

The Research on the Optimization of Natural Gas Distributed Power Supply and Pipeline Based on the Stochastic Expectation Model

Ming Zeng¹, Weicheng Chen¹, Yingxin Liu^{1, a, *}, Yanyan Zhang² and Xue Bin²

¹ State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing, China

² Powerchina Fujian Electric Power Survey & Design Institute CO., LTD, Fujian, China

^{a, *} Corresponding author e-mail: 2271616921@qq.com

Abstract. The joint planning of natural gas distributed power supply and gas pipeline in the park is of great significance to improve the efficiency of comprehensive energy utilization. First, the objective function to consider the uncertainty of the demand for electric power is the expected target function of the investment cost and operating cost. Secondly, the establishment of regional distributed power planning model and gas pipeline planning model, and introduce distributed power supply of natural gas and natural gas pipeline two planning problem of the coupling factor, set up joint programming model; Selection in the end, somewhere in Guangdong Province, the existing industrial park, power and gas supply basic data for example analysis, the results show that to build a joint planning model can guide the park natural gas well distributed power supply and gas pipe joint programme.

Key words Natural gas distributed energy; Plans for natural gas pipelines; Coupling factor; Stochastic expectation of the federated model

1. Introduction

Under the background of increasingly prominent contradictions between economic growth and environmental protection, comprehensive energy planning and improvement of comprehensive energy efficiency have become an important means to promote the energy revolution. Among the many ways of energy utilization, natural gas distributed power supply has become a hot spot for comprehensive energy development and utilization due to the characteristics of high energy conversion efficiency, low pollutant emission, quick start-stop, flexible operation, and the ability to satisfy users' diverse energy needs [1,2]. However, natural gas distributed power supply has a relatively large demand for natural gas. If the mutual influence and interaction between pipeline laying and natural gas distributed power supply investment cannot be well considered, it will result in a mismatch between energy supply and demand and reduce overall investment returns [3-5]. Therefore, it is urgent to establish a joint planning model of natural gas distributed power supply and natural gas pipeline, and comprehensively consider various factors in the planning problem, so that the planning results can meet the constraints and improve the



economy of the planning projects, and then improve the efficiency of comprehensive energy utilization and promote the energy revolution.

At present, there are two types of integrated energy planning methods for natural gas distributed power supply, one is typical planning model, and the other is dynamic programming model[6]. Typical planning models include Resource Technology Network Model (RTN Model), Energy Flow optimization Model (EFoM), the Market Allocation of Technologies Model (MARKAL)[7-9], et. These models often have mature commercial development and application background. In the process of energy planning, the influence and interaction of various energy sources are often overlooked, and the typical planning model has stringent requirements on data types and data formats, and lacks flexibility and dynamics, which often cannot be well applied to planning objects. When applied to the joint planning of natural gas distributed power supply and natural gas pipelines, the typical planning model cannot be compatible with the coupling factor between natural gas supply and demand optimization and natural gas distributed power supply planning, and the two kinds of energy planning in the planning result are independent, which makes the planning effect inaccurate. For example, the literature [10] established the model of the natural gas distributed power supply combined heat and cooling system based on the EFoM model without considering the interaction between electricity demand and natural gas supply. Literature [11] applies MARKAL model to study the regional supply and demand of coal and natural gas, and lacks the consideration of the coupling relationship of various energy supply and demand. The dynamic programming model takes the minimum cost or maximum benefit as the optimization goal, and introduces constraints on supply capacity constraints, supply balance constraints, technical development constraints, policy planning guidance constraints on energy supply and demand, and uses a certain optimization algorithm to solve the problem. The dynamic programming model has the characteristics of good adaptability and strong pertinence, but there are problems such as the complexity of the model solution, the difficulty of convergence, the insufficient consideration of the constraints and so on. In the study of the joint planning of natural gas distributed power supply and pipelines, the literature [12] aims to minimize the total energy costs of the park during the planning period, considers the supply and demand constraints and operational constraints of multiple energy sources, and constructs a mixed integer linear programming model of the park's energy planning, but lacks of consideration for uncertainty in energy demand. The natural gas distributed power supply established in literature [13] mainly considers the influence of natural gas distributed power supply planning on power supply and demand and traditional power system operation constraints, but does not consider the impact of distributed power supply on natural gas pipeline planning, and cannot achieve comprehensive energy planning goals.

In summary, at present, there is no mature joint planning method that specifically considers the coupling factors of natural gas distributed power supply and pipelines. The proposed joint planning of natural gas distributed power and pipeline based on Stochastic Expectation Model in this paper has strong practical significance and innovation

2. Model building

2.1. Model building ideas

The objective function of the joint planning problem of natural gas distributed power supply and natural gas pipelines can be divided into two basic problems: one is the issue of location and constant volume of distributed natural gas power supply, and the other is the optimization of natural gas pipelines. The two basic problems can be combined with the joint planning coupling factor of natural gas distributed power supply and pipeline. First, the location and installed capacity of the natural gas distributed power supply need to be confirmed to determine the natural gas demand of the natural gas distributed power supply. Then, the impact of natural gas distributed power supply planning on pipeline planning as a coupling factor of the two planning models was incorporated into the joint planning process, and the optimization planning and design are realized in turn. The overall architecture of the model is determined as shown in the Figure 1.

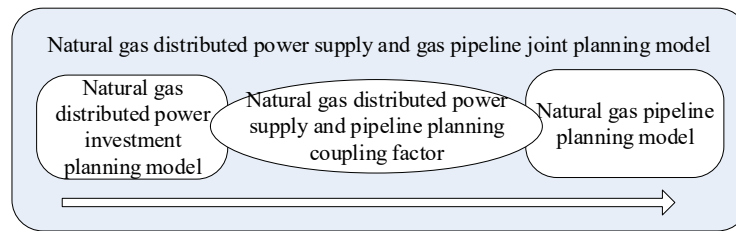


Figure 1. Model building ideas

2.2. Objective function

The objective function of the comprehensive planning problem is given in (1)-(8) formula. The objective function is the lowest annual investment and operating costs for distribution networks and natural gas distributed power supply and natural gas pipelines.

$$\min z = \sum_{t_0}^T \left[\sum_l C_1^{(l,t)} + \sum_{i,j} C_2^{(i,j,t)} + \sum_l E(C_3^{(l,t)}) \right] \quad (1)$$

Where t : time; T : project cycle; l : number of natural gas distributed power source location; $C_1^{(l,t)}$: annual investment value of the natural gas distributed power supply location in the natural gas pipeline numbered l ; $C_2^{(i,j,t)}$: annual value of investment in natural gas pipeline from node i to j ; E : expectation operator; $E(C_3^{(l,t)})$: natural gas distributed power supply operating costs under certain power demand expectations. Among them, since the model assumes that natural gas supply costs include operating costs for natural gas storage stations and pump stations, the operating costs of natural gas pipelines are not considered in the model summary.

The annual value coefficient is calculated as follows:

$$\mu = \frac{i_0}{1 - (1 + r_0)^{-T}} \quad (2)$$

where r_0 is reference rate of return.

The specific calculation formulas for distributed natural gas investment, natural gas pipeline investment, and their operating costs are shown as follows:

$$C_1^{(l,t)} = \mu P_1^{(l,t)} I_1^{(l,t)} \quad (3)$$

Where μ : annual value coefficient; $P_1^{(l,t)}$: peak capacity of the natural gas distributed power supply location in the natural gas pipeline numbered l ; $I_1^{(l,t)}$: cost of investing in natural gas distributed power supply at the natural gas pipeline numbered l .

$$C_2^{(i,j,t)} = \mu \Gamma_{(i,j)} (L_{(i,j,t+1)} - L_{(i,j,t)}) I_2^{i,j,t} \quad (4)$$

Where $\Gamma_{(i,j)}$ denotes unit capacity natural gas pipeline investment amount from node i to unit j .

The expected operating cost of a project considering the uncertainty of power demand is calculated as follows:

$$E[C_3^{(l,t)}] = \int_{-\infty}^{+\infty} C_3^{(l,t)}(D_e^{(l,t)}, \varphi) f(\varphi) d\varphi \quad (5)$$

where $f(\varphi)$ denotes power demand probability distribution density function. Equation (5) takes the uncertainty of power demand into consideration of the model.

$$E[C_3(\varphi)] = \sum_{\varphi \in \Phi} p_{\varphi}^{(b,t)} C_3^{(l,t)} D_{(e,\varphi)}^{(l,t)} \quad (6)$$

In the calculation of the model, it is very difficult to model the probability distribution of power demand. In this case, a general aggregation method considering a certain range of several situations Φ is adopted to reduce the calculation difficulty. In formula (6), $p_{\varphi}^{(b,t)}$ denotes the probability of occurrence in the case of φ , and $C_3^{(l,t)}$ denotes unit operating cost of position l at time t .

$$C_3 D_{(e,\varphi)}^{(l,t)} = \min[E_4^t C_4^t + \sum_l C_5^{(l,t,\varphi)} p_{\varphi}^{(b,t,\varphi)} + C_6^{(l,t)}] \quad (7)$$

Where $E_4^t C_4^t$: the cost of obtaining electricity from the grid when users are in shortage of distributed energy; C_4^t : unit cost; E_4^t : amount of electricity purchased; $C_5^{(l,t,\varphi)} p_{\varphi}^{(b,t,\varphi)}$: operating cost of distributed energy in the case of φ ; $C_6^{(l,t)}$: distributed power supply access grid power grid capacity compensation costs.

2.3. Constraint condition

① Power system operation constraints in integrated planning problems

Equations (8)-(10) take into account the phase power balance, the capacity limits of distributed energy in each line, and the operating power phase angle limitation of each line of the system.

$$\sum_l y_{(l,m,t)} + P_e^{(l,t)} = \sum_{\varphi} P_{(e,\varphi)}^{(l,t)} D_{(e,\varphi)}^{(l,t)} + C_{6,\varphi}^{(l,t)} \quad (8)$$

$$P_l^{\max} \leq P_{b,t} \leq P_l^{\max} \quad (9)$$

$$-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2} \quad (10)$$

The power phase angle characteristics are modeled by linearization, as shown in equation (11).

$$y_{(l,m,t)} = \frac{1}{X_{(l,m,t)}} (\theta_{(l,t)} - \theta_{(m,t)}) \quad (11)$$

② Coupling constraint of natural gas and distributed power supply

The annual demand for natural gas must meet the needs of the distributed power supply for natural gas. The annual gas demand model of a typical natural gas distributed unit is shown in equation (12).

$$D_{gas}^{(i,t)} = k_1^i + k_2^i P_i^{(l,t)} + k_3^i (P_i^{(l,t)})^2 \quad (12)$$

Where k_1^i , k_2^i , k_3^i are unit characteristic parameters at node i .

③ Planning and operation constraints of natural gas pipeline

First, the natural gas pressure constraints in the planning area are considered. Equation (13) indicates that the maximum natural gas pressure at all nodes is equal to the pressure at the starting node of the natural gas supply in the region. Inequation (14) indicates that the pressure of each node is within the pipeline pressure threshold set for ensuring pipeline safety and stable supply of natural gas.

$$\max[\rho_{(i,t)}] = \rho_{\text{ori}} \quad (13)$$

$$\rho_{\min} \leq \rho_{(i,t)} \leq \rho_{\max} \quad (14)$$

Where ρ_{ori} : gas pressure at the starting node of natural gas supply; $\rho_{(i,t)}$: gas pressure value at node i at time t ; ρ_{\min} : minimum gas pressure allowed by pipeline; ρ_{\max} : maximum gas pressure allowed by pipeline.

Second, natural gas supply and demand balance is considered. Equations (15) and (16) indicate that the total amount of gas used by distributed units and other units is equal to the gas supply from the supply source in the planning area in real time.

$$S_i = D_e^{(i,t)} + D_{\text{gas}}^{(i,t)} \quad (15)$$

$$\sum_{i,j} \vec{V}_{(j,i,t)} = 0, \quad \forall t \in [t_0, T] \quad (16)$$

Where S_i : natural gas supply at node i ; $D_e^{(i,t)}$: natural gas demand for distributed units; $D_{\text{gas}}^{(i,t)}$: natural gas demand for others units.

Third, the flow equation of natural gas in the pipe between different nodes is considered. It is assumed that natural gas is a constant temperature gas in the pipeline, which carries out general steady flow without considering the kinetic energy of natural gas.

$$Q_{(j,i,t)}^2 = 0.001494 \left(\frac{T_k}{\rho_l} \right)^2 \frac{\rho_{(i,t)}^2 - \rho_{(j,t)}^2}{GT_l L_{(i,j)} Z f} \Psi^{2.5} \quad (17)$$

Where T_k : temperature of natural gas in pipeline l ; G : natural gas gravity; ρ_l : pressure of natural gas in pipeline l ; T_l : flow of natural gas; Z : natural gas compressible coefficient; $L_{(i,j)}$: pipe length between node i and node j ; Ψ : pipe diameter.

Subject to:

$$\delta = 0.001494 \left(\frac{T_k}{\rho_l} \right)^2 \frac{\Delta^{2.5}}{GT_l L_{(i,j)} Z} \quad (18)$$

The $Q_{(j,i,t)}^2$ can be formulated as follows:

$$Q_{(j,i,t)}^2 = \delta [\rho_{(i,t)}^2 - \rho_{(j,t)}^2] \quad (19)$$

The gas pressure reduction and air flow direction constraints within the pipeline between different nodes are as shown in inequalities (20) to (21).

$$\begin{cases} \delta[\rho_{(i,t)}^2 - \rho_{(j,t)}^2] - V_{(j,i,t)}^2 \leq W(1 - H_{i,j,t}) \\ \delta[\rho_{(j,t)}^2 - \rho_{(i,t)}^2] - V_{(j,i,t)}^2 \geq W(H_{i,j,t} - 1) \end{cases} \quad (20)$$

$$H_{i,j,t}, h_{i,j,t} \in [0,1] \quad (21)$$

Where V : pipeline natural gas flow velocity; $H_{i,j,t}$: auxiliary variables with a set value of 0 or 1. When the pressure at node i is higher than the pressure at node j , $H_{i,j,t} = 1$, then the right side of the inequality is equal to 0, and the air flow direction is from the node i to the node j . To ensure that when $H_{i,j,t} = 0$, the pressure drop between the nodes is within the allowable pressure drop range, W is set to a value slightly smaller than pipeline pressure maximum value ρ_{\max}^2 .

In addition, in the above formula, the non-negative constraint of the variable is shown in formula (22).

$$\rho, V, D_e, D_{gas} \geq 0 \quad (22)$$

3. Example analysis

3.1. Basic data

An example was taken from an existing industrial park in a city in Guangdong Province and a 15-year natural gas distributed power supply development plan was developed. In the planning model, the distribution network of the park is a single busbar structure, and the structure of the park's power system and the user loads are shown in Figure 2 and Table 1.

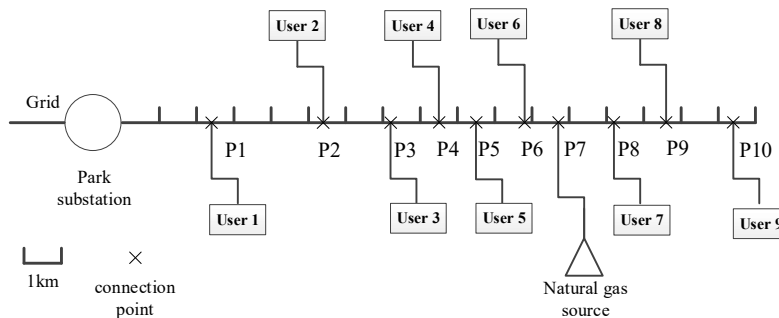


Figure 2. Power grid structure and loads conditions in the planning area

Table 1. User loads conditions

User ID	Annual average load /kw	Annual maximum load /kw
1	424	583
2	314	427
3	1800	4855
4	3421	4659
5	2319	3326
6	1969	2756
7	358	436
8	216	278
9	466	547

The example does not consider the line loss, substation control and adjustment, the expansion of the park's power grid, and the distance between user and bus. In order to achieve optimal planning and operation, the natural gas pipeline operation right and the distribution network operation right belong to the same entity in the park. All-natural gas pipelines in the park are new plans, and the natural gas source is between bus 6 and bus 7. The growth rate of power load is set to 3.2%, the capacity of bench transformer is 15MW, the investment cost of distributed power is 720,000 yuan/MW, the operating cost is 240 yuan/MW, the minimum unit size is assumed to be 2MW, and the user load loss cost is 6000 Yuan/MW, the cost of laying natural gas pipelines is 1,600,000 yuan/km. In the example, there are 5 kinds of uncertainties considered in the model, as shown in Table 2.

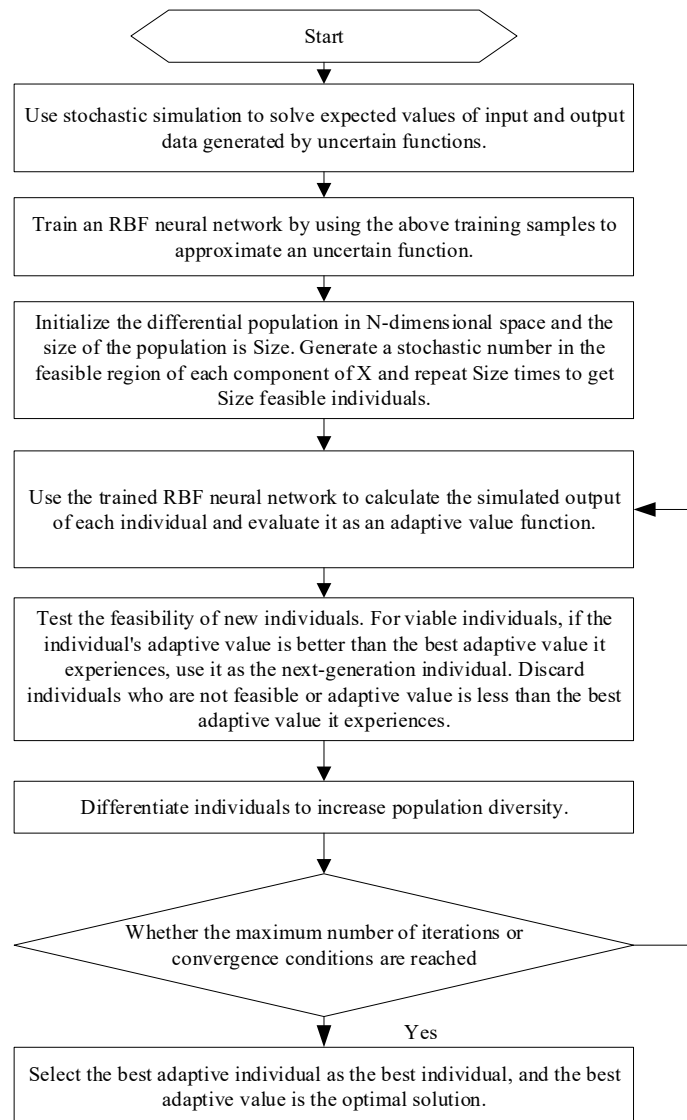
Table 2. Uncertainty of power demand

Situation	Load forecast value magnification	Probability
1	0.9	10%
2	0.8	5%
3	1	60%
4	1.1	10%
5	1.2	5%

3.2. Solving process

Stochastic programming is an effective method to solve optimal problems with stochastic variables. Stochastic programming introduces random variables in the process of establishing mathematical models. Relative to other deterministic mathematical programming methods, it can better reflect the actual situation of processes containing stochastic variables, and the solution results are more practical. Therefore, stochastic programming has been widely used in the optimization problem with stochastic processes. The main method of using stochastic programming model to solve practical problems is to establish the method of expectation value model, and then use certain optimization mechanism to find the optimal solution that satisfies the constraints. The method of using computer program to simulate stochastic process is as follows: first, establish a model that conforms to the stochastic distribution of variables; and then use the intelligent algorithm of genetic algorithm program to get the close solution of the optimal solution by the method of approximation [14]. In the joint planning of natural gas distributed power supply and natural gas pipelines, power demand is a key factor affecting project returns, but there is a certain error in power demand forecasting technology. The power demand is uncertain during the project investment decision-making period. And ignoring the uncertainty of the increment of the power demand will lead to unreliable planning results. Therefore, the uncertainty of power demand is considered in the model construction and a joint planning model based on the expected value is established. In the design of solving process, a hybrid differential evolution algorithm and BP neural networks algorithm is introduced.

The solution processes of hybrid differential evolution algorithm BP neural networks algorithm are shown below. First, according to the characteristics and objective functions of stochastic variables, a stochastic expectation model is established. When calculating stochastic simulations and a large number of samples, the calculation process and minimum value of the expected value of the stochastic expectation function are obtained. Second, the fitting expected value is calculated by using RBF neural network. Finally, differential evolution algorithm is used to realize population evolution and find its optimal solution. The specific solution steps are shown in Figure 3.

**Figure 3.** Solving process

3.3. Planning results

The goal of the joint planning program is to obtain the optimal location and capacity of the distributed power supply, and to ensure that it can meet the sustained growth of power load demand in the park. The final planning results are shown in Table 3.

Table 3. Planning results

Time node	Pipeline planning node	Pipeline length/km	Distributed power supply location	Distributed power supply capacity/MW	Investment/thousand yuan
1st year	P7-P9	3.3	P8	4	8160
4th year	P9-P10	1.5	P9	2	3840-
12th year	P5-P7	3.1	P5	2	640
14th year	P4-P5	1.9	P4	2	4480

4. Conclusion

Aiming at minimize investment and operation cost of natural gas distributed power supply and gas pipelines, uncertainty of the power demand, operation constraints of the regional distribution network and operation constraints of gas pipeline is considered, and the joint planning model of natural gas distributed power supply and pipeline is built. The natural gas distributed power supply planning problem in an industrial park in Guangdong Province is used as an example, and a hybrid differential evolution algorithm and BP neural network algorithm is designed to solve the problem. The planning results show that the joint planning model of natural gas distributed power supply and gas pipelines can achieve the joint planning goals well. The calculated planning scheme can effectively guide the development of natural gas pipeline and gas distributed power supply in the park.

References

- [1] Weiming Song. Development Status and Trend of Natural Gas Distributed Energy in China[J]. Energy of China, 2016,(10):41-45.
- [2] Bo C. Research on Building Energy Smart Grid Based on Natural Gas Based Distributed Energy System[J]. Journal of Engineering Thermophysics, 2012, 33(12):2047-2051.
- [3] Yingrui Wang, Bo Zeng, Jing Guo, et al. Multi-Energy Flow Calculation Method for Integrated Energy System Containing Electricity, Heat and Gas[J]. Power System Technology, 2016,(10):2942-2951.
- [4] Xiandong Xu, Hongjie Jia, Xiaolong Jin, et al. Study on Hybrid Heat-Gas-Power Flow Algorithm for Integrated Community Energy System[J]. Proceedings of the CSEE, 2015,(14):3634-3642.
- [5] Abeysekera M, Wu J, Jenkins N, et al. Steady state analysis of gas networks with distributed injection of alternative gas[J]. Applied Energy, 2016, 164:991-1002.
- [6] Shuyong Liu, Na Li, Ming Zeng, et al. Supply and Demand Optimization Method of Urban Energy System Based on Improved Multispecies Hybrid Evolutionary Algorithm[J]. Electric Power Construction, 2016, 37(1):23-29.
- [7] Hao Liang, Weiding Long. Research and application of integrated planning model for urban energy system[J]. Journal of Shandong Jianzhu University, 2010, 25(5):524-528.
- [8] Wei Gu, Shuai Lu, Jun Wang, et al. Modeling of the Heating Network for Multi-district Integrated Energy System and Its Operation Optimization[J]. Proceedings of the CSEE, 2017, 37(5):1305-1315.
- [9] Bo Wei. Beijing's Natural Gas Market Study and MARKAL Model Application[D]. Tsinghua University, 2006.
- [10] Hao Wang. Research on optimal allocation of natural gas CCHP system based on the gas turbine[D]. Hunan University, 2013.
- [11] Jiang B B, Chen W, Yu Y, et al. The future of natural gas coal consumption in Beijing, Guangdong and Shanghai: An assessment utilizing MARKAL[C]// Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the, Century. IEEE, 2008:3286-3299.
- [12] Yanling Luo, Liexiang Yan, Hai Lu, et al. Energy planning based on distributed power generation system in industrial parks[J]. Chemical Industry and Engineering Progress, 2013, 32(2):308-312.
- [13] Touretzky C R, McGuffin D L, Ziesmer J C, et al. The effect of distributed electricity generation using natural gas on the electric and natural gas grids[J]. Applied Energy, 2016, 177:500-514.
- [14] Baoding Liu. Random Planning and Fuzzy Planning[M]. Tsinghua University Press, 1998.