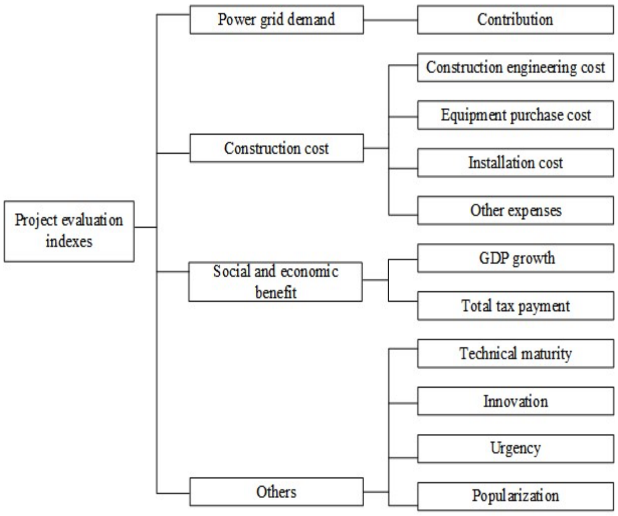


Fig. 2. Index system for project evaluation

(3) Evaluation model for distribution network projects

The evaluation value of a project is derived using cumulative prospect theory containing the time discount function, thereby considering the duration of project implementation and investors’ orientation toward investment.

The model of cumulative prospect theory [40–42] is:

$$U = \pi^{+}(p)v^{+}(G) + \pi^{-}(p)v^{-}(L) \tag{11}$$

where U is the prospect value; p is the probability variable of the project evaluation index; G and L are the values of gains and losses, respectively; $v^{+}(\cdot)$ and $v^{-}(\cdot)$ are the value functions of gains and losses, respectively; and $\pi^{+}(\cdot)$ and $\pi^{-}(\cdot)$ are the probability weighting functions of gains and losses, respectively.

The value functions are calculated as:

$$\begin{cases} v^{+}(G) = G^{\varepsilon} \\ v^{-}(L) = -\lambda |L|^{\xi} \end{cases} \tag{12}$$

where ε and ξ represent the degree of investors’ attention to gains and losses, respectively, and λ represents the degree of investors’ attention to losses relative to gains. Usually, $\varepsilon = \xi = 0.88$, and $\lambda = 2.25$.

The probability weighting functions are obtained as:

$$\begin{cases} \pi^{+}(p) = \dfrac{p^{\gamma}}{(p^{\gamma} + (1-p)^{\gamma})^{1/\gamma}} \\ \pi^{-}(p) = \dfrac{p^{\delta}}{(p^{\delta} + (1-p)^{\delta})^{1/\delta}} \end{cases} \tag{13}$$

where γ is the gain coefficient and δ is the loss coefficient. Usually, γ=0.61 , and δ=0.69 .

The cumulative prospect theory model containing the time discount function is expressed as:

$$V = D(t)U \tag{14}$$

where V is the evaluation value of a project, t is the duration of project implementation, and $D(t)$ is time discount function and expressed here in terms of the hyperbolic discount model as follows:

$$D(t) = (1+\alpha t)^{\frac{\beta}{\alpha}} \tag{15}$$

where α and β are constants greater than 0. Usually, α=4 and β=1 .

The number of projects and project evaluation indexes are assumed to be m and n, respectively, so the evaluation index vector of Project i is $\boldsymbol{l}_i = (l_{i1}, l_{i2}, \cdots, l_{ij}, \cdots, l_{in})$. Given that the determination of gain and loss values is a key issue in cumulative prospect theory, the distances between the values of the evaluation indexes of each project and the positive and negative ideal solutions, which are calculated by the TOPSIS method [43], are used to express the gains and losses.

In the standardization of each index, “the larger the better index” is obtained as:

$$y_{ij} = \frac{l_{ij} - \min(\{\boldsymbol{l}_i\})}{\max(\{\boldsymbol{l}_i\}) - \min(\{\boldsymbol{l}_i\})} \tag{16}$$

and “the smaller the better index” is derived as:

$$y_{ij}=\frac{\max(\{\boldsymbol{l}_i\})-l_{ij}}{\max(\{\boldsymbol{l}_i\})-\min(\{\boldsymbol{l}_i\})} \tag{17}$$

With y_{ij}, the positive and negative ideal solutions are determined to be $M^{+}=\{y_1^{+},y_2^{+},\cdots,y_j^{+},\cdots,y_n^{+}\}$ and $M^{-}=\{y_1^{-},y_2^{-},\cdots,y_j^{-},\cdots,y_n^{-}\}$, respectively. $y_j^{+}=\max\limits_{1\le i\le m}(y_{ij})$, and $y_j^{-}=\min\limits_{1\le i\le m}(y_{ij})$.

For Project i, the distance between value y_{ij} and positive ideal solution y_j^{+} and the distance between value y_{ij} and negative ideal solution y_j^{-} are obtained as:

$$\begin{cases} d_{ij}^{+}=w_j\left|y_{ij}-y_j^{+}\right| \\ d_{ij}^{-}=w_j\left|y_{ij}-y_j^{-}\right| \end{cases} \tag{18}$$

where w_j is the weight coefficient of project evaluation index j.

With Eq. (12), the value of the index j for Project i can be obtained as:

$$\begin{cases} v_{ij}^{+}=(d_{ij}^{+})^{\varepsilon} \\ v_{ij}^{-}=-\lambda\left|d_{ij}^{-}\right|^{\xi} \end{cases} \tag{19}$$

With Eqs. (11), (14), and (19), the prospect value of Project i can be calculated as:

$$V_i=[\sum_{j=1}^{n}v_{ij}^{+}\pi^{+}(p_j^{*})+\sum_{j=1}^{n}v_{ij}^{-}\pi^{-}(p_j^{*})]\times D(t_i) \tag{20}$$

where p_j^{*} represents the optimal solution of probability variable p of project evaluation index j, that is, the probability variable value that can maximize the total prospect value of m projects to reflect the real probability weight. t_i, in unit of years, is the duration of the implementation of Project i.

3.3 Optimization method for project group

The score of Project i in terms of V_i and h_i is calculated as:

$$F_i=\rho\frac{V_i}{1+h_i} \tag{21}$$

where ρ is the proportional coefficient that expands the representation of the score (10 in this study).

With the total score of the project group being the highest, the optimization model is derived as:

$$\begin{cases} \max\sum\limits_i F_i \\ s.t.\quad C\le C_0 \end{cases} \tag{22}$$

where $C\le C_0$ is the constraint on the total investment.

The hybrid bat algorithm is used to solve Eq. (22) and obtain the optimal project group.

The bat algorithm is an optimization method for emulating bat echolocation. Based on the classic bat algorithm, the hybrid bat algorithm has the following improvements. 1) The chaotic state is introduced to generate the initial population, enhance the diversity of the population and the quality of the initial solution, and improve operational efficiency. 2) The information interaction mechanism is introduced, that is, the information interaction between the best and the worst individuals in each iteration is assessed, guiding the worst individual to move to a good position to improve the convergence rate of the algorithm. The flowchart of the hybrid bat algorithm is shown in Fig. 3.

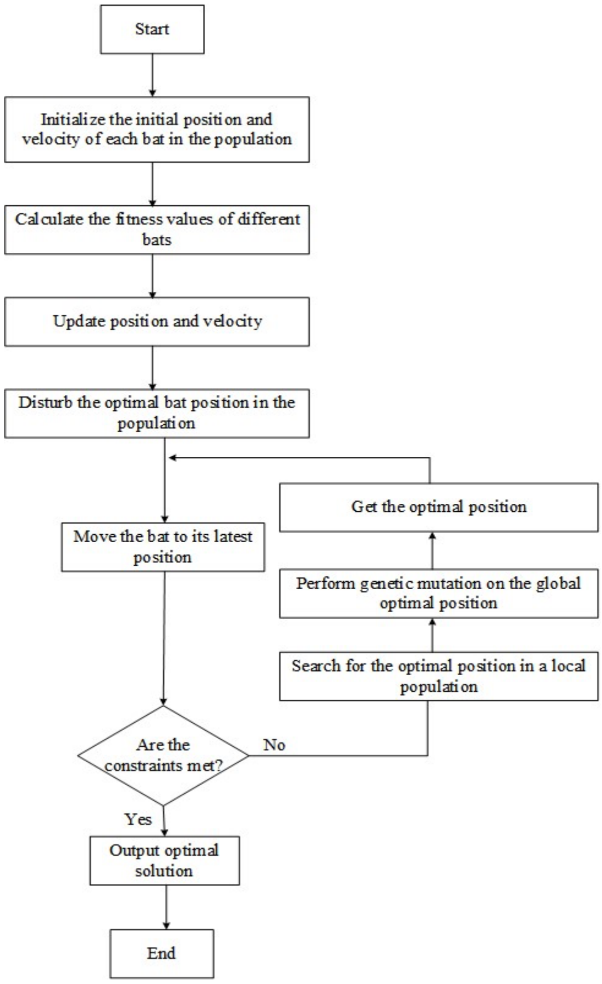


Fig. 3. Flowchart of the hybrid bat algorithm

4. Results Analysis and Discussion

4.1 Case analysis

The six distribution network investment projects in a city in China are used to verify the proposed method. Among them, Projects 5 and 6 are not related to each other and the four other projects.

The project evaluation index data and basic data are shown in Table 3.

Table 3. Project evaluation index data and basic data

Number of Project **Index**	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**
Contribution	0.053	0.063	0.089	0.056	0.064	0.0147
Construction engineering cost / RMB: CNY	100	200	200	350	250	150
Equipment purchase cost/ RMB: CNY	200	310	220	340	200	140
Installation cost / RMB: CNY	70	100	130	150	110	90
Other expenses/ RMB: million CNY	10	5	5	15	10	5
GDP growth	10	11	13	9	7	5
Total tax payment	30	40	30	40	30	20
Technical maturity	5	7	8	6	9	5
Urgency	5	5	5	6	5	5
Popularization	5	5	4	5	6	5
Innovation	2	3	2	5	3	2
Total cost /RMB: ten thousand CNY	1420	2520	3400	4660	2300	1400
Implementation time / year	1	2	2	3	2	2

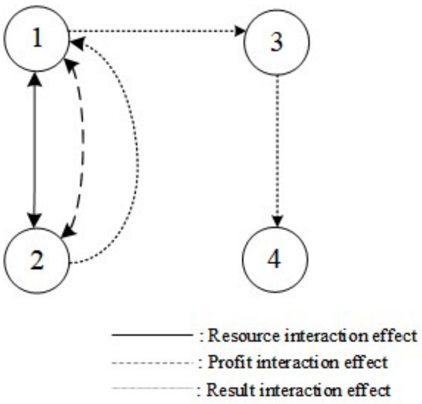


Fig. 4. Brittle links among four projects

As shown in Fig. 4, brittle links exist between Projects 1 and 2, Projects 1 and 3, and Projects 3 and 4. A complete brittle link exists between Projects 1 and 2 for resource and profit, and a unilateral brittle link exists between them for result. Therefore, links $1 \rightarrow 2$ and $2 \rightarrow 1$ can be expressed as r_{12} and r_{21}, respectively. Fig. 4 and Table 1 show that r_{21} represents resource, profit, and result for Projects 2 and 1. Table 1 indicates that a fluctuating link exists between Projects 2 and 1 in terms of the expected cost and expected profit, and the same link exists between them in terms of the expected risk. The probability that brittle similar, brittle opposite, and brittle fluctuating links exist between Projects 2 and 1 is $1/3$, 0, and $2/3$, respectively. In accordance with Table 1 and Eqs. (3)–(5), the brittle similar, brittle opposite, and brittle fluctuating entropy that exist between Projects 2 and 1 are calculated as:

$$H_a^{r_{21}} = -\frac{1}{3} \times \ln \frac{1}{3} = 0.366$$

$$H_b^{r_{21}} = 0$$

$$H_c^{r_{21}} = -\frac{2}{3} \times \ln \frac{2}{3} = 0.270$$

where r_{12} represents resource and profit for Projects 1 and 2. A fluctuating link exists between Projects 1 and 2 in terms of the expected cost, and an opposite link exists between them in terms of the expected profit and expected risk. The brittle similar, brittle opposite, and brittle fluctuating entropy between Projects 1 and 2 are calculated as:

$$H_a^{r_{12}} = 0$$

$$H_b^{r_{12}} = -\frac{2}{3} \times \ln \frac{2}{3} = 0.270$$

$$H_c^{r_{12}} = -\frac{1}{3} \times \ln \frac{1}{3} = 0.366$$

The values of $H_a^{r_{ij}}$, $H_b^{r_{ij}}$, $H_c^{r_{ij}}$, $H^{r_{ij}}$, w_a, w_b, and w_c are shown in Table 4.

Table. 4. The values of $H_a^{r_{ij}}$, $H_b^{r_{ij}}$, $H_c^{r_{ij}}$, $H^{r_{ij}}$, w_a, w_b and w_c

H, w r_{ij}	$H_a^{r_{ij}}$	w_a	$H_b^{r_{ij}}$	w_b	$H_c^{r_{ij}}$	w_c	$H^{r_{ij}}$
r_{12}	0	0	0.270	-0.646	0.366	0.778	0.110
r_{21}	0.366	0.605	0	0	0.270	0.721	0.416
r_{13}	0.366	0.605	0.366	-0.715	0.366	0.778	0.244
r_{34}	0.366	0.605	0.366	-0.715	0.366	0.778	0.244

With Eq. (8), the brittle risk of Project 1 is calculated as:

$$h_1 = H^{r_{12}} + H^{r_{13}} = 0.354$$

Likewise, the brittle risks of Projects 2 and 3 are obtained.

In accordance with Eqs. (16) and (17), the values of $\left| y_{ij} - y_j^+ \right|$ and $\left| y_{ij} - y_j^- \right|$ are shown in Tables 5 and 6, respectively.

The values of v_{ij}^+ and v_{ij}^- are obtained by Eq. (19), as shown in Tables 7 and 8, respectively.

With Eq. (20), the prospect values of Projects 1–6 are calculated to be 0.1212, 0.1130, 0.1211, 0.2726, 0.1129, and 0.1212, respectively, and the scores of the six projects obtained from Eq. (21) are shown in Table 9.

Table 5. The values of $\left|y_{ij}-y_j^+\right|$

Number of Project Index	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Contribution	0.044	0.032	0	0.04	0.031	0.091
Construction engineering cost / RMB: CNY	0	0.036	0.036	0.091	0.055	0.018
Equipment purchase cost/ RMB: CNY	0.027	0.077	0.036	0.091	0.027	0
Installation cost / RMB: CNY	0	0.034	0.068	0.091	0.046	0.023
Other expenses/ RMB: million CNY	0.046	0	0	0.091	0.046	0
GDP growth	0.034	0.023	0	0.046	0.068	0.091
Total tax payment	0.046	0	0.046	0	0.046	0.091
Technical maturity	0.091	0.046	0.023	0.068	0	0.091
Urgency	0.091	0.091	0.091	0	0.091	0.091
Popularization	0.046	0.046	0.091	0.046	0	0.046
Innovation	0.091	0.061	0.091	0	0.061	0.091

Table 6. The values of $\left|y_{ij}-y_j^-\right|$

Number of Project Index	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Contribution	0.047	0.059	0.091	0.051	0.06	0
Construction engineering cost / RMB: CNY	0.091	0.055	0.055	0	0.036	0.073
Equipment purchase cost/ RMB: CNY	0.064	0.014	0.055	0	0.064	0.091
Installation cost / RMB: CNY	0.091	0.057	0.023	0	0.046	0.068
Other expenses/ RMB: million CNY	0.046	0.091	0.091	0	0.046	0.091
GDP growth	0.057	0.068	0.091	0.046	0.023	0
Total tax payment	0.046	0.091	0.046	0.091	0.046	0
Technical maturity	0	0.046	0.068	0.023	0.091	0
Urgency	0	0	0	0.091	0	0
Popularization	0.046	0.046	0	0.046	0.091	0.046
Innovation	0	0.03	0	0.091	0.03	0

Table 7. The values of v_{ij}^+

Number of Project Index	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Contribution	0.064	0.048	0	0.059	0.047	0.121
Construction engineering cost / RMB: CNY	0	0.054	0.054	0.121	0.077	0.029
Equipment purchase cost/ RMB: CNY	0.042	0.105	0.054	0.121	0.042	0
Installation cost / RMB: CNY	0	0.051	0.094	0.121	0.066	0.036
Other expenses/ RMB: million CNY	0.066	0	0	0.121	0.066	0
GDP growth	0.051	0.036	0	0.066	0.094	0.121
Total tax payment	0.066	0	0.066	0	0.066	0.121
Technical maturity	0.121	0.066	0.036	0.094	0	0.121
Urgency	0.121	0.121	0.121	0	0.121	0.121
Popularization	0.066	0.066	0.121	0.066	0	0.066
Innovation	0.121	0.085	0.121	0	0.085	0.121

Table 8. The values of v_{ij}^-

Number of Project Index	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Contribution	-0.152	-0.187	-0.273	-0.163	-0.19	0
Construction engineering cost / RMB: CNY	-0.273	-0.174	-0.174	0	-0.122	-0.224
Equipment purchase cost/ RMB: CNY	-0.199	-0.051	-0.174	0	-0.199	-0.273
Installation cost / RMB: CNY	-0.273	-0.18	-0.181	0	-0.148	-0.212
Other expenses/ RMB: million CNY	-0.148	-0.273	-0.273	0	-0.148	-0.273
GDP growth	-0.18	-0.212	-0.273	-0.148	-0.273	0
Total tax payment	-0.148	-0.273	-0.148	-0.273	-0.104	0
Technical maturity	0	-0.148	-0.212	-0.081	-0.081	0
Urgency	0	0	0	-0.273	-0.148	0
Popularization	-0.148	-0.148	0	-0.148	-0.273	-0.148
Innovation	0	-0.104	0	-0.273	0	0

Table 9. The scores of the six projects

Score and investment amount	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Score	0.895	2.511	16.633	15.548	4.353	3.277
Investment amount /RMB: million CNY	1420	2520	3400	4660	2300	1400

The total investment amount is set to be 100 million CNY, and the hybrid bat algorithm is used to solve Eq. (22). Assume that the number of populations is 10, the number of iterations is 500, the initial pulse frequency is 0.7, the optimal individual is [0 0 1 1 0 1], and the corresponding investment scheme is to invest in Projects 3, 4, and 6. As indicated in Fig. 5, where the optimization result is shown, the highest total score of the project group is 35.458.

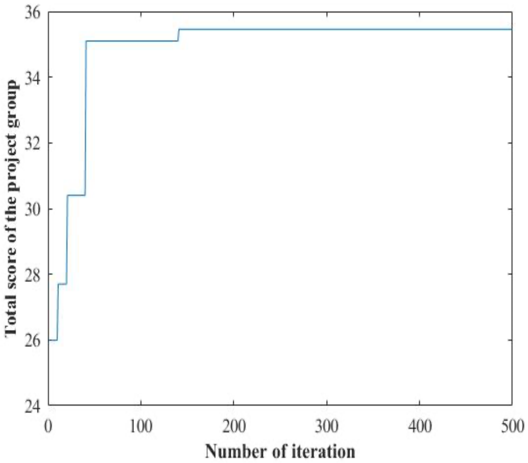


Fig. 5. Optimization result

4.2 Discussion

The basic procedure of investment planning for distribution network projects is revealed through in-depth discussions of the correlation analysis, investment evaluation methods of distribution network projects and the construction of project optimization models.

(1) This study delves into the complex interactive relationships that exist between different projects in terms of resource allocation, outcome, and economic benefits. These interactive relationships indicate that the implementation status of a certain project may affect the progress and effectiveness of other projects directly or indirectly, thereby triggering dynamic adjustments in the investment priority of the entire project group. Therefore, when investment strategies are formulated, the interactions between projects need to be comprehensively considered.

To scientifically quantify the investment risks brought about by the interactions between projects, this study introduces brittle entropy theory as an evaluation tool. Brittle entropy can determine uncertain factors in project systems effectively, including resource dependence, market fluctuations, and technical risks, thereby providing decision-makers with an objective, accurate basis for assessing risks. The case analysis shows that the brittle entropy of a certain project is related to the number of projects that exert interactive effects on itself and is determined by the type of interactive effects between projects. The case analysis also reveals that when Project i has interactive effects on Project j in terms of resources, benefits, and results, the unilateral brittle link entropy and investment risk of the former are high. However, in terms of resources and benefits, the unilateral brittle link entropy and investment risk of the former are small, so other projects have little influence on it.

(2) In the evaluation of the feasibility of project investment, the construction of distribution networks is an important factor that cannot be ignored. Distribution networks in different regions have various characteristics and demands because of their differences in geographical and economic conditions. In regions where the construction of distribution networks is relatively backward and their safety and reliability are low, this study suggests that investment should focus on solving key issues, such as line overload and grid contact rate improvement, to enhance the regional power supply capacity and reliability. In regions where the construction of distribution networks is already complete, this study recommends shifting the investment orientation to cutting-edge fields, such as smartness and low carbon, to promote the green transformation and sustainable development of the power grids.

To accurately reflect the contributions of investment projects to the construction of distribution networks, this study introduces contribution as a quantitative index. This index comprehensively reflects multiple aspects, such as regional differences, project demands, and investment benefits, thus providing strong support for optimizing resource allocation. In addition, this study emphasizes the importance of economic and social indexes, such as project cost and technical feasibility. The case analysis shows that the comprehensive evaluation method based on cumulative prospect theory containing the time discount function can provide comprehensive evaluation results in terms of the various indexes of projects. At the same time, it comprehensively considers the long- and short-term benefits, risks, and opportunities of a project on the basis of its implementation time, thereby providing a comprehensive scientific basis for project evaluation.

(3) On the basis of the accurate calculation of project prospect values, this study constructs an investment optimization model in terms of project prospect value. With this model, project investment schemes are comprehensively evaluated and optimized by considering the project prospects, investment risks, and resource constraints. Under the established investment constraints, optimization algorithms are used to automatically identify possible investment schemes and select the best one that can maximize overall returns and control risks effectively. The model not only improves the scientificity and accuracy of investment decisions, but also provides a strong guarantee for the sustainable development of enterprises. The case analysis reveals differences in the indexes, such as technology, economy, and grid contribution, among the projects. Some of the projects are worth considering in terms of technology promotion, but they do not have advantages in terms of economy. Other projects are superior in terms of grid contribution, but they are average in terms of technology. In this study, the risks of the projects are also considered. The above-mentioned project situations are reflected in the final score comprehensively. Under the constraints of the established investment amount, some projects with high scores also have high costs. Therefore, to obtain optimal investment benefits, an optimization model must be used to find the optimal investment scheme.

5. Conclusions

To solve the problems of blindness and lack of theoretical basis in distribution network investment, this study proposes an investment planning method for distribution networks on the basis of project optimization. The main conclusions are as follows:

1) The correlation between projects can be analyzed by brittle link entropy, and project investment risks can be measured by it. The higher brittle link entropy is, the greater the risks of project investment are, and vice versa.

2) A project evaluation index system that encompasses project contributions can reflect the project investment scheme comprehensively. The necessity of project implementation can be scored using the project evaluation method on the basis of cumulative prospect theory containing the time discount, and project optimization can be realized by an optimization model.

This study uses brittle entropy to analyze the correlation between projects and investigates the interaction effects among the resources, benefits, and results of different projects. However, in practical situations, the relationships between projects are complex, and the above-mentioned interaction effects may not necessarily represent the relationships between various projects. Future research should summarize the situation of power grid projects, analyze the complex relationships between projects, and extract typical interaction effects. Moreover, more state vectors should be put into use.

In addition, the results of this study require power enterprises to standardize their project library information and provide complete relevant information when applying for projects. Integrating the results of this research into the data platform of power enterprises can reduce personnel workload and misjudgment.

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