Research on Optimal Method of Multi-regional Power Grid Investment Project

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Abstract. The optimization of multi-regional power grid investment projects is the basis for ensuring the benefits of power companies and can meet the urgent needs of power grid development. This article first takes the historical benefits of power grids, planning benefits, power grid scale and development needs as indicators to establish a multi-regional power grid investment project optimization index system. Then this article puts forward the investment project optimization model. With the goal of maximizing investment benefits, with project portfolio constraints, grid scale development demand constraints and investment constraints as constraints, the binary particle swarm algorithm is used to optimize the investment project portfolio schemes of various regions. Finally, an example is used to verify the effectiveness and feasibility of the method proposed in this paper.

1. Introduction

Electricity is the lifeblood of national economic and social development. In the construction of power systems, grid planning is a complex project with a huge scale, many uncertain factors and a wide range of fields. In order to ensure reliable, economical, and high-quality operation of power grid construction projects after completion, the evaluation of power grid investment projects is also an important basis for project selection during the power grid construction process. At the same time, scientific and reasonable project selection methods can promote the sound development of enterprises and improve the economic benefits of power grid enterprises. Therefore, the decision-making of power grid investment projects is particularly important.

Among the traditional evaluation methods, the cost-benefit analysis method, as an economic analysis method, has received widespread attention in the power grid planning work, and has achieved certain research results [1-3]. In addition, in recent years, the evaluation of power grid investment projects has also been continuously introduced. Not only is the fuzzy multi-objective comprehensive evaluation decision-making theory applied in the short-term construction engineering decision-making of power grid planning [4], it is also proposed to use the analytic hierarchy process to evaluate the comprehensive benefits of the project, and then use linear programming to solve the maximize comprehensive benefits under a given investment quota [5]. In addition, network analysis method [6], entropy ideal method [7], gray correlation method [8], etc. have also been applied to the evaluation of...
power grid investment projects. At the same time, combined with genetic algorithm [9-10], particle swarm algorithm [11], ant colony algorithm [12] and other intelligent algorithms, the comprehensive ranking and optimization of power grid investment projects are realized. In recent years, domestic and foreign power grid investment project evaluation and optimization methods have been continuously explored, but they are still incomplete. There is a lack of comprehensive benefit evaluation of the integration of historical grid operation benefits and planned grid benefits, based on comprehensive benefit evaluation. The research on constructing the optimization index system and model of power grid investment projects lacks a comprehensive benefit and evaluation methods and standards for investment projects, so further research is needed.

This paper first establishes a multi-regional grid investment optimization index system, and then clarifies the comprehensive benefit evaluation method, then establishes a grid investment project optimization model, screens the grid investment project plans, and obtains the investment project portfolio plan of each region. Finally, an example is used to verify the effectiveness and feasibility of the proposed method.

2. Multi-regional grid investment optimization index system

This paper considers the influence of the comprehensive benefits of the entire process of power grid development on power grid investment. Among them, the comprehensive benefits of the entire process of power grid development include historical benefits and planning benefits. In addition, the selection of multi-regional power grid investment projects is also affected by the scale of power grids and development needs in each region. In order to optimize investment projects, this paper uses the historical benefits of power grids, planning benefits, grid scale and development needs as indicators to establish a multi-regional power grid investment optimization index system, which can well represent the investment benefits of multi-regional power grids. As shown in the table 1.

| First-level index       | Second-level index                                      |
|-------------------------|--------------------------------------------------------|
| Historical benefits     | Electricity Sales                                      |
|                         | Power supply reliability rate                          |
|                         | Comprehensive voltage qualification rate                |
|                         | Electricity replacement ratio                          |
| Planning benefits       | Average annual growth rate of line length               |
|                         | Average annual growth rate of substation capacity       |
|                         | Transformer utilization                                |
|                         | Line utilization                                       |
| Grid size               | Unit transformer capacity supports electricity load     |
|                         | Supporting electricity load per unit line length        |
| Development demand      | Scale of newly installed capacity                      |
|                         | Load growth scale                                      |

The meaning and calculation formula of each indicator are as follows:

1) Electricity sales refer to the electricity sales of the power grid within one year, and this indicator reflects the economic income status of the grid operation benefits. The power supply reliability rate directly reflects the power supply safety and reliability of the grid system. The comprehensive voltage qualification rate reflects the power quality of the power grid and the stable operation of the power grid.

2) The average annual growth rate of the line length refers to the average annual growth rate of the line scale under a specific voltage level during the planning year. Substation capacity refers to the average annual growth rate of transformer capacity during the planned year. The utilization efficiency of power transmission and distribution equipment such as transformers and lines refers to the utilization rate of the equipment after project investment.
3. Fuzzy comprehensive evaluation method of comprehensive benefit based on analytic hierarchy process

This comprehensive evaluation method uses fuzzy mathematics to make an overall evaluation of things or objects restricted by multiple factors. Specific steps are as follows:

1. Determine the set of objects to be evaluated. First determine the objects to be evaluated.
2. Determine the set of indicators. According to the selected indicators, a set of indicators is established.
3. Scoring of indicators. Calculate all the index values of each scheme, and use the efficiency coefficient method to make dimensionless processing for each index. The satisfactory value is the maximum value of each area, and the minimum value of each area is not allowed.
4. Determine the weight of each indicator. According to the analytic hierarchy process, each indicator is weighted.
5. Calculate the comprehensive score value of each object. The comprehensive score value of object i is equal to step 4) calculating the weight of each index multiplied by step 3) the score of each index calculated by the efficacy coefficient method.
6. The principle of maximum membership degree determines the result of fuzzy comprehensive evaluation. According to the score to determine the result evaluation grade, this report adopts 5-level evaluation [13], and the classification standard is shown in Table 2. By calculating the membership degrees of each level, the level with the largest membership degree is selected as the rating result of the program.

| Grade    | 1 (very poor) | 2 (poor) | 3 (medium) |
|----------|---------------|----------|------------|
| Points   | [0,20]        | [20,40]  | [40,60]    |
| Grade    | 4 (good)      | 5 (excellent) | / |
| Points   | [60,80]       | [80-100] | / |

4. Grid investment project optimization model

Based on the previously established multi-regional grid investment project optimization index system, a grid investment project optimization model is established.

4.1. Grid Investment Scheme Selection

The two types of indicators, planning benefits and adaptability to development needs, are selected to be comprehensively scored as the screening objective function to establish a grid investment plan screening model. The specific calculation method is shown below.

4.1.1. Screening objective function: The indicators that characterize the development needs of each region are installed capacity demand and load growth demand. Among them, the scale of installed capacity is for the power grid connection project, which is a rigid requirement for the power grid investment project, and does not participate in the investment optimization calculation. According to the above-established grid investment plan screening evaluation index system, comprehensive evaluation method is adopted to comprehensively score each plan, and the evaluation result is used as the screening objective function. The calculation formula of the objective function for grid investment scheme screening is shown in the formula (1).
In the formula, $X_i$ and $w_i$ are the scores and weights of the $i$-th index in the evaluation index system for the grid investment plan in the A region.

4.1.2. Screening method: Calculate the screening objective function of each plan, and screen out investment alternatives accordingly. The specific screening method is as follows.

(1) Index score. First, according to the calculation method of each indicator, calculate the value of each indicator of each program. Then, according to the satisfactory value and the disallowed value of each index, through the efficiency coefficient method, each index of each program is scored, and the score value of each index of each program is obtained.

(2) Determine the index weight. According to the analytic hierarchy process, determine the weight of each indicator $w = \{w_1, w_2, \ldots, w_m\}$.

(3) Determine the comprehensive score of each program. According to the calculation formula of the screening objective function, the comprehensive score of each scheme is calculated.

(4) Screening alternatives. Fuzzy evaluation is performed on the scores of various schemes, and the schemes with an evaluation grade of "excellent" are selected as a set of alternative schemes to participate in the optimization calculation of grid investment projects.

4.2. The Objective Function of the Optimization Model of Power Grid Investment Projects

This article aims at maximizing investment benefits, that is, in a project portfolio plan, the sum of the investment benefits of each region is the largest. As shown in the formula (2).

$$\max f = \sum_{i} X_i$$  \hspace{1cm} (2)

In the formula, $X_i$ is the investment benefit of area $i$, which is calculated through the established multi-region investment project optimization index system and comprehensive evaluation method. By comparing the objective function of each project portfolio plan, the largest project portfolio plan is selected as the final investment project portfolio.

4.3. Constraints on the Optimization Model of Grid Investment Projects

The constraints of the optimization model of power grid investment projects are mainly divided into three categories, project portfolio constraints, power grid scale development demand constraints and investment constraints. Project portfolio constraint is a constraint established by restricting projects from being able to be combined arbitrarily or meeting the relevance between projects. The grid scale development demand constraint is a constraint established to meet the rigid development requirements of the power grid in various regions. Investment constraints are constraints that meet the requirements of investment. They will be introduced separately below.

4.3.1. Project portfolio constraints: The project portfolio usually has certain requirements and various relationships. Each relationship has specific requirements for the combination of projects. Assuming there are $m$ reserve projects, create a project portfolio 0-1 matrix, where each element represents the investment situation of the corresponding project, 0 means no investment, 1 means investment. The detailed introduction is as follows.

(1) Independent relationship: If the projects are independent of each other, the elements in the project portfolio are independent of each other.

$$\sum_{i} q_i \leq m$$  \hspace{1cm} (3)

The meaning of this formula is that the value of each element in the 0-1 matrix $q_i$ of the project portfolio is less than or equal to the total number of reserved projects.

(2) Mutually exclusive relationship: If the two projects are mutually exclusive, it means that the
two projects cannot be invested and constructed at the same time.

\[ a_m + a_n \leq 1 \]  \hspace{1cm} (4)

In the formula, \( a_m \) and \( a_n \) the element value in the project portfolio matrix corresponding to the items m and n. According to the constraint relationship, the two element values cannot be 1 at the same time, that is, the sum of the two is less than or equal to 1.

(3) Progressive relationship: Progressive relationship means that a project can only choose to invest and build after another project has been invested and constructed.

\[ a_m - a_n \geq 0 \]  \hspace{1cm} (5)

The meaning expressed by this formula is that the element value corresponding to item m is larger than the element value corresponding to item n, because the element value is 0 or 1, therefore, only when the element value of item m is 1, the element value of item n may take 1. Comply with the constraint relationship.

(4) Dependency: Dependency means that two projects are accompanied at the same time, that is, two projects must be selected for investment or not selected at the same time.

\[ a_m - a_n = 0 \]  \hspace{1cm} (6)

The formula shows that the element values of project m and project n are equal, that is, whether the investment of the two projects is the same, and conforms to the constraint relationship.

4.3.2. Grid scale development demand constraints: The power grid scale development demand constraint means that the power grids in various regions have certain needs and requirements for their own scale and development. They will be introduced separately below.

(1) The capacity-to-load ratio constraint of a single area is to satisfy the constraint of the coordination of grid development. After investment, the capacity-load ratio of a single area needs to be kept within a reasonable range.

(2) The N-1 pass rate constraint is a restriction on the reliability requirements after power grid investment. According to the reliability requirements of various regions, the N-1 pass rate must be greater than the specified value after power grid investment.

(3) The utilization efficiency constraint of transformer equipment means that after power grid investment, the utilization efficiency of transformer should meet certain requirements to ensure the effectiveness of investment.

(4) The utilization efficiency constraint of line equipment means that after the power grid is invested, the utilization efficiency of the line should meet certain requirements to ensure the effectiveness of the investment.

(5) Constraints on project yield rate means that after a project is invested, its benefits should meet the expected requirements, and the project’s yield rate reflects the effectiveness of the investment, so relevant constraints are required.

4.3.3. Investment constraints refer to constraints on investment: The total amount of investment in various regions cannot exceed the prescribed investment scale, and the investment amount of the project portfolio plan cannot exceed the total investment amount.

4.4. The Solution Method of the Optimization Model of Power Grid Investment Projects
According to the established grid investment project optimization model, and the project portfolio 0-1 matrix is binary, this paper uses binary particle swarm optimization algorithm to optimize the grid investment project optimization model and find the optimal project portfolio plan.

The binary particle swarm algorithm is used to filter the objective function according to the grid investment plan, and the set of options for the grid investment project portfolio is selected. Then according to the objective function and constraint conditions of the grid investment project optimization model, the optimal plan for grid investment and the investment scale are determined. The specific steps are as follows.
(1) Initialize the population: Define the number of particles in the population, and make initial assignments to the 0-1 matrix of each project portfolio.

(2) Initialization speed: The speed of each particle is initialized. The speed of the particle has an upper limit and a lower limit. When the initialization is performed, randomization is generated within this range.

(3) Calculate the fitness of each particle, select individual optimal and global optimal particles: According to the screening objective function and constraint conditions, the fitness of each particle is calculated. Then, according to the fitness of each particle, the historical optimal position of each particle and the historical optimal position of all particles in the world are selected.

(4) Update speed: Through the individual optimal position and the global optimal position, the velocity of each particle is updated.

(5) Location update: Since the solution in this article is a binary matrix, the binary particle swarm optimization algorithm is adopted, and the position update formula is also binary.

(6) Iterative loop: Return to step (3) to perform an iterative loop until the change of the two optimal solutions is less than the specified value or the iteration reaches a certain number of times, and the loop ends. In each iteration, the scheme with the “excellent” comprehensive evaluation result is saved, and finally a set of optimal alternative schemes for power grid investment projects is obtained.

(7) Determine the optimal plan for power grid investment project portfolio: According to the objective function and constraint conditions of the power grid investment project optimization model, the alternatives are calculated separately, and the plan with the largest objective function is selected as the optimal plan for the power grid investment project portfolio.

5. Empirical analysis of power grid companies in typical provinces

5.1. Basic Information of Typical Empirical Evidence
Select four regions of A, B, C, and D to do an empirical analysis of the selection of investment projects in multiple regions, with a total investment of 2 billion yuan. The basic information of each region is shown in the table 3.

Table 3. Basic information of each region

| Region | Power supply reliability rate (%) | Comprehensive voltage qualification rate (%) | Electric energy substitution ratio (%) | Electricity sales (MVAh) | Load growth scale (MW) | New installed capacity (MW) |
|--------|-----------------------------------|---------------------------------------------|--------------------------------------|--------------------------|------------------------|-----------------------------|
| A      | 99.8202                           | 99.934                                      | 3.590312                             | 285.9118                 | 843.703                | 355                         |
| B      | 99.895921                         | 99.941769                                  | 3.477533                             | 821.897                  | 2146.801               | 785                         |
| C      | 99.926225                         | 99.946897                                  | 2.212973                             | 3472.927                 | 8518.099               | 1745                        |
| D      | 99.915945                         | 99.934797                                  | 3.219271                             | 716.2824                 | 1756.539               | 615                         |

| Region | Average annual growth rate of line length (%) | Average annual growth rate of substation capacity (%) | Transformer utilization rate (%) | Line utilization rate (%) | Unit substation capacity to support electricity load (MW) | Unit line length to support electricity load (MW) |
|--------|-----------------------------------------------|------------------------------------------------------|---------------------------------|-------------------------|--------------------------------------------------------|-----------------------------------------------|
| A      | 0.652806                                      | 21.014263                                             | 25.73                           | 15.65                   | 0.109224                                               | 0.009214                                      |
| B      | 0.318068                                      | 0                                                     | 21.33                           | 17.44                   | 0.108995                                               | 0.007335                                      |
| C      | 0.021225                                      | 17.350037                                             | 26.58                           | 24.83                   | 0.150493                                               | 0.017746                                      |
| D      | 0.145469                                      | 43.117282                                             | 25.8                            | 19.09                   | 0.120359                                               | 0.010536                                      |

The constraints of each region are shown in the table 4.
Table 4. Constraints by region

| Region | Lower limit of transformer utilization rate (%) | Lower limit of line utilization rate (%) | Lower limit of production rate (%) | Lower limit of N-1 pass rate (%) |
|--------|-----------------------------------------------|----------------------------------------|-----------------------------------|----------------------------------|
| A      | 10                                            | 10                                     | 40                                | 90                              |
| B      | 10                                            | 10                                     | 40                                | 90                              |
| C      | 10                                            | 10                                     | 40                                | 90                              |
| D      | 10                                            | 10                                     | 40                                | 90                              |

| Region | Upper limit of capacity ratio | Lower limit of capacity ratio | Upper limit of regional investment scale (100 million yuan) |
|--------|-------------------------------|------------------------------|------------------------------------------------------------|
| A      | 1.9                           | 1.6                         | 8.07284                                                   |
| B      | 1.9                           | 1.6                         | 3.26699                                                   |
| C      | 1.9                           | 1.6                         | 22.0514                                                   |
| D      | 1.9                           | 1.6                         | 12.2610                                                   |

There are currently 31 projects in the investment project database, which invest in various regions. The project information is shown in the table 5.

Table 5. Project library project information

| Project number | Region | Project investment /10,000 yuan | New substation capacity/MVA | New line length/km | N-1 Passed component quantity | Total component count |
|----------------|--------|---------------------------------|-----------------------------|-------------------|-------------------------------|-----------------------|
| 1              | A      | 2000                            | 180                         | 0                 | 1                             | 1                     |
| 2              | A      | 19600                           | 370                         | 85.6              | 3                             | 3                     |
| 3              | A      | 1000                            | 0                           | 4.97              | 2                             | 2                     |
| 4              | A      | 1000                            | 0                           | 5.16              | 1                             | 1                     |
| 5              | A      | 1600                            | 0                           | 7.72              | 1                             | 1                     |
| 6              | A      | 3200                            | 0                           | 16.3              | 1                             | 1                     |
| 7              | A      | 3600                            | 0                           | 18                | 1                             | 1                     |
| 8              | A      | 3000                            | 0                           | 15                | 1                             | 1                     |
| 9              | A      | 5000                            | 0                           | 24                | 2                             | 2                     |
| 10             | A      | 5000                            | 0                           | 25.8              | 2                             | 2                     |
| 11             | B      | 1000                            | 0                           | 5                 | 1                             | 1                     |
| 12             | B      | 4200                            | 0                           | 21                | 1                             | 1                     |
| 13             | B      | 5200                            | 0                           | 24                | 2                             | 2                     |
| 14             | B      | 8000                            | 0                           | 42                | 2                             | 2                     |
| 15             | B      | 11500                           | 0                           | 52.7              | 1                             | 1                     |
| 16             | B      | 12000                           | 0                           | 56                | 2                             | 2                     |
| 17             | B      | 16000                           | 0                           | 80                | 2                             | 2                     |
| 18             | B      | 3000                            | 0                           | 14.6              | 2                             | 2                     |
| 19             | B      | 4000                            | 0                           | 21.2              | 2                             | 2                     |
| 20             | B      | 8000                            | 0                           | 40                | 2                             | 2                     |
Simulate each project, and the simulation results obtained are shown in the table 6. Among them, 0 means not reaching production; 1 means reaching production.

| Project number | Region | Power Transmission by Transformer (MVAr) | Power Transmission by Line (MVAr) | Maximum Safety Power Transmission by Line (MVAr) | Production Status |
|----------------|-------|------------------------------------------|----------------------------------|-----------------------------------------------|------------------|
| 1              | A     | 46.314                                   | 0                                | 0                                             | 0                |
| 2              | A     | 95.201                                   | 13.3964                          | 85.6                                          | 1                |
| 3              | A     | 0                                        | 0.777805                         | 4.97                                          | 1                |
| 4              | A     | 0                                        | 0.80754                          | 5.16                                          | 0                |
| 5              | A     | 0                                        | 1.20818                          | 7.72                                          | 0                |
| 6              | A     | 0                                        | 2.55095                          | 16.3                                          | 0                |
| 7              | A     | 0                                        | 2.817                            | 18                                            | 0                |
| 8              | A     | 0                                        | 2.3475                           | 15                                            | 0                |
| 9              | A     | 0                                        | 3.756                            | 24                                            | 0                |
| 10             | A     | 0                                        | 4.0377                           | 25.8                                          | 1                |
| 11             | B     | 0                                        | 0.872                            | 5                                             | 0                |
| 12             | B     | 0                                        | 3.6624                           | 21                                            | 0                |
| 13             | B     | 0                                        | 4.1856                           | 24                                            | 0                |
| 14             | B     | 0                                        | 7.3248                           | 42                                            | 0                |
| 15             | B     | 0                                        | 9.19088                          | 52.7                                          | 0                |
| 16             | B     | 0                                        | 9.7664                           | 56                                            | 0                |
| 17             | B     | 0                                        | 13.952                           | 80                                            | 0                |
| 18             | B     | 0                                        | 2.54624                          | 14.6                                          | 0                |
| 19             | B     | 0                                        | 3.69728                          | 21.2                                          | 0                |
| 20             | B     | 0                                        | 6.976                            | 40                                            | 0                |
| 21             | C     | 47.844                                   | 2.483                            | 10                                            | 0                |
| 22             | C     | 237.0936                                 | 0.2483                           | 1                                             | 0                |
| 23             | C     | 202.0008                                 | 1.971502                         | 7.94                                          | 0                |
| 24             | C     | 180.744                                  | 1.4898                           | 6                                             | 1                |
| 25             | C     | 0                                        | 1.4898                           | 6                                             | 0                |
5.2. Analysis of Typical Empirical Results

The weight of each indicator is shown in the table 7.

|   |   |   |   |   |   |
|---|---|---|---|---|---|
|   |   |   |   |   |   |

Table 7. The weight of each indicator

| Electricity sales | Reliability rate of power supply | Comprehensive voltage qualification rate | Electricity substitution ratio | Average annual growth rate of line length | Average annual growth rate of substation capacity |
|-------------------|----------------------------------|------------------------------------------|-----------------------------|----------------------------------------|-----------------------------------------------|
| 0.100912          | 0.049372                         | 0.063479                                 | 0.041253                    | 0.071274                               | 0.06361                                       |

| Transformer utilization rate | Line utilization rate | Unit substation capacity to support electricity load | Unit line length to support electricity load | Scale of newly installed capacity | Load growth scale |
|-----------------------------|----------------------|-----------------------------------------------|------------------------------------------|---------------------------------|------------------|
| 0.111874                   | 0.117505             | 0.119818                                      | 0.057696                               | 0.065849                      | 0.1314           |

By improving each plan generated by the particle swarm algorithm, according to the comprehensive evaluation method, the theoretical maximum fitness value is 400. According to the evaluation rules, the fitness value with an excellent evaluation result should be greater than 80% of the maximum value, so the fitness is stored. Solutions with a value greater than 320 are used as the set of alternatives, and a total of 1743 alternatives are obtained.

This article calculates the objective function and checks the constraints on these alternatives, and gets the optimal solution. The results are shown in the table 8.

Table 8. The optimal investment plan

| Project | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| Investment situation | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 |
| Project | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| Investment situation | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

It can be seen from the results that the optimal investment plan is: Region A invests in No. 1, 2, 3, 4, 5, and 9 projects, with an optimal investment of 302 million; Region B invests in No. 11, 13, 14, 19, and 20 projects, The optimal investment amount is 262 million yuan; the optimal investment amount for No. 21, 22, 23, 24, 25, and 26 of Region C is 431 million yuan; the optimal investment amount of No. 27, 38, 29, 30, and 31 of Region D is the best The investment amount is 404 million. The total investment in multi-regional power grids is 1.39 billion yuan.

6. Conclusion

In order to solve the problem of selecting power grid investment projects in different regions, this paper uses power grid historical benefits, planning benefits, power grid scale and development needs as indicators to establish a multi-regional power grid investment project selection index system. Then this article puts forward the investment project optimization model. With the goal of maximizing
investment benefits, with project portfolio constraints, grid scale development demand constraints, and investment constraints as constraints, the binary particle swarm algorithm is used to optimize the portfolio of investment projects in various regions, and the investment scale can be allocated in various regions. Finally, the analysis of a typical power grid company example verifies the effectiveness and feasibility of the method proposed in this paper. The method proposed in this paper can effectively solve the problem of selecting power grid investment projects in multiple regions, and the results obtained are of reference significance and provide new ideas for power grid planning in multiple regions.

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