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Probability Distribution of China Aviation Network Nearest Neighbor Average Degree and Its Evolutionary Trace Based on Complex Network

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Abstract: In order to reveal the complex network characteristics and evolution principle of China aviation network, the probability distribution and evolution trace of node nearest neighbor average degree of China aviation network were studied based on the statistics data of China civil aviation network in 1988, 1994, 2001, 2008 and 2015. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. Based on the statistical data, the nearest neighbor average degrees of nodes in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method, it was found that the nearest neighbor average degree had the probability distribution of normal function and the position parameters and scale parameters of the probability distribution had linear evolution trace.

Key words: Complex network, China aviation network, nearest neighbor average degree, normal probability distribution, linear evolution trace.

1. Introduction

Aviation network is typical complex network with small world characters [1, 2]. About certain nation's aviation network, there are some unknown features in the field of complex network. This paper faces to the aviation network of China through analyzing the passenger data [3] of civil aviation airlines in year 1988, 1994, 2001, 2008 and 2015 to reveal the complex network feature. According to complex network theory, network system of airports and airlines of China was constructed with airports regarded as nodes and airline regarded as edges to study the probability distribution of nearest neighbor average degree and its evolution trace of aviation network of China. Based on the statistical data, the nearest neighbor average degrees of nodes in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method, it was found that the node nearest neighbor average degree had the probability distribution of normal function and the position parameters and scale parameters of the probability distribution had linear evolution trace.

2. Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network

For network $G=(V,E)$, where $v_i \in V$ is the node of G . V is the set of nodes. E is the set of edges [4], $(v_i,v_j)\in E$. Matrix $A=(a_{i,j})_{n\times n}$ was constructed, where:

$$a_{i,j}=\begin{cases}1,(v_i,v_j)\in E\\0,otherwise\end{cases} \tag{1}$$

Matrix A was called adjacent matrix of network G . The degree of node v_i was defined as the number

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of edges connected to v_i . The nearest neighbor average degree $k_{nn,i}$ of node v_i was defined as following [4]:

$$k_{nn,i} = \frac{\left[\sum_j (a_{i,j} \cdot k_j)\right]}{k_i} \tag{2}$$

In Eq. (2):

k_i —the degree of mode v_i ; k_j —the degree of other mode v_j in the network; $a_{i,j}$ —the element of adjacent matrix.

2.1 Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network in 1988

The adjacent matrix A_{1988} was gotten from statistic data [3]. The nearest neighbor average degrees of 85 nodes in 1988 were gotten from A_{1988} and Eq. (2). The data in Table 1 were obtained by statistics according to the interval in Table 1. The curve in Fig. 1 was drawn by the data in Table 1. It was similar to normal distribution function by observation. Let the quantity of nodes be N , the quantity of interval be m , the spacing of interval i be δ, the times of appearance in interval i be k_i, the frequency of appearance in interval i be q_i , the probability of appearance at median point in interval i be p_i. Here $N_{1988} = 85$, $m_{1988} = 7$, δ_{1988}=5.9 . It could be known from the probability density function of normal distribution [5] in Table 1 and Fig.1:

$$q_i = \frac{k_i}{N_{1988}}, \quad \sum_{i=1}^{m_{1988}} q_i = 1 \tag{3}$$

$$q_i = p_i \delta_{1988} \Rightarrow p_i = \frac{q_i}{\delta_{1988}}, \quad \sum_{i=1}^{m_{1988}} p_i = \frac{1}{\delta_{1988}} \tag{4}$$

The normal distribution function is $N(\mu,\sigma)$, μ is the location parameter, σ is the scale parameter, its probability density function is $f(x)$.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{5}$$

It could be gotten from the statistical properties of normal distribution [5]:

$$\hat{\mu}_{1988} = \frac{1}{N_{1988}} \sum_{i=1}^{N_{1988}} x_i = 19.747 \tag{6}$$

$$\hat{\sigma}_{1988} = \sqrt{\frac{1}{N_{1988}-1} \sum_{i=1}^{N_{1988}} (x_i - \bar{x})^2} = 10.847 \tag{7}$$

Let $\hat{\mu}_{1988}$ and $\hat{\sigma}_{1988}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{1988} = 0.0366 e^{-0.00421(x-19.747)^2} \tag{8}$$

The fitting curve in Eq. (8) and sample points $p_{i,1988}$ were drawn in Fig. 2 with good fitting effect to take $\varepsilon_{i,1988}$ (i = 1, 2, 3, 5, 6, 7) as residual to investigate the degree of approximation of fitting through the residual distribution [6].

$$\varepsilon_{i,1988} = p_{i,1988} - \hat{y}_{i,1988} \tag{9}$$

The residual $\varepsilon_{i,1988}$ was drawn in Fig. 3. All points in Fig. 3 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small. $\left|\varepsilon_{i,1988}\right| < 0.02 < \hat{\sigma}_{1988} = 10.847$. This illustrated that the fitting effect was very good.

Table 1 Probability distribution of China aviation network nearest neighbor average degree in 1988.

Interval	[2.85, 8.75]	(8.75, 14.65]	(14.65, 20.55]	(20.55, 26.45]	(26.45, 32.35]	(32.35, 38.25]	(38.25, 44.15]
Median	5.8	11.7	17.6	23.5	29.4	35.3	41.2
Times	11	17	23	16	7	1	10
Frequency	0.129	0.2	0.271	0.188	0.082	0.012	0.118
Probability	0.0219	0.0339	0.0459	0.0319	0.014	0.002	0.0199

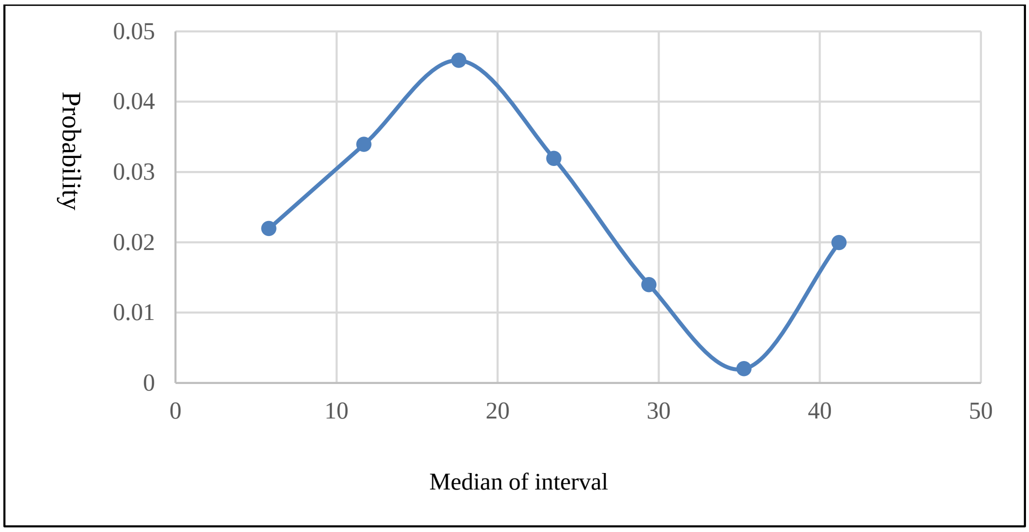

Fig. 1 **Probability distribution diagram of China aviation network nearest neighbor average degree in 1988.**

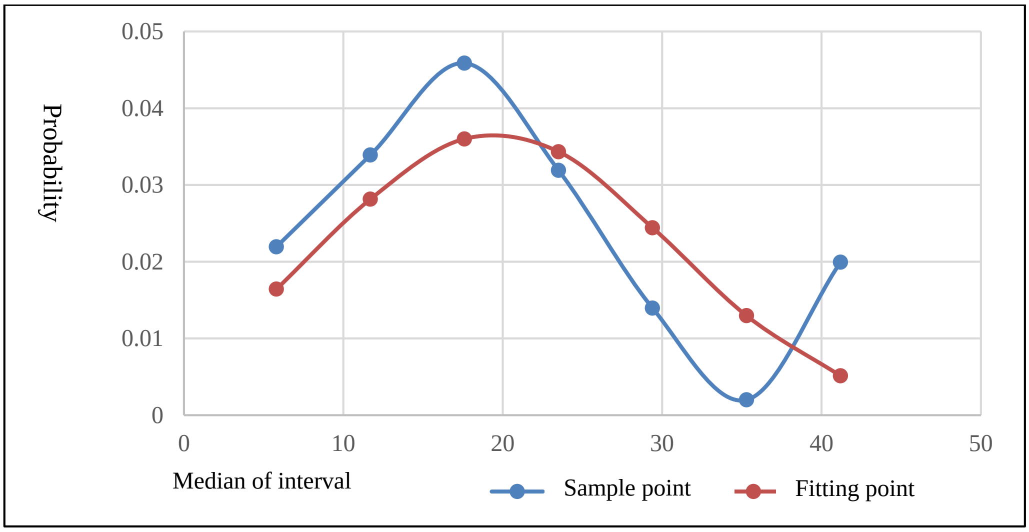

Fig. 2 **Fitting effect diagram of probability distribution of nearest neighbor average degree in 1988.**

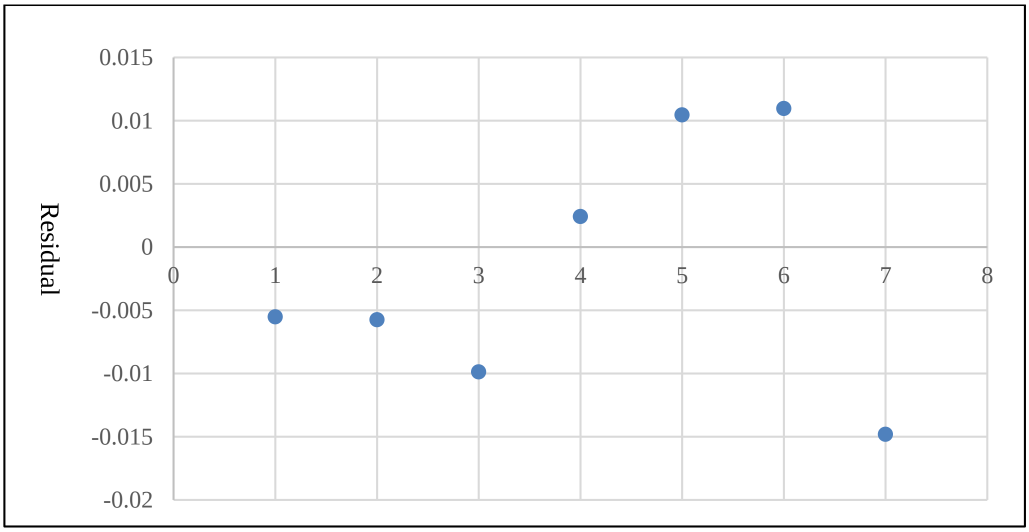

Fig. 3 **Residual diagram of fitting curve of probability distribution of nearest neighbor average degree in 1988.**

2.2 Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network in 1994

The adjacent matrix A_{1994} was gotten from statistic data. The nearest neighbor average degrees of 122 nodes in 1994 were gotten from A_{1994} and Eq. (2). The data in Table 2 were obtained by statistics according to the interval in Table 2. The curve in Fig. 4 was drawn by the data in Table 2. It was similar to normal distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Eq. (1). Here, $N_{1994}=122$, $m_{1994}=7$, $\delta_{1994}=10.5$. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{1994}=\frac{1}{N_{1994}}\sum_{i=1}^{N_{1994}}x_i=34.679 \quad (10)$$

$$\hat{\sigma}_{1994}=\sqrt{\frac{1}{N_{1994}-1}\sum_{i=1}^{N_{1994}}(x_i-\bar{x})^2}=15.405 \quad (11)$$

Let $\hat{\mu}_{1994}$ and $\hat{\sigma}_{1994}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{1994}=0.0259e^{-0.00211(x-34.679)^2} \quad (12)$$

The fitting curve in Eq. (12) and sample points $p_{i,1994}$ were drawn in Fig. 5 with good fitting effect.

To take $\varepsilon_{i,1994}$ (i = 1, 2, 3, 5, 6, 7) as residual to investigate the degree of approximation of fitting through the residual distribution [6].

$$\varepsilon_{i,1994}=p_{i,1994}-\hat{y}_{i,1994} \quad (13)$$

The residual $\varepsilon_{i,1994}$ was drawn in Fig. 6. All points in Fig. 6 were random fluctuation around $\varepsilon=0$ and the range of fluctuation was very small. $|\varepsilon_{i,1994}|<0.01<\hat{\sigma}_{1994}=15.405$. This illustrated that the fitting effect was very good.

Table 2 Probability distribution of China aviation network nearest neighbor average degree in 1994.

Interval	[1.75, 12.25]	(12.25, 22.75]	(22.75, 33.25]	(33.25, 43.75]	(43.75, 54.25]	(54.25, 64.75]	(64.75, 75.25]
Median	7	17.5	28	38.5	49	59.5	70
Times	6	22	34	36	11	6	7
Frequency	0.0492	0.1803	0.2787	0.295	0.0902	0.0492	0.0574
Probability	0.00468	0.01717	0.02654	0.0281	0.00859	0.00468	0.00546

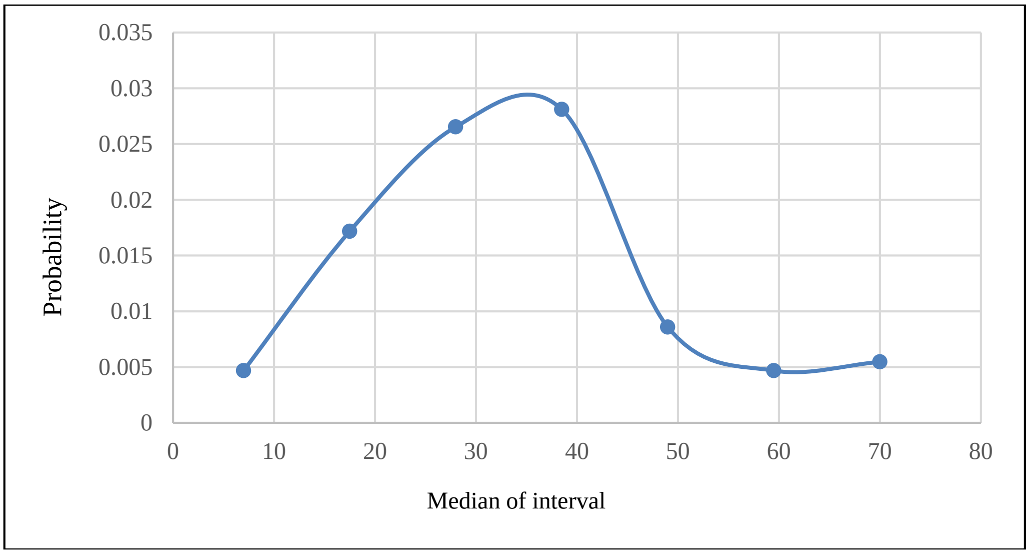

Fig. 4 Probability distribution diagram of China aviation network nearest neighbor average degree in 1994.

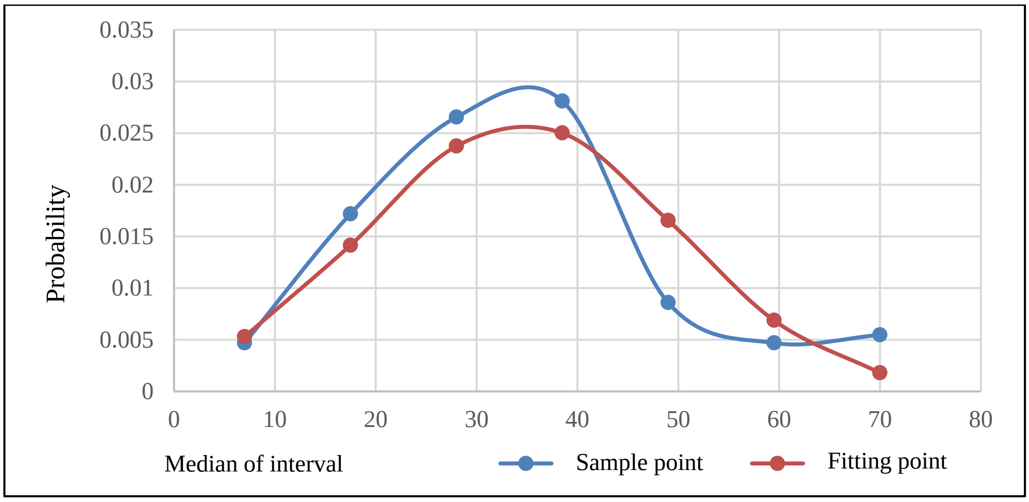

Fig. 5 Fitting effect diagram of probability distribution of nearest neighbor average degree in 1994.

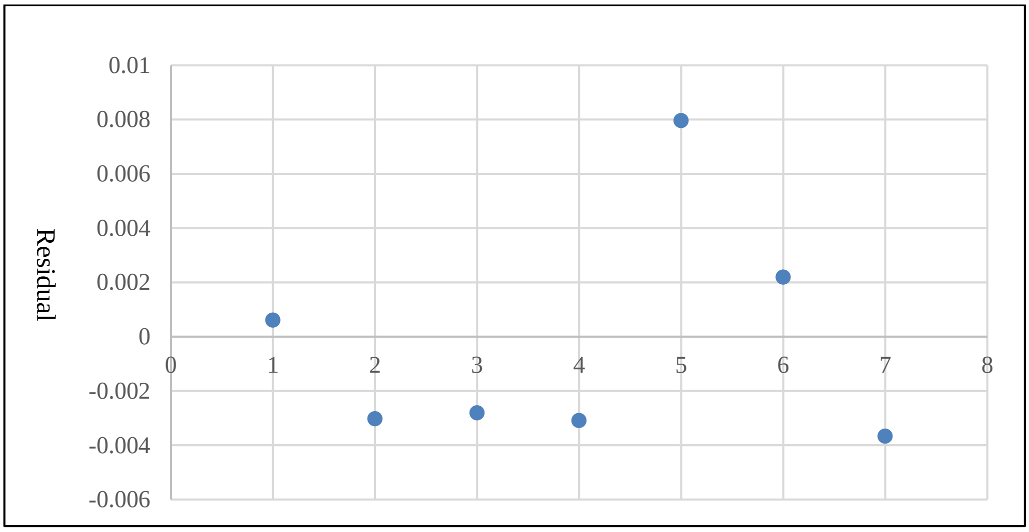

Fig. 6 Residual diagram of fitting curve of probability distribution of nearest neighbor average degree in 1994.

2.3 Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network in 2001

The adjacent matrix A_{2001} was gotten from statistic data. The nearest neighbor average degrees of 130 nodes in 2001 were gotten from A_{2001} and Eq. (2). The data in Table 3 were obtained by statistics according to the interval in Table 3. The curve in Fig. 7 was drawn by the data in Table 3. It was similar to normal distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Eq. (1). Here, $N_{2001}=130$, $m_{2001}=7$, $\delta_{2001}=12$. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2001}=\frac{1}{N_{2001}}\sum_{i=1}^{N_{2001}}x_i=39.008 \qquad (14)$$

$$\hat{\sigma}_{2001}=\sqrt{\frac{1}{N_{2001}-1}\sum_{i=1}^{N_{2001}}(x_i-\overline{x})^2}=15.625 \qquad (15)$$

Let $\hat{\mu}_{2001}$ and $\hat{\sigma}_{2001}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2001}=0.0255e^{-0.00205(x-39.008)^2} \qquad (16)$$

The fitting curve in Eq. (16) and sample points $p_{i,2001}$ were drawn in Fig. 8 with good fitting effect.

Table 3 Probability distribution of China aviation network nearest neighbor average degree in 2001.

Interval	[2, 14]	(14, 26]	(26, 38]	(38, 50]	(50, 62]	(62, 74]	(74, 86]
Median	8	20	32	44	56	68	80
Times	3	23	42	39	10	8	5
Frequency	0.0231	0.1769	0.3232	0.3	0.0769	0.0613	0.0385
Probability	0.00192	0.01474	0.02692	0.025	0.00641	0.00513	0.00321

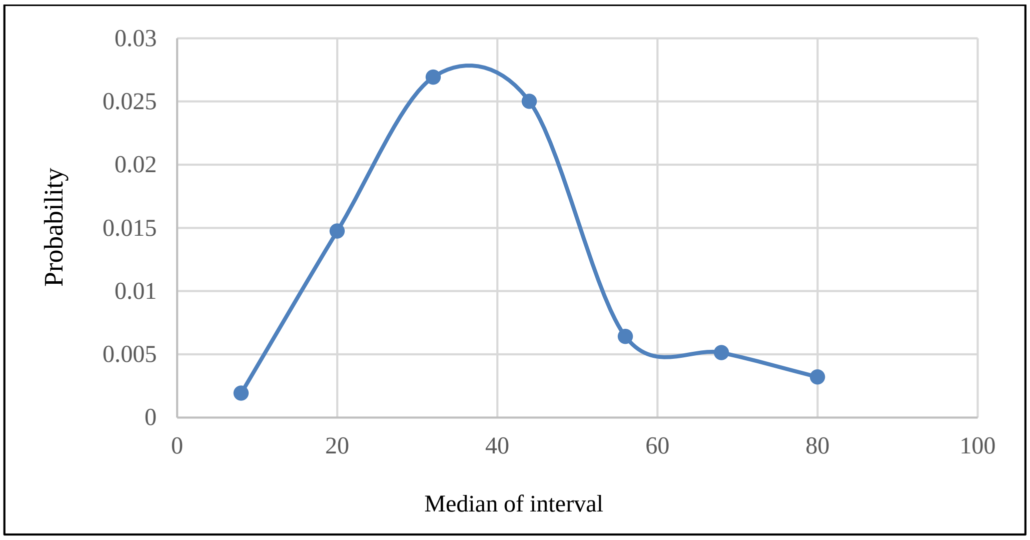

Fig. 7 Probability distribution diagram of China aviation network nearest neighbor average degree in 2001.

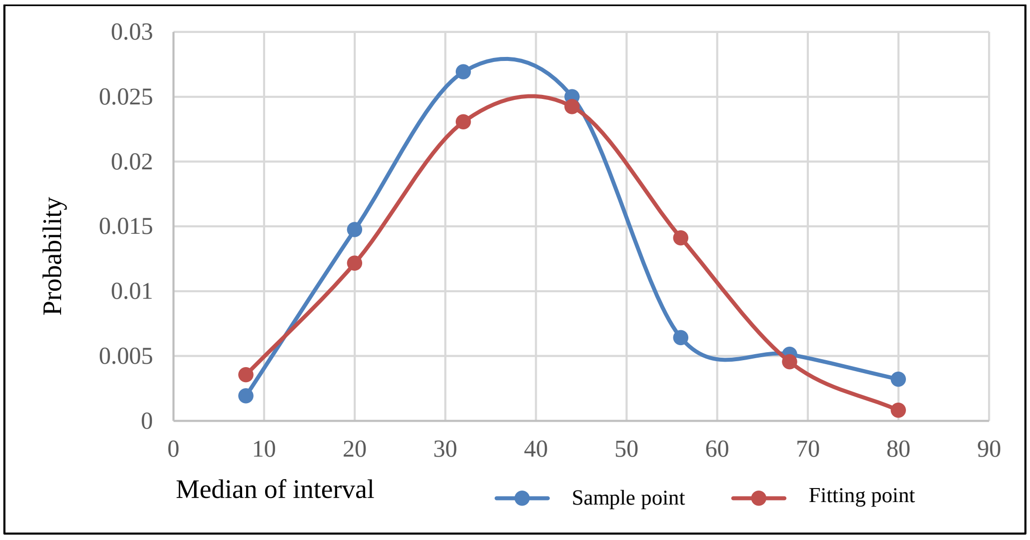

Fig. 8 Fitting effect diagram of probability distribution of nearest neighbor average degree in 2001.

To take $\varepsilon_{i,2001}$ (i = 1, 2, 3, 4, 5, 6,7) as residual to investigate the degree of approximation of fitting through the residual distribution:

$$\varepsilon_{i,2001} = p_{i,2001} - \hat{y}_{i,2001} \qquad (17)$$

The residual $\varepsilon_{i,2001}$ was drawn in Fig. 9. All points in Fig. 9 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small. $|\varepsilon_{i,2001}| < 0.008 < \hat{\sigma}_{2001} = 15.625$. This illustrated that the fitting effect was very good.

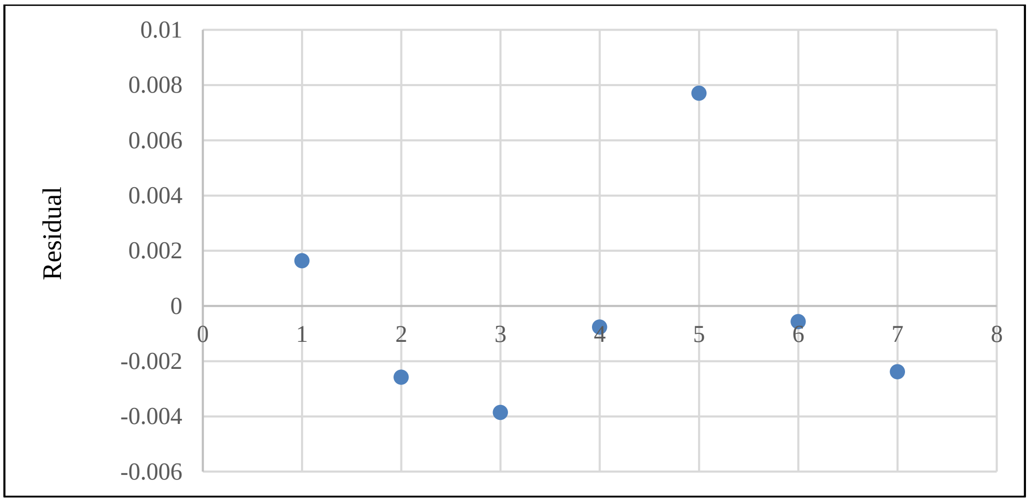

Fig. 9 Residual diagram of fitting curve of probability distribution of nearest neighbor average degree in 2001.

2.4 Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network in 2008

The adjacent matrix A_{2008} was gotten from statistic data. The nearest neighbor average degrees of 150 nodes in 2008 were gotten from A_{2008} and Eq. (2). The data in Table 4 were obtained by statistics according to the interval in Table 4. The curve in Fig. 10 was drawn by the data in Table 4. It was similar to normal distribution function by observation. The definition of parameters and relationship of parameters were similar with Eqs. (3) and (4) in Eq. (1). Here, $N_{2008}=150$, $m_{2008}=7$, δ_{2008}=13.2. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2008}=\frac{1}{N_{2008}}\sum_{i=1}^{N_{2008}}x_i=46.323 \quad (18)$$

$$\hat{\sigma}_{2008}=\sqrt{\frac{1}{N_{2008}-1}\sum_{i=1}^{N_{2008}}(x_i-\overline{x})^2}=17.285 \quad (19)$$

Table 4 Probability distribution of China aviation network nearest neighbor average degree in 2008.

Interval	[2, 14]	(14, 26]	(26, 38]	(38, 50]	(50, 62]	(62, 74]	(74, 86]
Median	8.6	21.8	35	48	61.2	74.1	87.6
Times	3	18	41	46	25	11	6
Frequency	0.02	0.12	0.2733	0.3067	0.1667	0.0733	0.04
Probability	0.001515	0.009091	0.020707	0.023232	0.012626	0.005556	0.00303

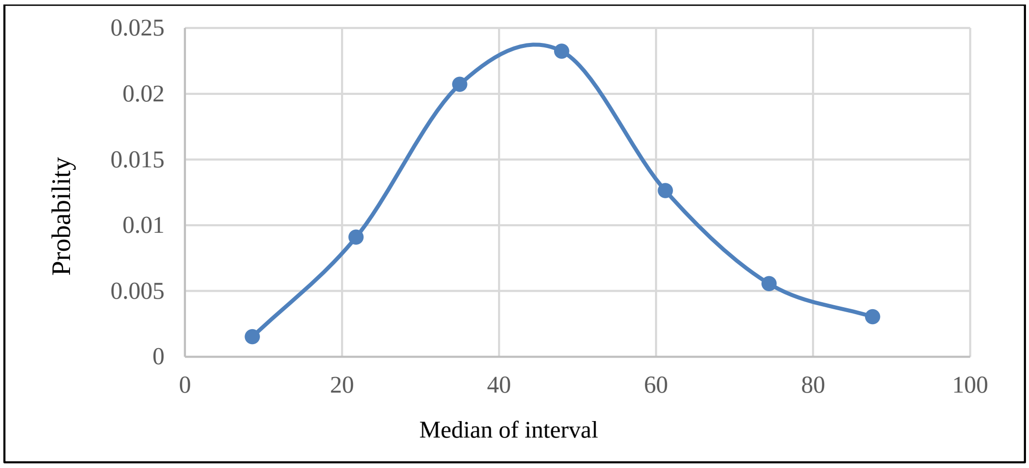

Fig. 10 Probability distribution diagram of China aviation network nearest neighbor average degree in 2008.

Let $\hat{\mu}_{2008}$ and $\hat{\sigma}_{2008}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2008} = 0.0231e^{-0.00167(x-46.323)^2} \quad (20)$$

The fitting curve in Eq. (20) and sample points $p_{i,2008}$ were drawn in Fig. 11 with good fitting effect to take $\varepsilon_{i,2008}$ (i = 1, 2, 3, 4, 5, 6,7) as residual to investigate the degree of approximation of fitting through the residual distribution [6].

$$\varepsilon_{i,2008} = p_{i,2008} - \hat{y}_{i,2008} \quad (21)$$

The residual $\varepsilon_{i,2008}$ was drawn in Fig. 12. All points in Fig. 12 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small. $|\varepsilon_{i,2008}| < 0.004 < \hat{\sigma}_{2008} = 17.285$. This illustrated that the fitting effect was very good.

2.5 Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network in 2015

The adjacent matrix A_{2015} was gotten from statistic data. The nearest neighbor average degrees of 203 nodes in 2015 were gotten from A_{2015} and Eq. (2). The data in Table 5 were obtained by statistics according to the interval in Table 5. The curve in Fig. 13 was drawn by the data in Table 5. It was similar to normal distribution function by observation. The definition

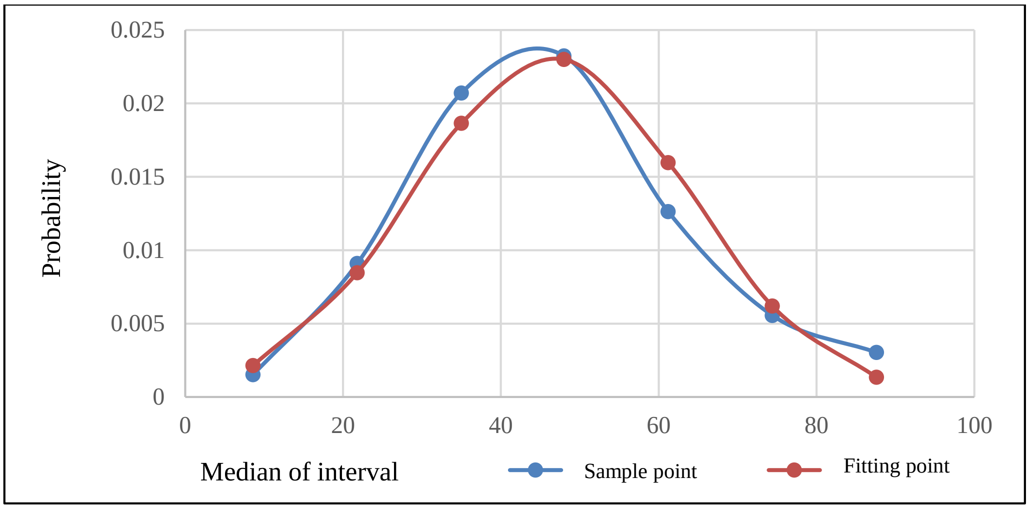

Fig. 11 Fitting effect diagram of probability distribution of nearest neighbor average degree in 2008.

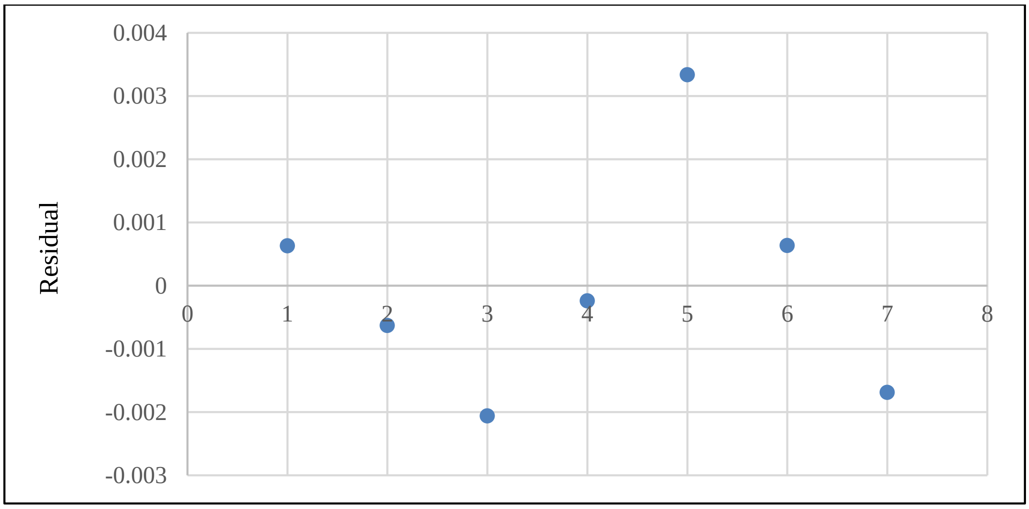

Fig. 12 Residual diagram of fitting curve of probability distribution of nearest neighbor average degree in 2008.

Table 5 Probability distribution of China aviation network nearest neighbor average degree in 2015.

Interval	[2, 14]	(14, 26]	(26, 38]	(38, 50]	(50, 62]	(62, 74]	(74, 86]
Median	11.8	28.9	46	63.1	80.2	97.3	114.4
Times	3	18	42	42	51	39	8
Frequency	0.01478	0.08867	0.206897	0.206897	0.25122	0.19212	0.03941
Probability	0.000864	0.005185	0.012099	0.012099	0.014692	0.011235	0.002305

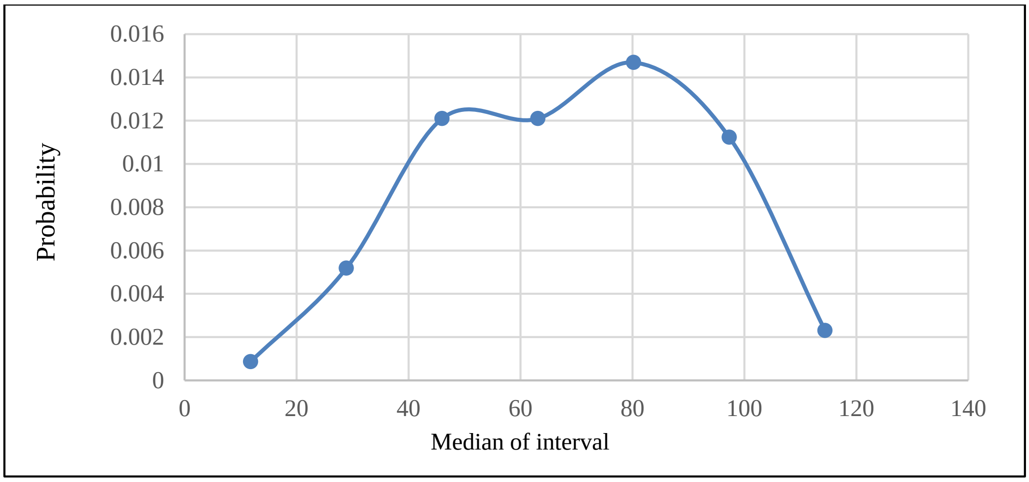

Fig. 13 Probability distribution diagram of China aviation network nearest neighbor average degree in 2015.

of parameters and relationship of parameters was similar with Eqs. (3) and (4) in Eq. (1). Here, $N_{2015}=203$, $m_{2015}=7$, δ_{2015}=17.1. It could be gotten from the statistical properties of normal distribution:

$$\hat{\mu}_{2015}=\frac{1}{N_{2015}}\sum_{i=1}^{N_{2015}}x_i=68.233 \quad (22)$$

$$\hat{\sigma}_{2015}=\sqrt{\frac{1}{N_{2015}-1}\sum_{i=1}^{N_{2015}}(x_i-\overline{x})^2}=24.475 \quad (23)$$

Let $\hat{\mu}_{2015}$ and $\hat{\sigma}_{2015}$ be location parameter and scale parameter to substitute in Eq. (5), the equation of fitting curve could be gotten:

$$\hat{y}_{2015}=0.0163e^{-0.000835(x-68.235)^2} \quad (24)$$

The fitting curve in Eq. (24) and sample points $p_{i,2015}$ were drawn in Fig. 14 with good fitting effect to take $\varepsilon_{i,2015}$ (i = 1, 2, 3, 4, 5, 6, 7) as residual to investigate the degree of approximation of fitting through the residual distribution.

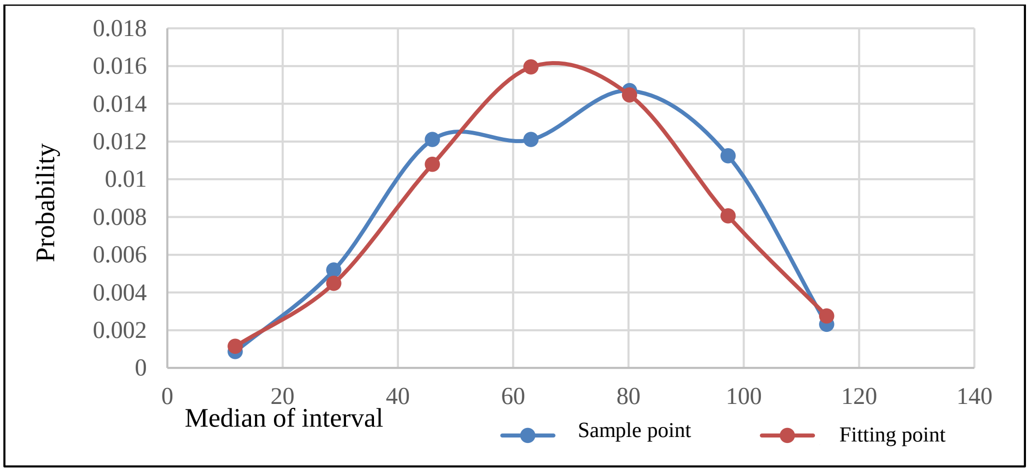

Fig. 14 Fitting effect diagram of probability distribution of nearest neighbor average degree in 2015.

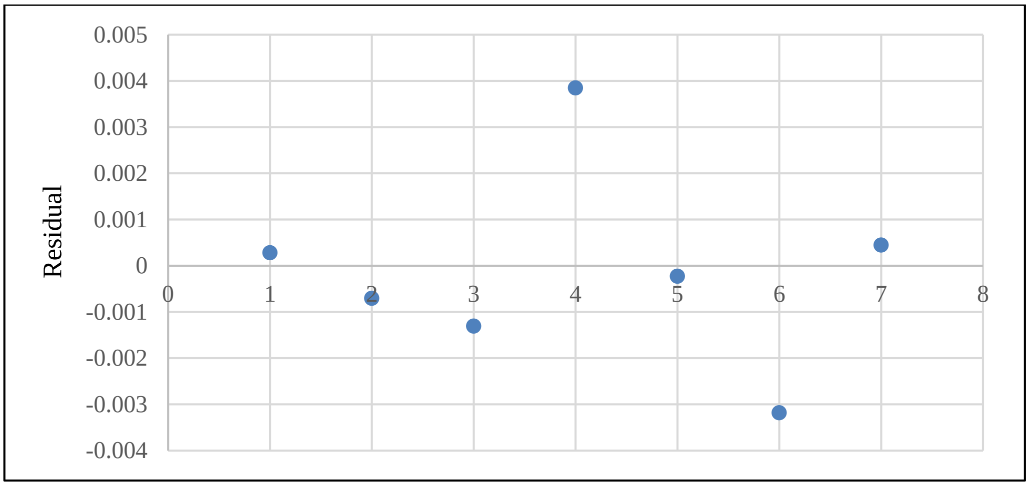

Fig. 15 Residual diagram of fitting curve of probability distribution of nearest neighbor average degree in 2015.

$$\varepsilon_{i,2015} = p_{i,2015} - \hat{y}_{i,2015} \tag{25}$$

The residual $\varepsilon_{i,2015}$ was drawn in Fig. 15. All points in Fig. 15 were random fluctuation around $\varepsilon = 0$ and the range of fluctuation was very small. $|\varepsilon_{i,2015}| < 0.004 < \hat{\sigma}_{2015} = 24.475$. This illustrated that the fitting effect was very good.

2.6 Evolution of the Probability Distribution of Nearest Neighbor Average Degree of China Aviation Network

The probability distribution parameters of the nearest neighbor average degree of nodes in China aviation network were listed in Table 6. In order to more intuitively observe the evolution trend of the probability distribution of the nearest neighbor average degree, the probability distribution function curves of these five years were plotted in Fig. 16. It could be found that in Fig. 16, the five normal distribution curves

Table 6 The evolution of probability distribution parameter of nearest neighbor average degree of China aviation network.

Year	1988	1994	2001	2008	2015
Location parameter	19.747	34.679	39.008	46.323	68.233
Scale parameter	10.847	15.405	15.625	17.285	24.475

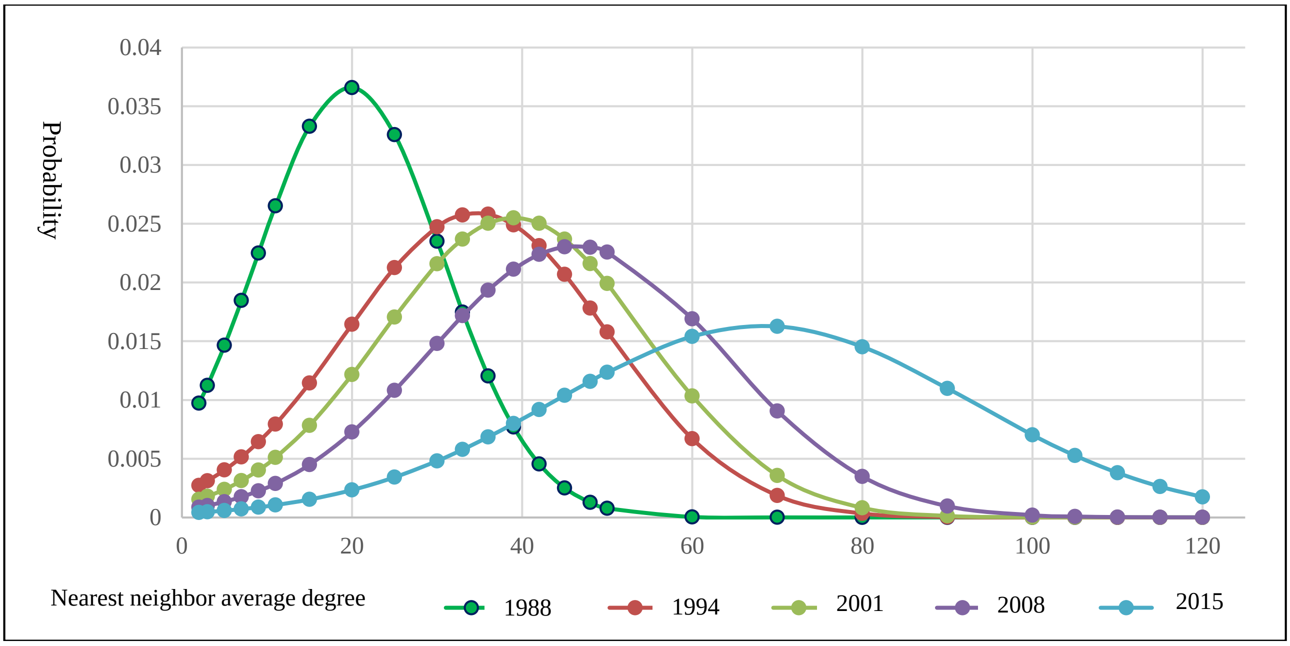

Fig. 16 The evolution diagram of probability distribution curve of nearest neighbor average degree of China aviation network.

from left to right were the probability distributions of 1988, 1994, 2001, 2008 and 2015 respectively. The width of the curve changed from narrow to wide and the peak value of the curve changed from high to low. The change of the position parameter reflected the same situation, that was, the median point of the curve moved to the right and became larger year by year. The change of scale parameters was also the same, that was, the scale parameters increase year by year, and the curve gradually wider. Because the area under the curve was unchanged and all were 1, the peak value became lower.

3. The Evolution Trace of Probability Distribution Parameter of Nearest Neighbor Average Degree of China Aviation Network

The evolution trace of probability distribution parameters of nearest neighbor average degree of nodes in China aviation network was discussed here. Let the location parameter of normal distribution be x. Let the scale parameter of normal distribution be y, to take x as abscissa and y as ordinate. The location parameters and scale parameters in Table 6 were drawn in Fig. 17 as scattered points. The correlation coefficient r of scattered points in Fig. 17 was calculated.

$$r = \frac{L_{xy}}{\sqrt{L_{xx}L_{yy}}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (26)$$

Here, $n = 5$. Using the data in Table 6, the value of correlation coefficient r was calculated, $r = 0.994$. The critical value of $r|_{\alpha=1\%, f=3}$ was 0.959 found in critical value table [6] at degree of freedom $f = n - 2 = 3$ and level of significant α of 1%. Since $|r| = 0.994 > 0.959 = r|_{\alpha=0.01, f=3}$, the scattered points in Fig. 17 had significant linear correlation. Least square method [6] was used as an approach in Eq. (27) to fit the line with points in Fig. 17.

$$\begin{cases} \hat{\beta}_0 = \bar{y} - \hat{\beta}_1\bar{x} = 5.204 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = 0.277 \end{cases} \quad (27)$$

The linear equation:

$$y = 0.277x + 5.204 \quad (28)$$

The fitting line in Eq. (28) was drawn with the sample points in one diagram of Fig. 18 with good fitting effect.

To take t test [6] of Eq. (28), test hypotheses is: $H_0 : \beta_1 = 0$.

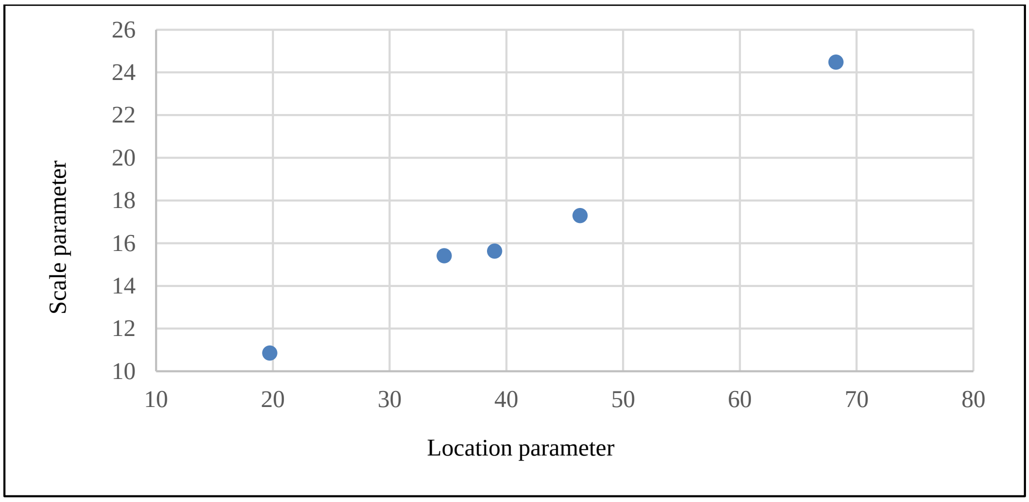

Fig. 17 The scattered points diagram of parameter relationship of probability distribution of nearest neighbor average degree.

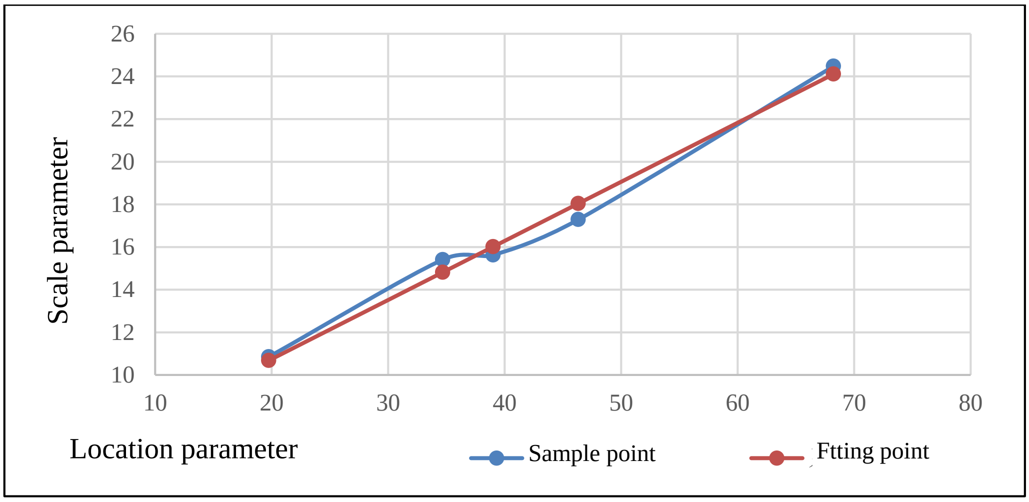

Fig. 18 The fitting effect diagram of linear relationship of probability distribution of nearest neighbor average degree.

When the hypothesis was true, there is:

$$\hat{\beta}_1 \sim N(0, \frac{\sigma^2}{L_{xx}}) \tag{29}$$

Here, $\hat{\beta}_1$ fluctuates near zero, statistic t is build.

$$t = \frac{\hat{\beta}_1}{\sqrt{\frac{\hat{\sigma}^2}{L_{xx}}}} = \frac{\hat{\beta}_1\sqrt{L_{xx}}}{\hat{\sigma}} \tag{30}$$

where:

$$\hat{\sigma}^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{31}$$

Statistic t was calculated by data in Table 6 and Eqs. (28), (30), and (31): $t = 15.36$.

To check the t distribution table [6], at significant level α of 0.01 and degree of freedom $f = n-2 = 3$ the value of $t_{|_{\alpha=0.01, f=3}}$ in the table is 4.541. So, $|t| = 15.36 > 4.541 = t_{|_{\alpha=0.01, f=3}}$, null hypothesis H_0 is refused. The linear correlation of Eq. (28) is significant. The linear relationship between location parameter and scale parameter in Fig. 18 illustrated that the evolution of probability distribution of nearest neighbor average degree of China aviation network had linear trace.

4. Conclusion

Based on the statistics of China civil aviation in 1988, 1994, 2001, 2008 and 2015, the probability distribution and evolution trace of the nearest neighbor average degree in China aviation network were studied. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. The nearest neighbor average degree of each node was calculated, and it was found that it had the probability distribution of normal function, and the position parameters and scale parameters of the probability distribution had linear evolution trace.

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