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Performance Evaluation of Automated Warehouse Based on Markov Chain

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Abstract: Compared with the United States and Europe, the overall efficiency of automated storage and retrieval system (AS/RS) in our country is lower. Scientific and reasonable performance evaluation method can effectively feedback the state of AS/RS to provide the strategic basis for decision-maker so as to improve system utilization and operational efficiency of equipment. Based on previous studies, the indicator variable for determining performance evaluation of AS/RS was established; according to the solving requirement of Markov method, a simple queuing model of AS/RS, single queue for the single desk, was built; on the basis of Marco Cardiff transfer matrix method, the variable expression of performance evaluation was got. Taking the background of AS/RS, and based on ARENA software, the accuracy of the mathematical solution model was verified by using error analysis. The innovation of this paper is that using Markov analysis to value the indicator variable of performance evaluation system and its feasibility and scientific nature is verified through simulation technology .

Keywords AS/RS; Performance evaluation; Queuing theory; Markov process analysis; ARENA simulation

INTRODUCTION

Currently, automated storage and retrieval system (AS/RS) has played an important role in the whole storage areas (Dong Fuhui, 2013). In addition, it is the core technology of logistics system. In AS/RS, there are many emerging technologies, such as computer technology and automation technology. To a large extent, it improves the operating efficiency. However, Compared with the United States and Europe, the overall efficiency of AS/RS in our country is lower. The main reason for this phenomenon is that the internal parameter setting and equipment layout, in AS/RS, are irrational. Therefore, to accurately assess the performance of AS/RS with scientific and reasonable method is very necessary.

In the performance assessment of logistics system, there are three common models: correlation matrix; fuzzy comprehensive evaluation model; analytic hierarchy process. In some fields, those methods are very effective. However, they are objected to static evaluation methods and their results have subjectivity to some extent. Therefore, the scope of their application is limited. As AS/RS is a dynamic multi-factor system, the dynamic and quantitative evaluation method should be selected to evaluate its performance.

Markov analysis, also known as Markov transfer matrix method, means that it is to predict future changes of the variables, under Markov process, by analyzing changes of random variables in the reality (Xu Zhihui, 2013). Although the application of this method is relatively less common in the logistics field, but using Markov analysis to assess AS/RS is very reasonable. Markov analysis is a dynamic research method, which can predict the state of the system at a certain moment, and the next prediction is easily to be done with less solid as its historical data have no aftereffect. In this paper, according to the characteristics of AS/RS, the performance evaluation model of AS/RS based on Markov chain is established. In addition, this paper presents a real case study with the comparative analysis to exemplify the following hypothesis: Markov analysis is suitable for assessing the performance of AS/RS.

PERFORMANCE INDICATORS OF AS/RS

The purpose for evaluating performance of AS/RS is to meet the storage requirements under the premise as well as to improve the efficiency of the whole system. There are many factors affecting the result of evaluation, which are closely related to the static parameters setting of system design and the dynamic characteristics of system. Such as, the task scheduling rules in storage and the operation cycle number of stocker. A lots of literature indicate that assessing the performance of AS/RS involves many indicators.

They are concluded as follows (Guan Shulin, 2009) (Hu Hongmei, 2008) (Wang Hongchun, 2013) (Zhou Yan, 2014).

1) Overall utilization of warehouse space (The indicator is used to measure the using degree of warehouse space, with the ratio of average stack area of the warehouse to total area or the ratio of average space stacked volume to the total.)
2) Utilization of warehouse cargo (The indicator is used to measure the utilization of cargo, with an average occupancy ratio, namely the ratio of average quantity warehouse cargo to the total . To some extent, the cargo space utilization reflects the storage quantity of raw materials.)
3) Throughput capacity of warehouse (Using the maximum throughput and average throughput quantity of system , in a period, measure the maximum warehouse operation capacity.)
4) Equipment utilization (The indicators are the time utilization of equipment and the capacity utilization. They, respectively, measure, the proportion of the actual working time and the ratio of the average load to the rated load.)
5) System responsiveness (The indicator reflects the response rate of system storage tasks, closely related to the scheduling system, by using the average waiting time of storage demands, processing time or blocking time.)
6) Logistics flow rate (The indicator can be expressed as average cargo storage time in the library bits, or average turnover frequency in a certain time (such as a month or a year)).
7) Operating error frequency (The indicator means the proportion of the number of error-operation accounting for the total number in a job.)

In this paper, there are eight index variables selected to make AS/RS performance assessment and concluded as follows. ① Average arrival quantity of demands within the system; ② Average waiting quantity of demands within the system; ③ Average arrival out-put quantity of demands within the system; ④Average arrival storage quantity of demands within the system; ⑤ Probability of system blockage at any time; ⑥ Staying-time of any demands within the system; ⑦ Average waiting time of demands within the system; ⑧ Server utilization within the system.

THE SYSTEM MODEL OF AS/RS

Case study

The three-dimensional database , AS/RS , covers an area of 1600 square meters (storage trolley channel does not occupy the treasury area). In addition, its other parameters involve height of nearly 18 meters and 3 roadway (6 rows of shelves). The warehouse uses the pallet as a storage location. In this case, the most important equipment is AGV vehicle. When the goods are sent to the warehouse, the system, through a wireless network, delivery order to ask idle AGV picking up products from a dock, and then transporting to the designated staging area (there are lots of storage staging area), and finally the stacker delivers goods to the storage area. In the input/output process of goods, when the goods reach the dock, system sends a request command to check if there is any AGV in idle. The idle AGV runs to the station to pick up goods and send to the designated dock in accordance with the instruction. If all AGV are busy, the goods will be placed in the waiting queue, until there is one idle AGV.

Build the System Model

Model assumptions

In order to make stochastic model more accuracy, some assumptions must be made, shown as follow:

1) In the operation process, AGV can only take one goods at a time. If the quantity of goods are two, this operation will be counted as twice. By that analogy, the number of task is counted.
2) Set working time as 8 hours;
3) Does not consider the machine's initial state. Namely, neglect the preheating time of AGV vehicle and stacker, such as the start-up time.

Model Building

In real situation, AS/RS involves many rows of shelves and a lot of AGV. There are many factors related to each other in the automatic system. Therefore, when there is no AGV in idle state, the demand is considered as being evenly allocated to every AGV. To reflect the actual status of AS/RS, in the process of model simplification, the model of one server with two queues is established, by making a independent AGV act as the server.

In the process of input/output product demands, if AGV is in busy station, demands will be divided into two queues, based on two different needs, to wait for service. When AGV lies in the idle state, the demands will be automatically processed. The Schematic diagram of model is shown in Figure 1:

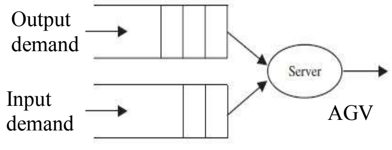

Figure 1. The demand flow model of AS/RS

The operation principle of AGV subjects to FIFO, one kind of service standards. In the system, the demand randomly arrives. When the prior service was completed, if the input/output demands arrive at the same time, AGV will perform the dual task. After delivering goods to accurate cargo space, AGV returns to the output-staging area, bringing corresponding goods according to different orders. If there is only one type of demand waiting for service, AGV will execute the single task. If there is no demand arriving to the system, AGV will be idle until the next demand arrives.

Model Updating

When using Markov forecast method to solve and analysis problems, some conditions must be met. First, the state of AS/RS should be divided. Second, the number of quantity and type of the demand should be known, before AGV begins to service. In the Above-mentioned model, two types of demand are arranged into two teams, which does not meet the solving-requirements of Markov forecast method. Therefore, the modification of that model should be, to some extent, done.

According to the above idea, priority factor is introduced to modification of model for solving the generalization problem. When there are two types of demand, the status has a priority of 1; When there is a single demand, the status has a priority of 0. So above model can be simplified to the simple queuing model with only one server one queue. The simplified model can be equivalent to the former one by introducing the priority factor. The Schematic diagram of modified model is shown in Figure 2.

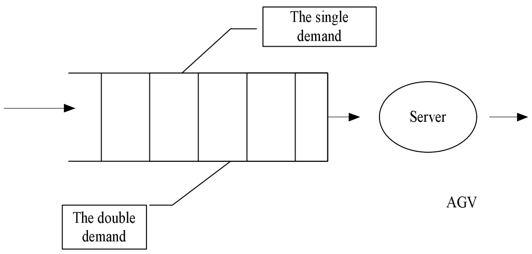

Figure 2. The schematic diagram of modified model

Relative Parameters Description

(1) Both of the input/output demand obey Poisson distribution (Based on experience and historical data statistical sample). The rates are, respectively, λ_1 and λ_2 and the arrival of demand is independent;

(2) In the system, there is only one single server, namely AGV. When AGV performs the single task, its running time is described by $S_s(x)$; When AGV performs the double task, its running time is expressed as $S_d(x)$;

(3) In the queue waiting for service, the maximum capacity of input demand is K; the maximum capacity of output demand is L. When the quantity of demands in the system reach a certain value, the demand into-port will be shut down.

PERFORMANCE EVALUATION BASED ON MARKOV CHAIN

System Status Analysis

Before establishing Markov model, the state of the system must be analyzed. In this paper, the type and quantity of demand in AS/RS is used to represent the status of system. $X = \{X_n, n = 0,1,2,...\}$ means a two-dimensional random process. Inaddition, $X_n = (i, j)$ indicates that the quantity of output/input demand are, respectively, i and j in the system. If $X_n = (i,0)$ or $(0, j)$ $(0 \le i \le K, 0 \le j \le L)$, the system has only one type of demand, meaning the service handled by AGV is a single task. If $X_n = (i, j)$ $(0 \le i \le K, 0 \le j \le L)$, AGV performs a double task. While the system start to enter the running period or the service in one period is finished, there will be come to the station transition. As the time and states are discrete, X constitutes a Markov chain .

The arrival of demand obeys Poisson arrival stream, consistent with the general nature of the Poisson distribution. In the model, v_{ij} and u_{ij} represent the arrival probability of output demand i and input demand j at any time .

If AGV performs a double task, namely $i \neq 0$ and $j \neq 0$, then

$$v_{ij} = \int_0^{\infty} \frac{e^{-\lambda_1}(\lambda_1 t)^i}{i!} \frac{e^{-\lambda_2}(\lambda_2 t)^j}{j!} dS_d(t) \quad (1)$$

If AGV performs a single task, namely $i = 0$ or $j = 0$, for convenience, the rate is noted as u_{ij} ,then

$$u_{ij} = \int_0^{\infty} \frac{e^{-\lambda_1}(\lambda_1 t)^i}{i!} \frac{e^{-\lambda_2}(\lambda_2 t)^j}{j!} dS_s(t)$$

$$= \int_0^{\infty} \frac{e^{-\lambda_1} e^{-\lambda_2}(\lambda_2 t)^j}{j!} dS_s(t)$$

$$\text{0r} = \int_0^{\infty} \frac{e^{-\lambda_1}(\lambda_1 t)^i e^{-\lambda_2}}{i!} dS_s(t) \quad (2)$$

So far, there is a Markov chain (0,0), (0,1) ... .. (0, L) (1,0) .... (K-1, L) (K, 0) ... .. (K, L) in the system. and based on prior studies, in this case the transfer matrix is showed as follow:

Noting :

$$
\mathrm{P} = \begin{bmatrix}
B_0 & B_1 & B_2 & \dots & B_{K-1} & B_K \\
A_0 & A_1 & A_2 & \dots & A_{K-1} & A_K \\
0 & A_0 & A_1 & \dots & A_{K-2} & A_{K-1}^* \\
0 & 0 & A_0 & \dots & A_{K-3} & A_{K-2}^* \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \dots & A_1 & A_2^* \\
0 & 0 & 0 & \dots & A_0 & A_1^*
\end{bmatrix}
$$

Semi-Markov Process Analysis of System

For the probability vector $\pi = (\pi_1, \pi_2, ..., \pi_n)$, with the condition $i, j \in S$: $\lim_{k \to \infty} p_j^{(k)} = \pi_j$, π represents the stationary distribution of Markov chain. After multiple transfers of steady-state distribution, there is a finite probability of system state j, independent to the system initial state. Due to the stationary distribution of Markov chain, the goals set can be achieved in accordance with the transfer of the intermediate state. According to the related properties from the stationary distribution of Markov chain(Wen Haishan et al., 2012), namely $\pi = \pi P$ and $\pi e = 1$, and the transfer of state, the following equations are valid.

$$
B_0 = \begin{bmatrix}
0 & \frac{\lambda_2}{\lambda_1 + \lambda_2} & 0 & \dots & 0 & 0 \\
u_{00} & u_{01} & u_{02} & \dots & u_{0L-1} & u_{0L}^* \\
0 & u_{00} & u_{01} & \dots & u_{0L-2} & u_{0L-1}^* \\
0 & 0 & u_{00} & \dots & u_{0L-3} & u_{0L-2}^* \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \dots & u_{01} & u_{02}^* \\
0 & 0 & 0 & \dots & u_{00} & u_{01}^*
\end{bmatrix}
$$

$$
B_1 = \begin{bmatrix}
\frac{\lambda_2}{\lambda_1 + \lambda_2} & 0 & 0 & \dots & 0 & 0 \\
u_{10} & u_{11} & u_{12} & \dots & u_{1L-1} & u_{1L}^* \\
0 & u_{10} & u_{11} & \dots & u_{1L-2} & u_{1L-1}^* \\
0 & 0 & u_{10} & \dots & u_{1L-3} & u_{1L-2}^* \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \dots & u_{11} & u_{12}^* \\
0 & 0 & 0 & \dots & u_{10} & u_{11}^*
\end{bmatrix}
$$

$$
A_i^* = \sum_{j=i}^{K} A_j, \quad i = 1, 2, ..., K-1
$$

$$
u_{ij}^* = \sum_{l \geq j} u_{il}, \quad v_{ij}^* = \sum_{l \geq j} v_{il}
$$

$$
A_i = \begin{bmatrix}
u_{i0} & u_{i1} & u_{i2} & \dots & u_{iL-1} & u_{iL}^* \\
v_{i0} & v_{i1} & v_{i2} & \dots & v_{iL-1} & v_{iL}^* \\
0 & v_{i0} & v_{i1} & \dots & v_{iL-2} & v_{iL-1}^* \\
0 & 0 & v_{i0} & \dots & v_{iL-3} & v_{iL-2}^* \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \dots & v_{i1} & v_{i2}^* \\
0 & 0 & 0 & \dots & v_{i0} & v_{i1}^*
\end{bmatrix},
$$

$$
i = 0, 1, 2, ..., K-1
$$

$$
\pi_i = \pi_0 B_i + \sum_{v=1}^{i+1} \pi_v A_{i+1-v}, i = 0,1,2..., K-1 \quad (3)
$$

$$
\pi_K = \pi_0 B_K + \pi_1 A_K + \sum_{v=2}^{K} \pi_v A_{K+1-v} \quad (4)
$$

π is a steady-state probability distribution, and the state is likely to be changed at any time. Taking into account the operational processes within the automated warehouse, In this paper, the semi-Markov method is used to analysis the status of system and get the quantify value of selected performance assess indicators.

There is different demands' capacity between Semi-Markov process with initial system. The time interval of Semi-Markov process is subject to the general time distribution, whose state transfer occurs only at the specified time, not randomly. Specific circumstance was shown in Figure 3:

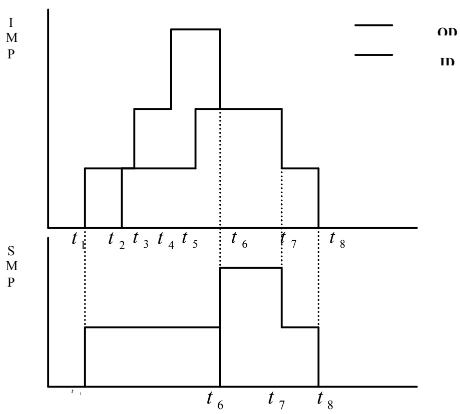

Figure 3. The comparison chart of two process
(Note: IMP = initial Markov chain; SMP = Semi-Markov chain; OD = output demand; ID = input demand)

In the initial-Markov process diagram, the state transition occurs at the moment $t_1, t_2, ..., t_8$, while in the semi-Markov process, state transition occurs only at the moment t_1, t_6, t_7, t_8.

Let η_{ij} indicate the intended stay time in the status (i, j), the equation is shown as:

$$\eta_{ij}=\begin{cases} \dfrac{1}{\lambda_1+\lambda_2}, i=j=0; \\ E(S_s), j=0 and 1\le i\le K,; i=0 and 1\le j\le L; \\ E(S_d), 1\le i\le K, 1\le j\le L. \end{cases} \quad (5)$$

And in the semi-Markov process, the probability of the system state (i, j) at any time is:

$$P_{ij}=\frac{\pi_{ij}\eta_{ij}}{\sum_{k=0}^{K}\sum_{l=0}^{L}\pi_{kl}\eta_{kl}} \quad (6)$$

Quantization of Performance Evaluation Index

Quantify formula

Based on the above analysis, the quantify formula of each assessment index in AS/RS is shown as follows:

1) The number of average arrival demand in system

$$E(N)=\sum_{i=0}^{K+1}\sum_{j=0}^{L+1}(i+j)P_{ij} \quad (7)$$

2)The number of average waiting demand in system

$$E(N_q)=\sum_{i=1}^{K+1}(i-1)P_{i0}+\sum_{j=1}^{L+1}(j-1)P_{0j}+\sum_{i=1}^{K+1}\sum_{j=1}^{L+1}(i+j-2)P_{ij} \quad (8)$$

3) The number of average output demand in system

$$E(N_{rc})=\sum_{i=0}^{K+1}\sum_{j=0}^{L+1}iP_{ij} \quad (9)$$

4) The number of average input demand in system

$$E(N_{sc})=\sum_{i=0}^{K+1}\sum_{j=0}^{L+1}jP_{ij} \quad (10)$$

5) The blockage probability of the system at any time

$$P_b=\frac{\lambda_1}{\lambda_1+\lambda_2}\sum_{j=0}^{L+1}P_{K+1,j}+\frac{\lambda_2}{\lambda_1+\lambda_2}\sum_{i=0}^{K+1}P_{i,L+1} \quad (11)$$

6) The staying time of any demand in the system (by the *Little* formula)

$$E(T)=\frac{E(N)}{\lambda}, \lambda=(\lambda_1+\lambda_2)(1-P_b) \quad (12)$$

7) The average waiting time of demand in the system

$$E(T_q)=\frac{E(N_q)}{\lambda}, \lambda=(\lambda_1+\lambda_2)(1-P_b) \quad (13)$$

8) Server utilization

$$\rho = 1 - P_{00} \quad (14)$$

Result Analysis

The quantify value of the Index is obtained by using the mathematical solving model based on the actual operating data of AS/RS, so as to evaluate the running status of the system. In this article, the main system operating parameters is shown in Table 1:

Table1. Major Parameters' Value

Index	Nomenclature	Parameters
Arrival of output demand	$\lambda_1=2$	Poisson(2)
Arrival of input demand	$\lambda_2=3$	Poisson(3)
Server time of single task	$S_s(t)$	Exponential(5)
Server time of double task	$S_d(t)$	Exponential(4)
Queue capacity of output demand	K	5
Queue capacity of input demand	L	5

The values of λ_1, λ_2, $S_s(t), S_d(t), K, L$ are substituted into the formula, then the staying time is shown as follow:

$$\eta_{ij}=\begin{cases} \frac{1}{5}, i=j=0; \\ \frac{1}{5}, j=0 and 1\le i\le 5; or; i=0 and 1\le j\le 5; \\ \frac{1}{4}, 1\le i\le 5, 1\le j\le 5 \end{cases} \quad (15)$$

And according to the transition matrix, probability and so on, the estimated value is obtained, as shown in Table 2:

Table2. The Estimated Value of Main Probability

	the estimated value		the estimated value		the estimated value
P_{00}	0.2023	P_{10}	0.0693	P_{20}	0.0227
P_{01}	0.1127	P_{11}	0.0687	P_{21}	0.0311
P_{02}	0.0626	P_{12}	0.0513	P_{22}	0.0289
P_{03}	0.3539	P_{13}	0.0348	P_{23}	0.023
P_{04}	0.0199	P_{14}	0.0226	P_{24}	0.0172
P_{05}	0.0103	P_{15}	0.0144	P_{25}	0.0127
P_{30}	0.0074	P_{40}	0.0024	P_{50}	0.0007

P_{31}	0.0126	P_{41}	0.0048	P_{51}	0.0017
P_{32}	0.0139	P_{42}	0.0061	P_{52}	0.0024
P_{33}	0.0128	P_{43}	0.0064	P_{53}	0.0029
P_{34}	0.0109	P_{44}	0.0063	P_{54}	0.0032
P_{35}	0.0091	P_{45}	0.0059	P_{55}	0.0038

From above data, the following conclusions can be got. The allocation of resources in AS/RS is relatively reasonable; There is balance between the number of input demand and output demand; the system blocking rate is low. So the utilization of facilities and equipment is high, such as AGV and there is no such circumstances, such as largely demand clogging.

SIMULATION ANALYSIS

To effectively verify the accuracy of the above mathematical model, using Arena simulation model analyzes the performance of AS/RS. And compare the results.

Simulation results analysis

By simulation, the use efficiency of AGV in system is shown in Figure 3:

Figure 3. Use efficiency map of AGV

According to the report, some information can be known. AGV carry one product each time, whose utilization is 84% almost equal to the value from the previous analysis of the Markov method. Likewise, the waiting time of any demands can be drawn from the report in Figure 4:

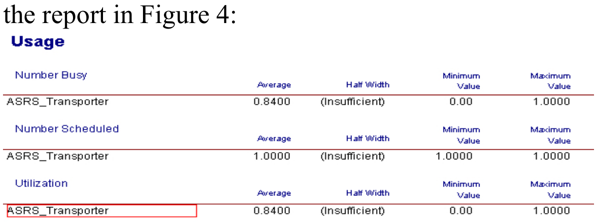

Figure 4 the waiting time of any demands

According to report statistics, the quantify values of performance evaluation index in AS/RS are shown in Table 4:

Table 4. The simulation value of each indicator

Evaluation index	Estimated value
Average number of demands in system	2.8542
Average queue number of demand in the system	1.6062
Average number of output demand in system	1.0805
Average input quantity of demand in the system	1.7737
Blockage probability of the system at any time	0.0279
Staying time of any demand in the system (minute)	0.5872
Waiting time of any demand in the system (minute)	0.3304
Use efficiency of server (%)	82.7646

Comparative Analysis

By comparative analysis of Table 4 and Table 5, the mean relative error is obtained by the following equation:

$$\text{the mean relative error} = \frac{\text{Total relative error}}{(K+1)(L+1)},$$

$$\text{Total relative error} = \sum \frac{(|\text{Estimated value} - \text{Simulation value}|)}{\text{Simulation value}};$$

In addition, the comparison results are shown in Table 6:

Table 6. The Comparative Value of Two Methods

Performance evaluation index	Relative error rate (%)
Average number of demands in system	0.1517
Average queue number of demand in the system	0.1980
Average number of output demand in system	0.2573
Average input quantity of demand in the system	0.0841
Blockage probability of the system at any time	0.3582
Staying time of any demand in the system (minute)	0.1334
Waiting time of any demand in the system (minute)	0.1879
Use efficiency of server (%)	0.0136

By the result of comparing the value of two methods, using Markov analysis method to play performance evaluation of AS/RS is effective.

CONCLUSION

This paper mainly analyzes the performance assessment of AS/RS based on Markov chain. The operational status of AS/RS is researched by using mathematical performance analysis to construct a simple queuing model. Against the assessment index, on the basis of the steady-state distribution of Marco chain of AS/RS, the quantitative expression of the performance evaluation indicators is obtained and the solving mathematical model with Markov chain is established, through the process analysis of Semi-Markov Chain. Overall, the performance evaluation model in this paper has a strong practical and innovative value. Innovation mainly is shown as follows:

(1) According to the solving requirements of Markov method, introducing the priority factor, a simple model of one server with one queue is built, in accord with the operating characteristics of AS/RS;

(2) Based on the characteristics analysis to steady-state of Markov chain, introducing the semi-Markov process analysis, the state probabilities of system can be exported at any state (i, j).

By applying the real case and using comparative analysis of two methods' result, the mathematical solving model based on Markov chain is scientific and feasible. In addition, to some extent, the studies in this paper has reference value to other relative issues, such as performance evaluation.

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