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Multi-objective production planning model for equipment manufacturing enterprises with multiple uncertainties in demand

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A B S T R A C T

A production planning model with multiple uncertainties was established in this paper. Customers' demands for quantity, quality, delivery time and price are different. For an ambiguous number of customers, the expectation of the degree of satisfaction was determined by a triangular fuzzy number method. A trapezoidal fuzzy number method was used for customer prices to determine the expectation of satisfaction of the delivery date. Fuzzy intervals and interval numbers were used to describe quality uncertainty and price uncertainty, respectively. A multi-objective planning model was established, which consists of four objectives, namely, meeting customers' needs, minimizing costs, minimizing delivery time and maximizing corporate profits. Then, the non-dominated sorting genetic algorithm (NSGA-II) was implemented to simulate and solve the problem of uncertain optimization. This modal resolved multiple uncertainties in customer demand during the process of production planning for the equipment manufacturing enterprises. The results of the running showed and generated a series of Pareto solutions, which are consistent with the results of a multi-objective planning solution. Manufacturers can obtain the best production plans according to the company's production objective priority rules. Finally, the adaptability and feasibility of the model were verified.

A R T I C L E I N F O

Keywords:
Production planning;
Multiple uncertainties;
Manufacturing enterprise;
Multi-objective model;
Non-dominated sorting genetic algorithm (NSGA-II)

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1. Introduction

Equipment manufacturing companies need to have flexible manufacturing capabilities because of the diversity, individuation, and differentiation of customer needs, and their production plans must respond quickly to fluctuations in demand. When operating near system limits, unexpected modifications to production plans can be very challenging. Scholars and experts have used mathematical models to research the management of uncertain needs. Rahdar *et al.* built a two-stage, tri-level optimization model under the uncertainty of demand and date of delivery [1]. Ho *et al.* built a model that addresses the problem of capacity allocation for multi-variety products when customer needs are uncertain [2]. Shi *et al*. established a mathematical model to solve the uncertainty of demand and returns and adopted the Lagrangian relaxation method [3]. Diabat *et al.* established a joint network positioning inventory model. The model solved the uncertainty of demand and lead-time using simulated annealing and direct search methods [4]. Feng and Nagi used a scenario analysis approach to deal with uncertain demand. They established an optimization model to solve the problem of cost changes brought about by uncertain demand [5]. Erdogan and Denton established a multistage stochastic linear model. This model solves the problem of uncertain service dates and customer numbers on a specific date [6]. Cho and Tang studied three sales strategies to solve the problem of uncertainty in supply and demand [7]. Aghezzaf *et al.* established a stochastic model to solve the cyclical demand uncertainty of the finished product [8]. Chica *et al.* established a multi-objective optimization assembly line balancing model to address the variability and uncertainty of the demand for mixed products for industrial scenarios [9]. Chica *et al.* set up a multi-objective optimization model for assembly line balancing to address changes in demand for different products [10]. Xu *et al.* created multi-objective decision-making methods [11-12]. Tang *et al.* solved problems by establishing nondeterministic models [13-14]. Galal *et al.* built simulation models with uncertain demand quantities and delivery cycles to address agricultural supply issues [15]. Said *et al.* established a distribution operation model under fuzzy demand [16]. Liu and Zhang considered dual uncertainties and established a multi-objective planning model [17]. This paper extends research on this basis.

The paper has four sections. In Section 2, we describe the problem, conditional assumptions, and variable symbols. In Section 3, we focus on multiple uncertainties of demand and adopt a scenario analysis method to establish a multi-objective model for equipment manufacturing enterprises. In Section 4, we solve the model by using an NSGA-II algorithm. In Section 5, we conduct a case analysis and present a discussion.

2. Problem descriptions and premise assumptions

2.1 Problem description

Due to the impact of issues such as raw material supply times and finite order periods, most equipment manufacturing enterprises manage their production according to the customers' wishes. However, the processes involved in signing, manufacturing, and fulfilling orders may not be consistent. Therefore, in cases of order modification and emergency orders, or changes in customer demand for quantities, varieties, qualities, delivery times and prices, manufacturing processes are affected, and cause disruptions in production plans and the scheduling of equipment. Fig. 1 is a description of the multiple uncertainties in customer demand for an equipment manufacturing enterprise.

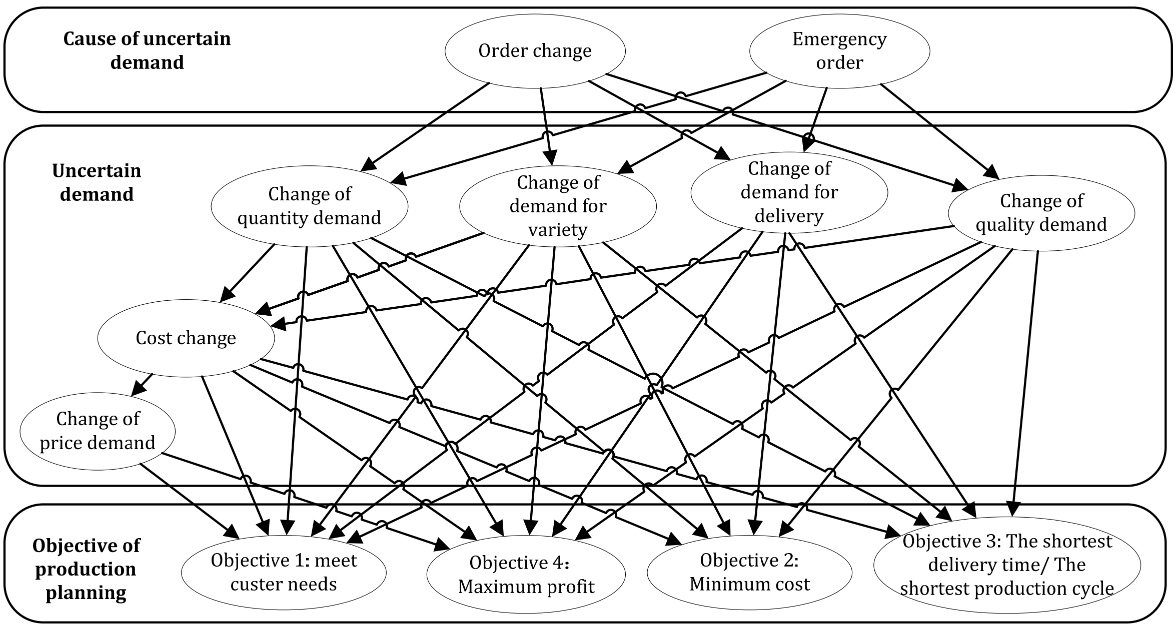

Fig. 1 Multiple uncertainties of customer demand

2.2 Premise assumptions

Based on the description of the multiple uncertainties of customer demands in Fig. 1, the following hypotheses are put forward:

1) Assume that the probability of order changes and emergency orders of the equipment manufacturing enterprises is known.
2) Assume that the manufacturing enterprise has production capacity constraints, inventory constraints, and resource acquisition capacity constraints.
3) Assume that order changes and urgent orders cause changes in the enterprises' production plans.

2.3 Variables and parameters description

The basic symbols and variables involved in the model and their meanings are in Table 1. The subscripts *i*, *j*, *t* in Table 1 are denoted as the *i*-th product, the *j*-th resource, and the *t*-th period, respectively. The variable *i* is an integer between 1 and *n*, and *j* is an integer between 1 and *m*.

Table 1 The meaning of basic symbols and variables

Symbols	Meanings
n	The number of product types of the enterprise.
m	The number of types of production resources.
N_{it}	The number of demands for original planned products.
N'_{ijt}	The number of resource requirements for the original plan.
R_{it}	The stock of the product.
R'_{jt}	Inventory of resource.
MR_i	The maximum stock of product.
MR'_j	The maximum stock of resource.
ln_{it}	The amount of stockout.
lt_{it}	The shortage time of production.
lq_{it}	The quality deviation.
lp_{it}	The price deviation.
C_{it}	The production cost.
RC_{it}	The production preparation costs.
MC_{it},	The minimum cost.
C'_{jt}	The acquisition cost.
P_{it}	The original planned price.
PM_{it}	The market price.
T_{it}	The total lead time to meet the demand.
RT_{it}	The production preparation lead-time.
ET_{it}	The lead time for emergency production.
TN_{it}	The customer's original demand time.
ls_i	The economic batch quantity.
Q_{it}	The original planned demand quality.
QF_{it}	The quality.
W_{it}	Ability to produce products
MW_{it}	Maximum ability to produce products.
W'_{jt}	Ability to produce or acquire resource.
MW'_{jt}	Maximum ability to produce or acquire resource.
E_{it}	The cost of opportunity loss.
F_{it}	The unit inventory holding cost.
G_{it}	The planned production quantity.
ΔN_{it}	Changes in the quantity of demand.
ΔTN_{it}	Changes in the time of demand.
ΔP_{it}	Changes in the price of demand.
ΔQ_{it}	Changes in the quality of demand
$\widehat{N}_{it}$	The quantity required of customer demand.
$\widehat{TN}_{it}$	The required time of the customer's demand.
$\hat{P}_{it}$	The customer's demand price.
$\hat{Q}_{it}$	The quality of the customer's demand.

3. Multi-objective production planning model

Taking into account the multiple uncertainties of the needs of equipment manufacturing companies' customers, this paper considers several objectives such as customer satisfaction, production cost, production cycle, and profit. We create a multi-objective production-planning model in Eq. 1.

$$\begin{gathered} min\, F(X\_vm) = \big(f_1(X\_vm), f_2(X\_vm), f_3(X\_vm), f_4(X\_vm)\big) \\ s.t. \quad X \in \Omega \\ G(X) = 0 \\ H(X) \leq 0 \end{gathered} \tag{1}$$

In the model, f_1 is customer satisfaction, objective f_2 is production cost, objective f_3 is a production cycle objective, and f_4 is a corporate profit objective. X_vm is an optimization variable of the multi-objective model. It is a multidimensional vector matrix (SF, CS, PT, PF), where SF is the quantity vector matrix of the product produced by the enterprise, CS is the cost vector matrix of the product produced by the enterprise, PT is the production cycle vector of the products produced by the enterprise, PF is the profit vector matrix of the products produced by the enterprise, Ω is a feasible solution space, G is an equality constraint function, and H is an inequality constraint function.

3.1 Objective functions

In cases where a customer changes the order requirements and requires an emergency order, a scenario analysis method is used to describe the situation. The variables are: S_1 describes the scenario of the order change demand occurred, p_{s1} is the probability of occurrence of S_1, S_2 describes the scenario of the emergency order demand occurred, and p_{s2} is the probability of occurrence of S_2.

The S_1, S_2 combinations constitute S scenarios. S is a series of scenarios for equipment manufacturing enterprises' multi-variety production order change and emergency order demand. In addition, $p_s = \{p_{s1}, p_{s2}\}, p_{s1} + p_{s2} = 1$. According to the above description, the four production operation objectives are as follows:

Objective 1: High customer satisfaction is the objective, that is, low customer dissatisfaction is not an objective. The model is Eq. 2 in the form:

$$\begin{gathered} f_1 = min \sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \xi_{N1}^{ts-} + min \sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \xi_{T1}^{ts-} + min \sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \xi_{Q1}^{ts-} \\ + min \sum_{s=1}^{S}\sum_{t=1}^{T} p_s \cdot \xi_{P1}^{ts-} \end{gathered} \tag{2}$$

Subject to:

$$\sum_{i=1}^{n} (\widehat{N}_{it}^{s} - ln_{it}^{s}) / \sum_{i=1}^{n} N_{it}^{s} + \xi_{N1}^{ts-} - \xi_{N1}^{ts+} = 1, \forall t \in N, \forall s \in S \tag{3}$$

$$\sum_{i=1}^{n} (\widehat{TN}_{it}^{s} - lt_{it}^{s}) / \sum_{i=1}^{n} TN_{it}^{s} + \xi_{T1}^{ts-} - \xi_{T1}^{ts+} = 1, \forall t \in N, \forall s \in S \tag{4}$$

$$\sum_{i=1}^{n} (\widehat{P}_{it}^{s} - lp_{it}^{s}) / \sum_{i=1}^{n} P_{it}^{s} + \xi_{P1}^{ts-} - \xi_{P1}^{ts+} = 1, \forall t \in N, \forall s \in S \tag{5}$$

$$\sum_{i=1}^{n} (\widehat{Q}_{it}^{s} - lq_{it}^{s}) / \sum_{i=1}^{n} Q_{it}^{s} + \xi_{Q1}^{ts-} - \xi_{Q1}^{ts+} = 1, \forall t \in N, \forall s \in S \tag{6}$$

In Eqs. 2 to 6:

ξ_{N1}^{ts-} and ξ_{N1}^{ts+}, respectively, are ratios of the quantity of customer demand that has not been reached or exceeded;
ξ_{T1}^{ts-} and ξ_{T1}^{ts+}, respectively, are ratios of the delivery date of customer demand that has not been reached or exceeded.
ξ_{Q1}^{ts-} and ξ_{Q1}^{ts+}, respectively, are ratios of the quality of customer demand that has not been reached or exceeded.
ξ_{P1}^{ts-} and ξ_{P1}^{ts+}, respectively, are ratios of the price of customer demand that has not been reached or exceeded.

$\xi_{N1}^{ts-}, \xi_{N1}^{ts+}, \xi_{T1}^{ts-}, \xi_{T1}^{ts+}, \xi_{Q1}^{ts-}, \xi_{Q1}^{ts+}, \xi_{P1}^{ts-}, \xi_{P1}^{ts+}$ are all in the t-th period. In addition, the customer's preference for the quantity of demand, delivery time of demand, demand quality and demand price are different so the satisfaction coefficient of expectation is also different. Therefore, we can define one vector matrix as:

$$\beta = [\beta 1_k^{ts}, \beta 2_k^{ts}, \beta 3_k^{ts}, \beta 4_k^{ts}]$$

For any given $\forall t,\ s,\ k$ where $\beta 1_k^{ts}, \beta 2_k^{ts}, \beta 3_k^{ts}, \beta 4_k^{ts}$ the values are all [0,1], and

$$\beta 1_k^{ts} + \beta 2_k^{ts} + \beta 3_k^{ts} + \beta 4_k^{ts} = 1$$

$\beta 1_k^{ts}$ is the satisfaction expectation coefficients of the customer's demands for the quantity, $\beta 2_k^{ts}$ is the satisfaction expectation coefficients of the customer's demands for delivery time, $\beta 3_k^{ts}$ is the satisfaction expectation coefficients of the customer's demands for the quality, and $\beta 4_k^{ts}$ is the satisfaction expectation coefficients of the customer's demands for the price.

Then, $\beta 1_k^{ts}, \beta 2_k^{ts}, \beta 3_k^{ts}, \beta 4_k^{ts}$ are respectively added to the corresponding satisfaction rates of Eq. 2. Therefore, Eq. 2 can be modified to Eq. 7.

$$f_1 = min \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{k=1}^{K} p_s \cdot \xi_{N1}^{ts-} \cdot \beta 1_k^{ts} + min \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{k=1}^{K} p_s \cdot \xi_{T1}^{ts-} \cdot \beta 2_k^{ts} + min \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{k=1}^{K} p_s \cdot \xi_{Q1}^{ts-} \cdot \beta 3_k^{ts} + min \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{k=1}^{K} p_s \cdot \xi_{P1}^{ts-} \cdot \beta 4_k^{ts} \quad (7)$$

Objective 2: Low manufacturing enterprise production cost is the objective. The model is Eq. 8 in the form:

$$f_2 = min \xi C_2^+ \quad (8)$$

$s.t.$

$$C/MC + \xi C_2^- - \xi C_2^+ = 1 \quad (9)$$

$$\sum_{s=1}^{S} p_s \sum_{t=1}^{T} \left\{ \sum_{i=1}^{n} (C_{it}^s + RC_{it}^s + \sum_{j=1}^{m} C_{jt}^{'s} \cdot N_{ijt}^{'s}) \cdot \widehat{N}_{it}^s + \sum_{i=1}^{n} E_{it}^s \cdot Max(\widehat{N}_{it}^s - G_{it}^s, 0) + \sum_{i=1}^{n} F_{it}^s \cdot Max(G_{it}^s + N_{it}^s, 0) \right\} - C \leq 0 \quad (10)$$

The variables are: C is the actual cost incurred in the production process of an enterprise, MC is the ideal lowest cost incurred in the production process of an enterprise, ξC_2^- is the part that is higher than the planned cost, and ξC_2^+ is the part that is lower than the planned cost.

Objective 3: Short production cycle, short delivery time and the production arrangement are the most reasonable. The model is Eq. 11 in the form:

$$f_3 = min \sum_{s=1}^{S} \sum_{t=1}^{T} \xi T_3^{ts-} \tag{11}$$

s.t.

$$\sum_{i=1}^{N} \widehat{TN}_{it}^{s-} / TT_t^s + \xi T_3^{ts-} - \xi T_3^{ts+} = 1, \ \forall t \in N, \forall s \in S \tag{12}$$

Under the scenario s, TT_t^s is the minimum production cycle pursued by the t-th cycle production operation; ξT_3^{ts-} is a part of the delivery time demand. ξT_3^{ts+} is the exceeded part of the delivery time demand.

Objective 4: Maximization of the enterprise's profit is the objective. The model is Eq. 13 in the form:

$$f_4 = min(1 - \xi Pr_4^+) \tag{13}$$

$s.t.$

$$PRF/MPRF + \xi Pr_4^- - \xi Pr_4^+ = 1 \tag{14}$$

PRF is the actual profit produced by the enterprise; $MPRF$ is the maximum profit produced by the enterprise; ξPr_4^- and ξPr_4^+ indicate the unreached parts and the excess parts of objective 4, respectively. The equation is:

$$\begin{aligned} PRF = & \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} (\hat{P}_{it}^s - C_{it}^s - RC_{it}^s - \sum_{j=1}^{m} C_{jt}^{'s} \cdot N_{ijt}^{'s}) \cdot \widehat{N}_{it}^s \\ & - \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} E_{it}^s \cdot Max(\widehat{N}_{it}^s - G_{it}^s, 0) - \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{i=1}^{n} F_{it}^s \cdot Max(G_{it}^s + N_{it}^s, 0) \end{aligned} \tag{15}$$

3.2 The constraints of the objective function

The objective function should satisfy the following constraints in addition to Eqs. 3, 4, 5, 6, 9, 10, 12, and 14:

$$ln_{it} = N_{it} - R_{it} \tag{16}$$

$$N_{it} - R_{it} \leq W_i \tag{17}$$

$$ln_{it} \leq W_i \tag{18}$$

$$ln_{it} \leq N_{it} \tag{19}$$

$$\sum_{i=1}^{n} N'_{ijt} - R'_{jt} \leq W'_j \tag{20}$$

$$R_{i\cdot(t+1)} = R_{i\cdot t} + N_{i\cdot(t-T_i)} - R_{i\cdot(t-T_i)} \tag{21}$$

$$R_{it} \leq MR_i, \ R_{i\cdot(t+1)} \leq MR_i \tag{22}$$

$$TN_{it} \geq T_{it} + ET_{it} \tag{23}$$

$$RT_{it} \geq ET_{it} \tag{24}$$

$$lt_{it} = T_{it} + ET_{it} - TN_{it} \tag{25}$$

$$\begin{gathered} N_{it}, \ R_{it}, \ W_{it}, \ N'_{ijt}, \ R'_{jt}, \ W'_{jt}, \ P_{it}, \ C_{it}, \ C'_{jt}, \ E_{it}, \ F_{it}, \ G_{it} \geq 0, \\ i = 1,2,\dots,n, \ j = 1,2,\dots,m, \ \forall t \in N, \forall s \in S \end{gathered} \tag{26}$$

Eqs. 16 to 20 are mainly constraints on production capacity. Eqs. 21 and 22 are mainly constraints on inventory. Eqs. 23 to 25 are mainly constraints on production time, and Eq. 26 is a nonnegatively constrained variable.

3.3 The triangular fuzzy description of the number of demands with fuzziness

For quantity demand $\widetilde{N}_{it}^{s}$, we use triangular fuzzy numbers $\widetilde{N}_{it}^{s} = (dn_{1it}^{s}, dn_{2it}^{s}, dn_{3it}^{s})$ to express the uncertain demand quantity, for which dn_{1it}^{s} and dn_{3it}^{s} are the lower and upper boundaries of the fuzzy number. That is, the number of demands is within this range $[dn_{1it}^{s}, dn_{3it}^{s}]$. dn_{2it}^{s} is the point where the degree of membership is 1. The membership function is Eq. 27 in the form:

$$\beta 1_{k}^{ts} = \rho(z) = \begin{cases} 0 & z \leq dn_{1it}^{s} \\ \dfrac{(z - dn_{1it}^{s})}{(dn_{2it}^{s} - dn_{1it}^{s})}, & dn_{1it}^{s} < z < dn_{2it}^{s} \\ \dfrac{(dn_{3it}^{s} - z)}{(dn_{3it}^{s} - dn_{2it}^{s})}, & dn_{2it}^{s} < z < dn_{3it}^{s} \\ 0 & z \geq dn_{3it}^{s} \end{cases} \quad \forall t,\ s,\ i \tag{27}$$

We suppose $dn_{2it}^{s} = N_{it}^{s}$, and let $dn_{1it}^{s}, dn_{3it}^{s}$ be the upper and lower bounds of the demand quantity, we obtain the customer demand for the membership function; z is the actual demand of the customer $\widehat{N}_{it}^{s}$.

3.4 Trapezoidal fuzzy description of demand delivery with fuzziness

For the delivery time demand $\widetilde{TN}_{it}^{s}$, the research in this paper uses trapezoidal fuzzy numbers $\widetilde{TN}_{it}^{s} = (dtn_{1it}^{s}, dtn_{2it}^{s}, dtn_{3it}^{s}, dtn_{4it}^{s})$ to indicate an uncertain demand lead time. In the fuzzy numbers, dtn_{1it}^{s} and dtn_{4it}^{s} indicate the upper and lower bounds of the fuzzy number; dtn_{2it}^{s} and dtn_{4it}^{s} are the peak value of this fuzzy number. Its membership function is Eq. 28 in the form:

$$\beta 2_{k}^{ts} = \varphi(z) = \begin{cases} 0 & z \leq dtn_{1it}^{s} \\ \dfrac{(z - dtn_{1it}^{s})}{(dtn_{2it}^{s} - dtn_{1it}^{s})}, & dtn_{1it}^{s} < z < dtn_{2it}^{s} \\ 1, & dtn_{2it}^{s} \leq z \leq dtn_{3it}^{s} \\ \dfrac{(dtn_{4it}^{s} - z)}{(dtn_{4it}^{s} - dtn_{3it}^{s})}, & dtn_{3it}^{s} < z < dtn_{4it}^{s} \\ 0 & z \geq dtn_{4it}^{s} \end{cases} \quad \forall t,\ s,\ i \tag{28}$$

3.5 Interval rough description of demand quality with roughness

For quality demand $\tilde{Q}_{it}^{s}$, we use an interval roughness of $\tilde{Q}_{it}^{s} = ([dq_{1it}^{s}, dq_{2it}^{s}], [dq_{3it}^{s}, dq_{4it}^{s}])$ representing the quality demands; the assumptions are only two roughness sets, represented by the pairs of the top approximation and the bottom approximation. Among the interval roughness variables, dq_{1it}^{s} and dq_{2it}^{s} are the lower and upper bounds of the lower approximate; dq_{3it}^{s} and dq_{4it}^{s} are the lower and upper bounds of the upper approximation. The membership function is Eq. 29 in the form:

$$\tilde{\tilde{Q}}_{it}^{s} = \omega(z) = \begin{cases} 0, & z < dq_{1it}^{s} \\ \dfrac{(dq_{1it}^{s} + dq_{2it}^{s})}{2}, & dq_{1it}^{s} \leq z \leq dq_{2it}^{s} \\ 0, & dq_{2it}^{s} < z < dq_{3it}^{s} \\ \dfrac{(dq_{3it}^{s} + dq_{4it}^{s})}{2}, & dq_{3it}^{s} \leq z \leq dq_{4it}^{s} \\ 0, & z > dq_{4it}^{s} \end{cases} \quad \forall t,\ s,\ i \tag{29}$$

3.6 Fuzzy description of fuzzy demand price

For the price demand $\tilde{P}_{it}^{s}$, because the price fluctuates within a certain range, we define a value interval, denoted as $[dp_{1it}^{s}, dp_{2it}^{s}]$, and request $dp_{1it}^{s} \leq \tilde{P}_{it}^{s} \leq dp_{2it}^{s}$. Among the value interval variables, dp_{1it}^{s} is the lowest price the enterprise can accept, and dp_{2it}^{s} is the highest price the customer can accept. This adds a constraint, Eq. 30, for the price demand $\tilde{P}_{it}^{s}$. The membership function is Eq. 30 in the form:

$$dp_{1it}^{s} \leq \tilde{P}_{it}^{s} \leq dp_{2it}^{s} \tag{30}$$

$$\beta 4_{k}^{ts} = \begin{cases} 0 & , \quad \tilde{P}_{it}^{s} < dp_{1it}^{s} \\ \dfrac{\left(\tilde{P}_{it}^{s} - dn_{1it}^{s}\right)}{\left(dn_{2it}^{s} - dn_{1it}^{s}\right)} & , \quad dp_{1it}^{s} \leq \tilde{P}_{it}^{s} \leq dp_{2it}^{s} \\ 0 & , \quad \tilde{P}_{it}^{s} > dp_{2it}^{s} \end{cases} \tag{31}$$

In summary, the multi-objective production-planning model established in this paper is as follows:

- the objective function is composed of Eqs. 1, 7, 8, 11, and 13,
- the constraints are composed of Eqs. 9, 10, 12, 14, Eqs. 16 to 25, and Eqs. 27 to 31,
- Eq. 26 is the nonnegative statement.

4. Used method

The production-planning model of this paper is a multi-objective optimization problem. At the same time, it is also an NP-hard problem. It needs to be solved using a multi-objective optimization algorithm. A process analysis diagram for solving this problem, based on the NSGAII concept is presented in Fig. 2.

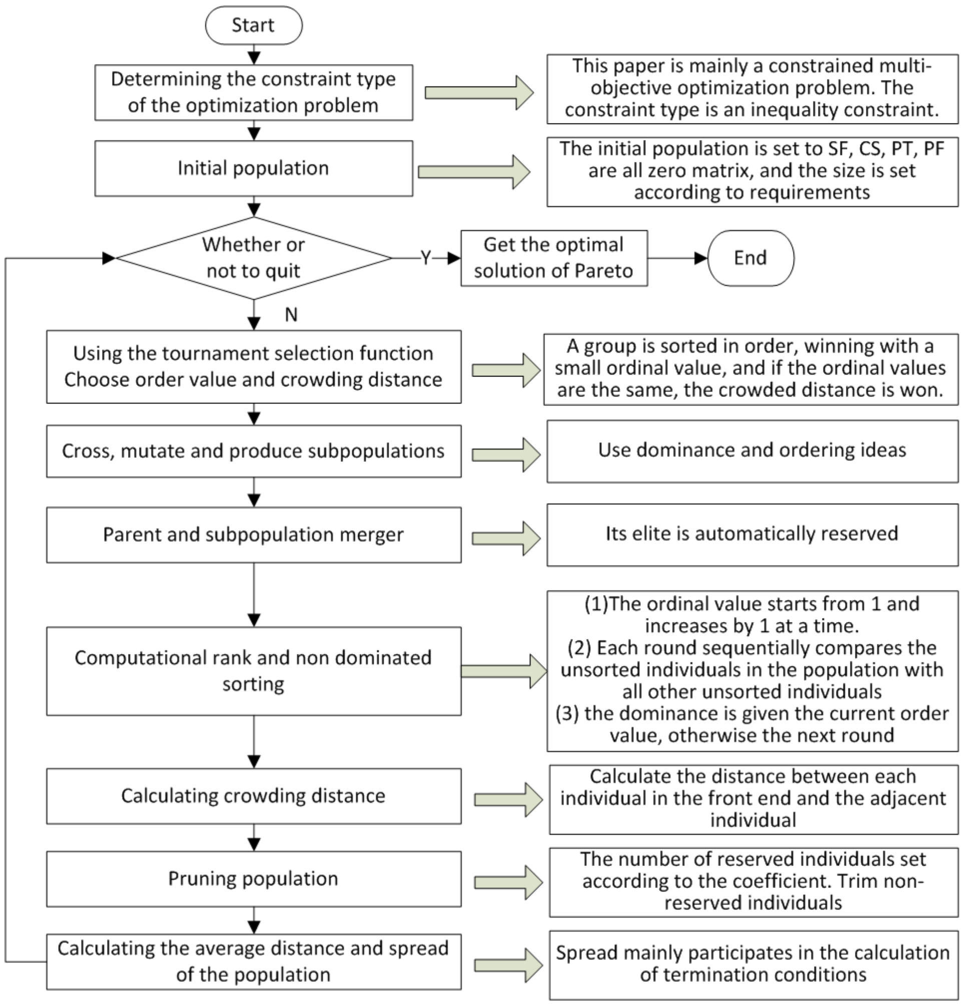

Fig. 2 Process analysis diagram for solving this problem based on the NSGAII concept

This article mainly uses Kalyanmoy Deb's Nondominated Sorting Genetic Algorithm II (NSGA-II). The NSGA-II algorithm uses an elite strategy. The next generation of populations includes a parent population and a child population. The good individuals in the parent population are preserved. Each individual group is layered and stored in two generations. Therefore, the best individuals in the group will be retained to the end. The NSGA-II algorithm is used to solve many practical problems. Fallah-Mehdipour *et al.* used this algorithm to solve a problem in building project management [18]. Huang *et al.* used this algorithm to solve a telecom customer churn problem [19]. The NSGA-II algorithm changes the fitness strategy of the sharing radius and proposes a comparison operator of congestion degree [20]. The algorithm performs fast sorting. Then, the winning criterion is set so that the individual is evenly distributed in the Pareto domain. The sorting improves calculation speed and preserves the diversity of the population.

5. Results and discussion

According to the above model, the examples are combined for simulation and analysis. MATLAB's 2015b version is adopted to carry out the simulation's calculations and analyze the results.

5.1 Initial data

(1) An equipment manufacturing enterprise is supposed to have the ability to produce 5 kinds of products, and there are 10 kinds of resources required. That is, $n = 5, m = 10$. The probability of order modification and emergency ordering is assumed to be 0.3 and 0.7, respectively. We assume that at some point *t* = 1, the initial values of some parameter variables are as follows:

$$N'_{ijt} = \begin{bmatrix} 2 & 3 & 1 & 1 & 0 & 3 & 0 & 4 & 3 & 4 \\ 0 & 4 & 4 & 2 & 0 & 3 & 3 & 0 & 4 & 4 \\ 0 & 2 & 3 & 4 & 3 & 4 & 0 & 2 & 3 & 3 \\ 1 & 3 & 0 & 0 & 2 & 3 & 1 & 0 & 0 & 4 \\ 0 & 2 & 3 & 0 & 1 & 3 & 2 & 3 & 2 & 1 \\ 0 & 3 & 3 & 0 & 4 & 1 & 2 & 1 & 0 & 3 \end{bmatrix} \quad N_{it} = \begin{bmatrix} 1800 & 1000 & 1400 & 1000 & 800 \\ 200 & 1600 & 600 & 1600 & 1800 \\ 1600 & 2000 & 800 & 2000 & 200 \\ 2000 & 200 & 1400 & 1000 & 1800 \\ 2000 & 2000 & 400 & 1200 & 200 \end{bmatrix}$$

$$\Delta N_{it} = \begin{bmatrix} 300 & 1000 & 900 & 400 & 500 \\ 300 & 800 & 900 & 900 & 900 \\ 800 & 600 & 600 & 100 & 900 \\ 900 & 200 & 500 & 800 & 600 \\ 800 & 400 & 1000 & 900 & 300 \end{bmatrix} \quad G_{it} = \begin{bmatrix} 5700 & 5100 & 5300 & 4700 & 5300 \\ 6500 & 5700 & 6500 & 4400 & 6000 \\ 4800 & 4100 & 6300 & 6200 & 6100 \\ 4800 & 5100 & 6600 & 7000 & 5600 \\ 4700 & 4500 & 3600 & 6400 & 5900 \end{bmatrix}$$

$$BN_{it} = \begin{bmatrix} 500 & 900 & 900 & 200 & 100 & 600 & 500 & 600 & 400 & 700 \\ 400 & 300 & 600 & 100 & 1000 & 400 & 100 & 600 & 300 & 300 \\ 500 & 900 & 100 & 1000 & 800 & 600 & 500 & 200 & 800 & 600 \\ 700 & 500 & 400 & 200 & 400 & 700 & 800 & 1000 & 700 & 200 \\ 800 & 300 & 900 & 800 & 800 & 400 & 400 & 600 & 800 & 400 \end{bmatrix}$$

$$\widehat{TN}_{it} = \begin{bmatrix} 14 & 15 & 13 & 9 & 11 & 10 & 13 & 10 & 11 & 15 \\ 8 & 10 & 10 & 6 & 11 & 10 & 11 & 12 & 11 & 12 \\ 14 & 12 & 8 & 14 & 8 & 10 & 9 & 13 & 9 & 12 \\ 10 & 15 & 15 & 10 & 12 & 15 & 11 & 11 & 12 & 10 \\ 9 & 6 & 11 & 11 & 5 & 7 & 8 & 11 & 5 & 7 \end{bmatrix}$$

$$E_{it} = \begin{bmatrix} 2 \\ 2 \\ 2 \\ 2 \\ 2 \end{bmatrix} \quad C_{it} = \begin{bmatrix} 20 \\ 30 \\ 25 \\ 35 \\ 40 \end{bmatrix} \quad RC_{it} = \begin{bmatrix} 10 \\ 15 \\ 12 \\ 14 \\ 12 \end{bmatrix} \quad F_{it} = \begin{bmatrix} 5 \\ 5 \\ 5 \\ 5 \\ 5 \end{bmatrix}$$

$$T_{it} = \begin{bmatrix} 7 \\ 5 \\ 6 \\ 8 \\ 4 \end{bmatrix} \quad RT_{it} = \begin{bmatrix} 2 \\ 1 \\ 2 \\ 2 \\ 1 \end{bmatrix} \quad ET_{it} = \begin{bmatrix} 8 \\ 5 \\ 7 \\ 9 \\ 5 \end{bmatrix} \quad F_{it} = \begin{bmatrix} 11 \\ 8 \\ 10 \\ 12 \\ 7 \end{bmatrix}$$

$$RC_{jt} = [2 \quad 3 \quad 2 \quad 1 \quad 2 \quad 3 \quad 4 \quad 3 \quad 1 \quad 2]'$$

(2) The triangular fuzzy number $\widetilde{BN}_{it}^{s} = (dn_{1it}^{s}, dn_{2it}^{s}, dn_{3it}^{s})$. Suppose that the triangular fuzzy number $dn_{2it}^{s} = BN_{it}$, then:

$$\widetilde{BN}_{it} = \begin{bmatrix} (0,500,1000) & (0,900,1000) & (0,900,1000) & (0,200,1000) & (0,100,1000) & (0,600,1000) & (0,500,1000) & (0,600,1000) & (0,400,1000) & (0,700,1000) \\ (0,400,1000) & (0,300,1000) & (0,600,1000) & (0,100,1000) & (0,1000,1000) & (0,400,1000) & (0,100,1000) & (0,600,1000) & (0,300,1000) & (0,300,1000) \\ (0,500,1000) & (0,900,1000) & (0,100,1000) & (0,1000,1000) & (0,800,1000) & (0,600,1000) & (0,500,1000) & (0,200,1000) & (0,800,1000) & (0,600,1000) \\ (0,700,1000) & (0,500,1000) & (0,400,1000) & (0,200,1000) & (0,400,1000) & (0,700,1000) & (0,800,1000) & (0,1000,1000) & (0,700,1000) & (0,200,1000) \\ (0,800,1000) & (0,300,1000) & (0,900,1000) & (0,800,1000) & (0,800,1000) & (0,400,1000) & (0,400,1000) & (0,600,1000) & (0,800,1000) & (0,400,1000) \end{bmatrix}$$

Assuming the actual number of customer needs $\widehat{BN}_{it}$:

$$\widehat{BN}_{it} = \begin{bmatrix} 600 & 600 & 800 & 900 & 500 & 100 & 700 & 100 & 500 & 900 \\ 600 & 800 & 400 & 200 & 700 & 900 & 900 & 900 & 300 & 800 \\ 200 & 900 & 200 & 700 & 800 & 1000 & 100 & 400 & 200 & 300 \\ 800 & 400 & 300 & 1000 & 100 & 500 & 300 & 200 & 500 & 700 \\ 500 & 500 & 500 & 100 & 1000 & 500 & 500 & 800 & 200 & 100 \end{bmatrix}$$

Bring $\widehat{BN}_{it}$ as z to Eq. 27, then:

$$\beta 1_{k}^{ts} = \begin{bmatrix} 0.800 & 0.667 & 0.889 & 0.126 & 0.556 & 0.167 & 0.601 & 0.167 & 0.834 & 0.336 \\ 0.667 & 0.287 & 0.667 & 0.889 & 0.700 & 0.168 & 0.112 & 0.252 & 1.000 & 0.287 \\ 0.400 & 1.000 & 0.889 & 0.700 & 1.000 & 0.002 & 0.200 & 0.750 & 0.250 & 0.500 \\ 0.668 & 0.800 & 0.750 & 0.001 & 0.250 & 0.714 & 0.375 & 0.200 & 0.714 & 0.376 \\ 0.625 & 0.715 & 0.556 & 0.125 & 0.005 & 0.834 & 0.834 & 0.501 & 0.250 & 0.250 \end{bmatrix}$$

(3) Trapezoidal fuzzy numbers:

$$\widetilde{TN}_{it}^{s} = (dtn_{1it}^{s}, dtn_{2it}^{s}, dtn_{3it}^{s}, dtn_{4it}^{s}) = \begin{bmatrix} (8,11,15,18) \\ (6,10,12,15) \\ (7,12,16,20) \\ (8,13,16,20) \\ (4,8,11,14) \end{bmatrix}$$

Assume that the actual customer demand lead time $\widehat{\mathrm{TN}}_{\mathrm{it}}$ is entered as z into Eq. 28, which results in:

$$\beta 2_{k}^{ts} = \begin{bmatrix} 1.000 & 1.000 & 1.000 & 0.333 & 1.000 & 0.667 & 1.000 & 0.667 & 1.000 & 1.000 \\ 0.500 & 1.000 & 1.000 & 0.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 \\ 1.000 & 1.000 & 0.200 & 1.000 & 0.200 & 0.600 & 0.400 & 1.000 & 0.400 & 1.000 \\ 0.400 & 1.000 & 1.000 & 0.400 & 0.800 & 1.000 & 0.600 & 0.600 & 0.800 & 0.400 \\ 1.000 & 0.500 & 1.000 & 1.000 & 0.250 & 0.750 & 1.000 & 1.000 & 0.250 & 0.750 \end{bmatrix}$$

(4) Assume that each product produced by the enterprise has only two specifications (high, low), and the rough set of the quality requirements for each product is (0.3, 0.6, 0.6, 0.9). We suppose the customer quality requirements are:

$$\tilde{Q}_{it}^{s} = \begin{bmatrix} 0.900 & 0.900 & 0.600 & 0.500 & 0.600 & 0.400 & 0.400 & 0.900 & 0.700 & 0.800 \\ 0.300 & 0.600 & 0.500 & 0.300 & 0.900 & 0.400 & 0.700 & 0.600 & 0.900 & 0.600 \\ 0.400 & 0.300 & 0.600 & 0.900 & 0.600 & 0.700 & 0.900 & 0.800 & 0.600 & 0.500 \\ 0.500 & 0.800 & 0.900 & 0.700 & 0.400 & 0.900 & 0.500 & 0.500 & 0.500 & 0.400 \\ 0.600 & 0.600 & 0.600 & 0.400 & 0.400 & 0.800 & 0.900 & 0.400 & 0.300 & 0.400 \end{bmatrix}$$

and place it into z into Eq. 29, then we get:

$$\beta 3_{k}^{ts} = \begin{bmatrix} 0.750 & 0.750 & 0.450 & 0.450 & 0.450 & 0.450 & 0.450 & 0.750 & 0.750 & 0.750 \\ 0.450 & 0.450 & 0.450 & 0.450 & 0.750 & 0.450 & 0.750 & 0.450 & 0.750 & 0.450 \\ 0.450 & 0.450 & 0.450 & 0.750 & 0.450 & 0.750 & 0.750 & 0.750 & 0.450 & 0.450 \\ 0.450 & 0.750 & 0.750 & 0.750 & 0.450 & 0.750 & 0.450 & 0.450 & 0.450 & 0.450 \\ 0.450 & 0.450 & 0.450 & 0.450 & 0.450 & 0.750 & 0.750 & 0.450 & 0.450 & 0.450 \end{bmatrix}$$

(5) Assuming that the price of each product is consistent for the customer within a certain period, then as long as the price is within a certain range, it can be assumed that the customer wants the price to be $P_{it}^{s} = [100,200,150,160,140]'$,

$$\tilde{P}_{it}^{s} = (\, dp_{1it}^{s}, dp_{2it}^{s}) =$$

$$\begin{bmatrix} (94,108) & (99,107) & (98,107) & (94,105) & (92,107) & (96,103) & (97,108) & (96,109) & (94,100) & (98,103) \\ (193,201) & (198,201) & (192,206) & (192,206) & (200,202) & (191,200) & (195,205) & (191,208) & (193,209) & (197,202) \\ (147,154) & (148,154) & (146,159) & (149,150) & (150,153) & (142,153) & (141,153) & (141,151) & (149,158) & (150,158) \\ (176,188) & (175,181) & (171,184) & (173,180) & (177,189) & (176,183) & (179,182) & (176,185) & (178,189) & (180,185) \\ (114,120) & (115,128) & (111,125) & (119,124) & (116,122) & (115,123) & (112,121) & (118,125) & (116,124) & (120,125) \end{bmatrix}$$

Bring $\tilde{P}_{it}^{s}$ to Eq. 31

$$\beta 4_{k}^{ts} = \begin{bmatrix} 0.571 & 0.875 & 0.778 & 0.455 & 0.467 & 0.429 & 0.727 & 0.692 & 0.000 & 0.600 \\ 0.125 & 0.333 & 0.429 & 0.429 & 1.000 & 0.000 & 0.500 & 0.471 & 0.563 & 0.400 \\ 0.571 & 0.667 & 0.692 & 0.000 & 1.000 & 0.273 & 0.250 & 0.100 & 0.889 & 1.000 \\ 0.667 & 0.167 & 0.308 & 0.000 & 0.750 & 0.429 & 0.667 & 0.556 & 0.818 & 1.000 \\ 0.000 & 0.615 & 0.357 & 0.800 & 0.333 & 0.375 & 0.111 & 0.714 & 0.500 & 1.000 \end{bmatrix}$$

5.2 Operation results

We bring all the data into the formula and use MATLAB for programming a solution with the NAGAII algorithm. The objective function is a random number [1,100]. The production batch size of the enterprise setting is 100. That is, $PL = 100$. In addition, the population size of the genetic algorithm is set to 400. Its optimal front individual coefficient is set to 0.25. The algebra is 300, and the fitness function has a bias of 0.001. Fig. 3 is a diagram of the individual distances, individual average distances, and the Pareto front.

From the distribution of the running Pareto front graph, it can be seen that the solution is even. The distance of individuals indicates the distance between the individual and other individuals. It can be seen from Fig. 3 that the crowded distances differ greatly, indicating that the populations are not crowded and the population diversity is better. The average distance represents the average distance between individuals. It shows that the population distance tends to be balanced and flat. By solving the objective functions, 100 Pareto optimal solutions are obtained. Since there are four objective functions in this paper, we need to sort according to the priority of four objectives. First, the solutions are sorted in ascending order according to objective 1 (i.e., the highest customer satisfaction). In the case of the same objective 1 value, objective 2 (i.e., the lowest production cost) is sorted in ascending order. If objective 2's values are also the same, the solutions are sorted in ascending order according to objective 3 (i.e., the shortest delivery time). Finally, the solutions are sorted in descending order according to objective 4 (i.e., the largest profit). That is, objective 1>> objective 2>> objective 3>> objective 4. Fig 4 is a multidimensional contrast scatter plot of the first two objective functions plotted.

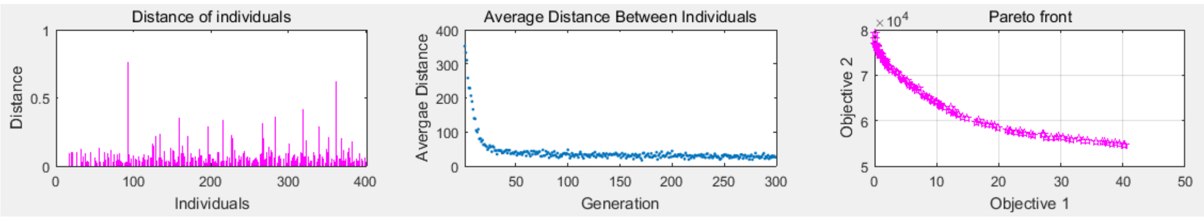

Fig. 3 The distance and the average distance between individuals and Pareto front

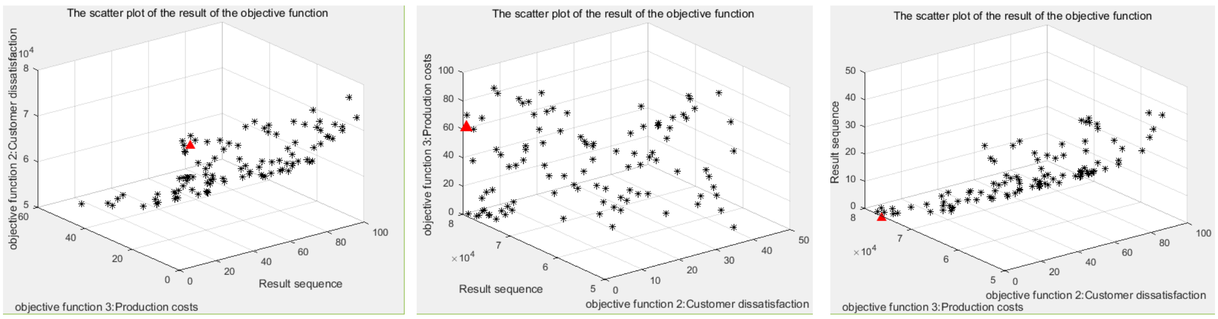

Fig. 4 Multidimensional contrast scatter plot of the first two objectives

It can be seen, from Fig. 4, that the triangle symbol in the figure indicates the point of maximum customer satisfaction, minimum production cost, and shortest delivery time. In addition, the 100 Pareto optimal solutions calculated by this model are evenly distributed in one plane. This shows that the results of the operation basically meet the results of the multi-objective planning solution. Some of the results (first six of the 100) are shown in Table 2. From the calculation results, it can be found that the 71-st set of data satisfies the minimum customer dissatisfaction, the ratio is 0, and the minimum production cost is 79173.137. Additionally, Table 3 is the production plan quantity that runs out at time t = 1.

Table 2 Partial result (first six of the 75)

Customer dissatisfaction	Production cost	Production cycle	Serial number
0	79173.14	3823	71
0.06	78805.17	3734	2
0.126666667	77884.72	3409	41
0.201666667	77839.99	3486	63
0.226666667	77220.7	3328	3
0.301666667	76777.69	3185	4

Table 3 The production plan quantity (t = 1)

Products \ Period	k = 1	k = 2	k = 3	k = 4	k = 5	k = 6	k = 7	k = 8	k = 9	k = 10	Total
$n(1)$	700	500	600	900	700	1100	800	800	600	800	7500
$n(2)$	900	800	800	900	1000	500	600	500	600	700	7300
$n(3)$	900	800	700	900	300	900	600	500	600	1000	7200
$n(4)$	1000	600	900	800	1000	500	1000	800	800	600	8000
$n(5)$	900	1000	800	800	900	800	500	800	1000	600	8100

6. Conclusion

In this paper, we analyze the various uncertainties arising from order modification and emergency orders. There were a variety of vague uncertainties in the number of customer requirements, delivery dates, quality, and prices. According to their characteristics, we use triangular fuzzy numbers, trapezoidal fuzzy numbers, fuzzy intervals, etc. to handle these multiple uncertainties. Using the scenario analysis method, two scenarios are set, namely, the emergency ordering scenario and the order modification scenario. Based on this, a multi-objective model is established to solve the production-planning problem of equipment manufacturers by using the NSGA-II algorithm. We combine the analyses of the model to simulate the model and obtain the feasibility of the model. This will help equipment manufacturing companies to rationalize their production-planning and scheduling. Future research will further refine the model and complete the dispatch of the production plan.

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