Production scheduling of small batch materials based on dynamic programming

Binling Luo*, Changqi Wei, Shuhua Lou

Guangxi Vocational College of Water Resources and Electric Power, Guangxi, China

*Corresponding author: 530039473@qq.com

Abstract. With the development of society, more and more enterprises begin to pay attention to internal management, such as material production arrangement, inventory management, etc. No matter what type of products or services an enterprise produces or operates in any industry, a certain amount of production preparation time and production time are required to provide products and services required by the market. Therefore, it is necessary for any enterprise to forecast the future demand of the target market and make production plans. This paper selects six kinds of key materials, comprehensively considers the forecast value of demand, demand characteristics, inventory and out of stock, and reasonably arranges and forecasts the number of material production plans. Further analysis and forecast the demand and production plan when the materials planned to be produced in this week can only be used in k (k $\geqslant$ 2) weeks.

Keywords: Material Production, Demand Forecast, Production Design, Dynamic Programming.

1. Introduction

With the continuous improvement of social economy and technology, people's life style has also undergone tremendous changes. The development of the Internet has affected all aspects of human society. What is more prominent is that the development of logistics industry has greatly changed the lifestyle of contemporary young people and middle-aged and old people [1]. According to the China Procurement Development Report, the domestic logistics cost is still at a high level compared with the global advanced level. According to statistics, in 2021, China's total annual social logistics will be 335.2 trillion yuan, 1.5 times that of the early 13th Five Year Plan period, with a year-on-year growth of 9.2% [2]. As a relatively developed country in the global logistics industry, the logistics cost in the United States only accounts for 8.5% of GDP. Compared with other countries with the same level of development, China's logistics costs are still on the high side. According to the report, logistics costs in some developing countries remain high due to backward management and low efficiency, accounting for 15% to 25% of production costs [3]. Then, if the enterprise can reasonably arrange the production plan and improve the inventory maintenance efficiency, the production cost of the enterprise will decrease, and the logistics cost will also decrease, thus promoting the logistics industry to enter a new stage of development.

In actual production, because some materials may have peak demand, seasonal demand and cyclical demand, some demand may be regular, and some demand may be irregular, so how to predict the demand for materials has become a difficult problem for enterprises to think about [4]. Because more production will cause inventory, occupy a lot of funds, and have no income; If there is less production, there will be a shortage of goods. If the time goes on, the reputation of the enterprise will decline, which is not conducive to the development of the enterprise.

No matter what type of products or services an enterprise produces or operates in any industry, a certain amount of production preparation time and production time are required to provide products and services required by the market [5] - [7]. But customers are often unwilling to wait after making a purchase decision. Therefore, if the enterprise does not forecast the demand in advance and always starts production after receiving the order, a large number of sales losses will occur [8]. On the contrary, if an enterprise produces a large number of materials to avoid stock outs, it will result in a large number of inventories, which increases the enterprise's inventory management costs and takes up a large amount of funds. Neither is appropriate. Therefore, it is necessary for any enterprise to forecast the future demand of the target market and make production plans. The contribution of this paper lies in the comprehensive consideration of demand frequency, unit price, demand fluctuation rate, etc. when selecting key materials; The model structure is complete, and the model is more interpretable than machine learning; Because the weekly demand of some materials is small and the time interval is large, if the time series forecasting method is used to solve the demand (such as ARIMA), the inappropriate time series relationship may not be brought in, increasing the error. Therefore, this paper chooses to extract the demand characteristics to forecast.

2. Research Design

2.1 Model Assumptions

(1) Suppose that the inventory and out of stock at the end of the 100th week are both 0, and the number of production plans in the 100th week is exactly equal to the actual demand in the 101st week.

(2) The inventory cost only considers the amount of capital occupied, that is, the management expenses and storage expenses are ignored.

(3) The week of January 2, 2019 is set as the first week, and the subsequent weeks start from Monday to Sunday.

2.2 Research objects

This paper selects six indicators, including total sales, total demand, average unit price, frequency of occurrence and variance of demand, from January 2, 2019 to May 21, 2022, to comprehensively evaluate the importance of materials. Based on the comprehensive evaluation method, the key materials were extracted, and the materials with the highest RSR were finally selected as the research objects [9], with the numbers of 6004010252, 6004010321, 6004020503, 6004021055, 6004010256, and 6004020375 respectively.

2.3 Symbol definition

Symbol definition is shown in Table 1.

Table 1. Symbol description

Number	Symbol	Meaning
1	var_t	Weekly demand variance at time t
2	N_t	Demand frequency at time t
3	P_t	Average selling price at time t
4	y_t	Output at time t
5	c_t	Inventory at time t
6	q_t	Out of stock at time t
7	$\hat{y}_t$	Planned production at time t
8	d_t	Actual demand at time t

3. Establishment and solution on model

3.1 Demand forecast

Material demand forecasting requires that according to the relationship between the current and historical material demand status of the enterprise and the factors that affect the change of the enterprise's material demand, certain empirical judgments, technical methods and forecasting models should be used, and appropriate scientific methods should be used to reflect the change of the enterprise's material demand target and the development trend. According to this prediction, the material control director can accurately and timely grasp the change law of the enterprise's demand, Timely adjust the material control plan.

(1) Prediction index selection

This paper considers extracting the characteristics of demand, including weekly demand variance, demand frequency, weekly demand and average sales price. Starting from December 31, 2018.

(2) Model selection

Generally, demand forecasting includes qualitative forecasting and quantitative forecasting. For time series with good continuity, we can use moving average method and exponential smoothing method to forecast sales volume. However, due to the large span of weekly demand in some logistics, for example, there is demand in two adjacent times, which is 48 weeks apart, this paper believes that using time series forecasting may lead to large errors.

This paper uses the demand variance, demand frequency and average sales price of the previous week to forecast the demand of this week, that is, lag one period. We bring the material number into the linear model and find that the goodness of fit is only 0.655, and the mean square error is high. Therefore, this paper establishes a linear model for each of the six materials. Due to space constraints, only three typical materials are listed in this paper, such as Table2 - Table4, where the dependent variable is the weekly demand.

Table 2. 6004020375 Linear Regression Analysis Results (n=153)

	unstandardized coefficients		standardization coefficient	t	p	VIF	R^2	Adjust R^2	F
	B	Standard Error	Beta						
c	-6.858	3.583	-	-1.914	0.058	-	0.969	0.968	F=1528.02 P=0.000
weekly demand variance	0.868	0.061	0.21	14.181	0.000	1.035			
demand frequency	1.036	0.016	0.986	65.913	0.000	1.059			
average selling price	0.022	0.011	0.03	1.957	0.052	1.084			

Table 3. 6004020503 Linear Regression Analysis Results (n=148)

	unstandardized coefficients		standardization coefficient	t	p	VIF	R^2	Adjust R^2	F
	B	Standard Error	Beta						
c	4.676	8.82	-	0.53	0.597	-	0.654	0.647	F=90.916 P=0.000
weekly demand variance	0.151	0.021	0.356	7.222	0.000	1.015			
demand frequency	1.443	0.092	0.77	15.604	0.000	1.016			
average selling price	0.009	0.04	0.012	0.235	0.815	1.002			

Table 4. 6004021055 Linear Regression Analysis Results (n=75)

	unstandardized coefficients		standardization coefficient	t	p	VIF	R^2	Adjust R^2	F
	B	Standard Error	Beta						
c	59.434	71.18	-	0.835	0.407	-	0.806	0.798	F=98.329 P=0.000
weekly demand variance	0.201	0.025	0.439	7.927	0.000	1.122			
demand frequency	8.265	0.675	0.664	12.235	0.000	1.079			
average selling price	-0.062	0.067	-0.049	-0.92	0.361	1.043			

From the analysis of F test results, it can be concluded that the coefficient is significant and the original assumption that the regression coefficient is 0 is rejected. Therefore, the model basically meets the requirements. For the variable colinearity performance, the VIF is all less than 10, and the model is well constructed.

To sum up, the six material demand forecasting models are shown in Table 5.

Table 5. Demand forecast model

Number	Demand forecast equation
6004010252	$y_t=0.421\,var_{t-1}+0.305N_{t-1}+0.095P_{t-1}$
6004010321	$y_t=0.42\,var_{t-1}+0.4N_{t-1}+0.149P_{t-1}$
6004020503	$y_t=4.676+0.151\,var_{t-1}+1.443N_{t-1}+0.009P_{t-1}$
6004021055	$y_t=0.439\,var_{t-1}+0.664N_{t-1}-0.049P_{t-1}$
6004010256	$y_t=0.47\,var_{t-1}+0.724N_{t-1}+0.018P_{t-1}$
6004020375	$y_t=-6.858+0.868\,var_{t-1}+1.036N_{t-1}+0.022P_{t-1}$

The mean square error of the model is obtained by comparing the predicted monthly actual values:

$$MSE=\frac{1}{6}\sum_{i=1}^{6}\sqrt{\sum_{t=1}^{177}(\hat{y}_{it}-y_{it})^2}=3.6231$$

3.2 Production plan forecast

3.2.1 Index analysis

(1) Inventory

Set the planned production quantity of week t as $\hat{y}_t$,the actual demand is d_t,Inventory is c_t,Assume that the inventory and out of stock at the end of the 100th weekend are both zero,so $c_{100}=c_{101}=0$

As the materials produced this week are only for use next week,so $c_t=c_{t-1}+(\hat{y}_{t-1}-d_t)$, $101\le t\le 177$.

(2) Out of stock

Let the shortage quantity of week t be qt. Similarly, q100=q101=0. It is related to the production plan quantity of the current week, the actual demand quantity and the material shortage quantity of the last week,so $q_t=q_{t-1}+(d_t-\hat{y}_{t-1})$, $101\le t\le 177$.

(3) Service level

Service level refers to the percentage that meets user needs. It is generally related to the shortage quantity and the actual material demand [10]. It can be used to measure the reasonableness of the current week's production plan, and can dynamically adjust future production plans accordingly. Let the service level of week t be ω_t, so $\omega_t = 1 - \frac{q_t}{d_t}$, $101 \le t \le 177$.

3.2.2 Model establishment

Generally speaking, service level is the inventory performance target set by enterprise managers when making production plans. Therefore, this paper selects the average service level of 101 weeks to 177 weeks as the objective function of the dynamic programming model, and maximizes it, that is

$$\max \omega = \frac{1}{77} \times \sum_{t=101}^{177} \omega_t \tag{1}$$

The average service level of 77 weeks from 101 to 177 is required to be no less than 85%，so

$$[(1-\frac{q_1}{d_1}) + (1-\frac{q_2}{d_2}) + \cdots + (1-\frac{q_{77}}{d_{77}})] \times \frac{1}{77} \ge 85\% \tag{2}$$

The dynamic programming model of material production plan can be obtained by combining it with inventory and out of stock.

$$\max \frac{1}{77} \times \sum_{t=101}^{177} (1-\frac{q_t}{d_t})$$
$$st.\begin{cases} c_t = c_{t-1} + (\hat{y}_{t-1} - d_t) \\ q_t = q_{t-1} + (d_t - \hat{y}_{t-1}) \\ \frac{1}{77} \times \sum_{t=101}^{177} (1-\frac{q_t}{d_t}) \ge 85\%, \quad t=101,102,\cdots,177 \\ c_{100} = c_{101} = q_{100} = q_{101} = 0 \\ \hat{y}_{100} = d_{101} \end{cases} \tag{3}$$

To sum up, the production plan dynamic planning algorithm flow established in this paper is shown in Table 6.

Table 6. Dynamic Planning Process of Production Plan

Dynamic Planning of Production Planning

Input: d_1, q_0, c_0

Output: ω, $\hat{y}_t$

For t = 1:77

  $c_t = c_{t-1} + (\hat{y}_{t-1} - d_t)$

  $q_t = q_{t-1} + (d_t - \hat{y}_{t-1})$

  For j = 1:t

    $\omega_j = \frac{1}{j} \times \sum_{j}^{t} \omega_j$

  end

$\omega = \frac{1}{t} \times \sum_{j}^{t} \omega_j$

end

3.2.3 Solution of model

6004020503 material is selected in this paper, and the calculation results are shown in Table 7. See Table 8 for the comprehensive results of six materials (the average values of the 101-177 weeks).

Table 7. Production Plan and Actual Demand of 6004020503 Materials in Week 101-110

Week	Production Plan	Actual Demand	Inventory	Shortage	Service Level
101	11.6564	12	0	0.0038	0.9997
102	27.1738	27	0.1738	0	1
103	15.8978	16	0.0717	0	1
104	13.1056	13	0.1772	0	1
105	4.8842	4	1.0614	0	1
106	16.0361	17	0.0975	0	1
107	27.8316	28	0	0.0708	0.9975
108	17.3108	17	0.3108	0	1
109	23.2674	24	0	0.4218	0.9824

Table 8. Comprehensive Results of 6 Materials (Unit: piece/week)

number	Average productio n plan	Average actual demand	Average inventory	Average shortage	Average service level
6004010252	34.125	34.125	0.0011	0.0001	1
6004010321	144.2726	144.2727	0.001253	7.12E-05	1
6004020503	22.238	22.5303	0.4676	0.2872	0.9898
6004021055	38.5309	38.5362	0.042	0.0019	0.9997
6004010256	10.9247	11.5541	5.8429	0.0818	0.9554
6004020375	10.3919	11.3134	35.0144	0	0.9567

4. Further analysis

If the materials planned to be produced in this week can only be used in two weeks or later,Then the inventory or out of stock quantity at time t is determined by the inventory or out of stock quantity at time t-1, the production plan quantity at time t-2, and the actual demand quantity at time t, so

$$\begin{cases} c_{100}=q_{100}=0 \\ c_{101}=q_{101}=0 \\ c_t=c_{t-1}+(\hat{y}_{t-2}-d_t), \quad t=101,102,\cdots,177 \\ q_t=q_{t-1}+(d_t-\hat{y}_{t-2}) \\ \hat{y}_{100}=d_{101} \end{cases} \quad (4)$$

To sum up, if the occupation of inventory funds is not considered, we can solve the planned production volume by establishing the following goal programming:

$$\max \frac{1}{77} \times \sum_{t=101}^{177} \omega_t$$
$$st.\begin{cases} c_t = c_{t-1} + (\hat{y}_{t-2} - d_t) \\ q_t = q_{t-1} + (d_t - \hat{y}_{t-2}) \\ \frac{1}{77} \times \sum_{t=101}^{177} \omega_t \geq 85\% \\ c_{100} = c_{101} = q_{100} = q_{101} = 0 \\ \hat{y}_{100} = d_{101} \end{cases}, \quad t=101,102,\cdots,177 \tag{5}$$

If the inventory capital occupation is considered, the goal planning can be established as follows:

$$\min \frac{1}{77} \sum_{t=101}^{177} c_t \times p_t$$
$$s.t.\begin{cases} q_t = q_{t-1} + (d_t - \hat{y}_{t-2}) \\ c_t = c_{t-1} + (\hat{y}_{t-2} - d_t) \\ \frac{1}{77} \sum_{t=101}^{177} (1 - \frac{q_t}{y_t}) \geq 86\% \\ c_{100} = q_{100} = 0 \\ c_{101} = q_{101} = 0 \\ \hat{y}_{100} = d_{101} \end{cases}, \quad t=101,102,\cdots,177 \tag{6}$$

To promote the above model, if the materials planned to be produced in this week can only be used in k (k≥2) weeks and beyond, regardless of the proportion of inventory funds, the goal plan is:

$$\max \omega = \frac{1}{77} \times \sum_{t=101}^{177} \omega_t$$
$$st.\begin{cases} c_t = c_{t-1} + (\hat{y}_{t-k} - d_t) \\ q_t = q_{t-1} + (d_t - \hat{y}_{t-k}) \\ \frac{1}{77} \times \sum_{t=101}^{177} \omega_t \geq 85\% \\ c_{100} = c_{101} = q_{100} = q_{101} = 0 \\ \hat{y}_{100} = d_{101} \end{cases}, \quad t=101,102,\cdots,177 \tag{7}$$

The target planning considering the proportion of inventory funds is:

$$\min c_t \times p_t$$
$$s.t.\begin{cases} q_t = q_{t-1} + (d_t - \hat{y}_{t-k}) \\ c_t = c_{t-1} + (\hat{y}_{t-k} - d_t) \\ \frac{1}{77} \sum_{t=101}^{177} (1 - \frac{q_t}{y_t}) \geq 86\% \\ c_{100} = q_{100} = 0 \\ c_{101} = q_{101} = 0 \\ \hat{y}_{100} = d_{101} \end{cases}, \quad t=101,102,\cdots,177 \tag{8}$$

5. Conclusions

This paper constructs four indicators, namely, weekly demand variance, demand frequency, weekly demand volume and average sales price, to perform linear fitting for six materials respectively.

The fitting effect is excellent, and the selected materials are solved by dynamic programming in turn. In the further analysis, the production plan is adjusted based on the inventory and service level. It is also discussed that if the materials planned to be produced in this week can only be used for two weeks or later, the inventory or out of stock quantity at the moment is determined by the inventory or out of stock quantity at the moment, the production planned quantity at the moment and the actual demand quantity at the moment. In this case, the production planned quantity needs to lag two items in the constraints. Similarly, if the materials planned to be produced in this week can only be used in the week and beyond, the production planned quantity needs to be delayed.

There are still some deficiencies in this paper. Future research can be improved from the following aspects: long iteration time, relatively complex model and slow convergence speed; The weekly demand data of some materials is less, so the error of the prediction model may be large; Try to find out how to arrange an appropriate production plan when the materials planned to be produced in this week can only be used for k (k≥2) weeks or later; In addition to considering service level, inventory quantity, stock out quantity and capital possession, as inventory cost not only includes capital possession, but also includes inventory management, inventory price reduction risk, etc., the target function will be further refined in the future.

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