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A model of airport security work flow based on petri net

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Abstract. Extremely long lines at airports in the United States have been sharply criticized. In order to find out the bottleneck in the existing security system and put forward reasonable improvement plans and proposal, the Petri net model and the Markov Chain are introduced in this paper. This paper uses data collected by transportation Security Agency (TSA), assuming the data can represent the average level of all airports in the United States, to analyze the performance of security check system. By calculating the busy probabilities and the utilization probabilities, the bottleneck is found. Moreover, recommendation is given based on the parameters’ modification in Petri net model.

1 Introduction
During 2016, the U.S. Transportation Security Agency (TSA) came under sharp criticism for extremely long lines, in particular at Chicago’s O’Hare international airport. This phenomenon not only can easily lead to mass incidents but also brings a lot of negative impact on the air transport industry. Therefore, in order to reduce the security queue length as well as improve security efficiency, this article analyzes the airport security check workflow and its performance.

At present, researches of workflow and performance based on Petri net are common while application of Petri net in security check process is rare. In terms of passengers’ service process, Guanghui Gu applied Service Model to general departure process in China and used the approach to assess working flow in different airports as well as made recommendation [1]. Besides, Naiyi Li used simulation software to simulate flight departure, reflecting the customers’ leaving process dynamically [2]. When it comes to Petri net modeling and performance analysis, Xiaqing Zhang established the Petri net model of the urban traffic emergency management system to determine its weaknesses and propose improvement measures [3]. Jun Xiao extended the Petri net model to evaluate the performance of four basic model instances of the workflow in the Exsept environment [4]. Jiangtao Qin built a model of the manufacturing system using a hierarchical colouring Petri net method and parameter call technique [5].

To make feasible proposals, this article takes Chicago’s O’Hare international airport’s security check process as a standard and establishes a simple Petri net model, analyzing its overall performance.

2 Airport Security Process Analysis

2.1 Security Check Work Flow
The goals of security measures are to prevent passengers from hijacking or destroying aircraft and to keep all passengers safe during their travel. Chicago’s O’Hare international airport’s security check process can be separated into four zones.
The workflow can be divided into two parts, one is that passengers should go through millimeter wave scanner or metal detector, and another is that all their belongings should pass X-ray screening machine.

Passengers randomly arrive at zone A and wait in a queue until a security officer can inspect their identification and boarding documents. After passengers’ identifications checked, they enter zone B waiting for millimeter wave scanner or metal detector while their belongings ready for being X-ray screened. Passengers must remove shoes, belts, jackets, metal objects, electronics, and containers with liquids, placing them in a bin to be X-rayed separately; laptops and some medical equipment also need to be removed from their bags and placed in a separate bin. All of their belongings, including the bins containing the aforementioned items, are moved by conveyor belt through an X-ray machine, where some items are flagged for additional search or screening by a security officer (Zone D). Passengers that fail this step receive a pat-down inspection by a security officer (Zone D). The passengers finally proceed to the conveyor belt on the other side of the X-ray scanner to collect their belongings and depart the checkpoint area.

2.2 Assumptions
According to the working flow of security check, we make the assumptions as below:
• Collected data can represent staffs’ average working efficiency in Chicago’s O’Hare international airport.
• No time was observed for placing items on the belt going into X-ray.
• Transit time between process stations is contained in the waiting time.
• People can leave security check area only if he or she has retrieved their belongings with themselves and their belongings checked.
• Passengers are considered to leave the system if they enter the zone D and it will not have an effect on efficiency.

3 Mathematical Model of Airport Security Work Flow Based on Petri Net

3.1 GSPN Model Establishment
According to the security checkpoint process, build up a single-channelled security checkpoint process GSPN model, that is, the channel consists of only one security officer, one X-ray scanning machine and one millimeter wave scanning machine. The GSPN model is given by Fig.1.

![Fig. 1GSPN model that can represent a single-channelled security checkpoint](image)

Illustration of symbols used in PSGN model is given by Table.1 and Table.2.
Table 1: Places and their meanings

| Place | Meaning |
|-------|---------|
| i     | Passengers enter the security checkpoint |
| P1    | Passengers that pass ID check process |
| P2    | Items wait for x-ray scanning |
| P3    | Passengers wait for millimeter wave scanning |
| P4    | Items wait for being retrieved |
| P5    | Passengers wait for retrieving belongings |
| o     | Passengers leave the security check point |

Table 2: Transitions and their meanings

| Transition | Meaning |
|------------|---------|
| t1         | Passengers get their identification and board documents checked |
| t2         | Passengers move to the screening line |
| t3         | Passengers’ belongings move through x-ray machine |
| t4         | Passengers go through millimeter wave scanning machine |
| t5         | Passengers retrieve their belongings |

3.2 Markov Chain Establishment

The MC (Markov Chain) of a SPN can be obtained from the reachability graph of the Petri net \((N, M_0)\). The MC state space is the reachability set \(R(M_0)\), and the transition rate from state \(M_i\) to state \(M_j\) is given by \(q_{ij} = \lambda_{ij}'\), the firing rate of transition \(t_i\) transforming \(M_i\) into \(M_j\) (\(q_{ij} = \lambda_{11}' + \lambda_{12}' + \cdots\)), if there are two or more transitions \(t_{i1}, t_{i2}\) transforming \(M_i\) into \(M_j\); \(q_{ij} = 0\) if no transitions transforming \(M_i\) into \(M_j, (i \neq j)\). The square matrix \(Q = [q_{ij}]\) of order \(s = |R(M_0)|\) is known as the transition rate matrix [6].

(1) Passengers’ arrival
The arrival of the passenger is independent of the arrival of the preceding passenger. Calculate the average arrival rate of channels.

| Total Time | 0:17:99.5 |
| Arrival Rate (p/min) | 5.7 |

(2) ID Check
Consider the machines’ and staffs’ handling capacity as a whole, we have assumed that the data can represent the average level of airport efficiency.

| Time | 00:08.0 | 00:05.3 | 00:11.1 | 00:10.0 |
|------|---------|---------|---------|---------|
| Time | 00:09.0 | 00:09.0 | 00:12.6 | 00:15.0 |
| Time | 00:14.6 | 00:11.8 | 00:14.8 | 00:20.4 |
| Time | 00:07.7 | 00:07.5 | 00:10.9 | 00:11.9 |
| Average Time (s) | 11.225 | Processi ng Rate (p/min) | 5.35 |

(3) Passengers’ Arrival at security Check Area
We assume a passenger arrives at the security check area once he or she leaves the ID check service counter, so the firing rate is the same as ID check processing rate, which is 5.35 person per minute.

(4) Millimeter Wave Scanning

Table. 5 Data processing of millimeter wave scanning

| Total Time | Leaving Rate (p/min) |
|------------|----------------------|
| 0:07:33.8  | 40                   |
| 5.29       |                      |

(5) X-Ray Scanning

Table. 6 Data processing of x-ray scanning

| Total Time | Leaving Rate (p/min) |
|------------|----------------------|
| 0:0:26.4   | 15                   |
| 10.41      |                      |

(6) Passengers’ Leaving of Security Check Area

People can leave security check area only if he or she has retrieved their belongings with themselves and their belongings checked. The whole scanning process’ average service rate can be treated as people’s average leaving rate from security area.

Table. 7 Data processing of passengers’ leaving

| Total Time | Leaving Rate (p/min) |
|------------|----------------------|
| 0:13:50    | 29                   |
| 2.1        |                      |

Firing rates of each transition are yielded by Table.8 (with regular security check mechanism)

Table. 8 Transitions and their firing rates

| Transition | Average Time/s | Firing Rate | Firing Rate Value |
|------------|----------------|-------------|------------------|
| t1         | 11.225         | λ1          | 5.35             |
| t2         | 11.225         | λ2          | 5.35             |
| t3         | 5.76           | λ3          | 10.41            |
| t4         | 11.345         | λ4          | 5.29             |
| t5         | 28.62          | λ5          | 2.1              |
| t6         | 9.05           | λ           | 5.7              |

Add firing rates to the GSPN, the model can be modified into Fig.3 and the MC can be inferred (Fig.4).

Fig. 2 Modified GSPN model
3.3 Bottlenecks Identification

Since the SPN is reversible, i.e., \( m_0 \in R \) for every \( m_i \in R(m_0) \), then, the SPN can generate an ergodic continuous-time MC and it is possible to compute the steady-state probability distribution \( X \) by solving the linear system

\[
\begin{cases}
XQ = 0 \\
\sum_{i=1}^n x_i = 1
\end{cases}
\]

(1)

Transition rate metrics is given by

\[
Q = \begin{bmatrix}
-\lambda_1 & \lambda_1 & 0 & 0 & 0 & 0 \\
0 & -\lambda_2 & \lambda_2 & 0 & 0 & 0 \\
0 & 0 & -\lambda_3 & \lambda_4 & 0 & 0 \\
0 & 0 & 0 & -\lambda_4 & 0 & \lambda_4 \\
0 & 0 & 0 & 0 & -\lambda_5 & \lambda_5 \\
\lambda & 0 & 0 & 0 & 0 & -\lambda
\end{bmatrix}
\]

(2)

Assume the steady-state probability is

\[
X = [x_1, x_2, x_3, x_4, x_5, x_6]
\]

(3)

We can get the linear system

\[
\begin{align*}
-\lambda_1 x_0 + \lambda_2 x_6 &= 0 \\
\lambda_1 x_0 - \lambda_2 x_1 &= 0 \\
\lambda_2 x_1 - (\lambda_3 + \lambda_4) x_2 &= 0 \\
\lambda_3 x_2 - \lambda_4 x_3 &= 0 \\
\lambda_4 x_2 - \lambda_5 x_4 &= 0 \\
\lambda_4 x_3 + \lambda_3 x_4 - \lambda_5 x_5 &= 0 \\
\lambda_5 x_5 - \lambda x_6 &= 0
\end{align*}
\]

(4)

Thus the steady-state probability of MC is given by
\[
\begin{align*}
x_0 &= 0.1499 \\
x_1 &= 0.1499 \\
x_2 &= 0.0511 \\
x_3 &= 0.1005 \\
x_4 &= 0.0260 \\
x_5 &= 0.3819 \\
x_6 &= 0.1407
\end{align*}
\] (5)

The expected value of the number of tokens: Let \( B(i, n) \) be the subset of \( R(m_i) \) for which the number of tokens in a k-bounded place \( p_i \) is \( n \). Then, the expected value of the number of tokens in place \( p_i \) is given by

\[
E[m_i] = \sum_{n=1}^{k} nP[B(i, n)]
\] (6)

Transition utilization probability is the sum of steady-state probabilities of states that enable the transition.

Table. 9 Expected token of each place and transition utilization probability of each transition

| Place | Expected token | Transition | Transition Utilization Probability |
|-------|----------------|------------|-----------------------------------|
| \( i \) | 0.1499 | \( t_1 \) | 0.1499 |
| \( P_1 \) | 0.1499 | \( t_2 \) | 0.1499 |
| \( P_2 \) | 0.0771 | \( t_3 \) | 0.0771 |
| \( P_3 \) | 0.1516 | \( t_4 \) | 0.1516 |
| \( P_4 \) | 0.4824 | \( t_5 \) | 0.3819 |
| \( P_5 \) | 0.4079 | | |
| \( o \) | 0.1407 | | |

As can be seen from the table, there are problems at places and tokens. For one thing, token numbers at \( P_4 \) and \( P_5 \) is larger. \( P_4 \) and \( P_5 \) are all part of the extraction of baggage. Accumulation of passengers here may be caused by uncoordinated work efficiency between X-ray scanner and millimeter wave scanner. That results in either passengers waiting for their items or baggage waiting to be retrieved. For another thing, the utilization rate of change \( t_5 \) is 40.79\%, which is relatively busy compared with other transitions. \( t_5 \) is also part of the extraction of baggage, this may be caused by some passengers’ low packing up efficiency.

4 Improve Proposals

By analyzing the data, we conclude that \( E[p_4] = x_3 + x_5 \) and \( E[p_5] = x_4 + x_5 \) are larger than others. The part they share is \( x_5 \), so decreasing \( x_5 \) can make the values smaller, and thus reduce the congestion.

According to the analysis:

\[
\begin{align*}
-\lambda_1 x_0 - \lambda_2 x_6 &= 0 \\
\lambda_1 x_0 - \lambda_2 x_1 &= 0 \\
\lambda_2 x_1 - (\lambda_3 + \lambda_4) x_2 &= 0 \\
\lambda_3 x_2 - \lambda_4 x_3 &= 0 \\
\lambda_4 x_2 - \lambda_3 x_4 &= 0 \\
\lambda_4 x_3 + \lambda_3 x_4 - \lambda_5 x_5 &= 0 \\
\lambda_5 x_5 - \lambda x_5 &= 0
\end{align*}
\] (7)
Obviously, changing the relevant variable $x_3$ and $x_4$ will reduce $x_5$. The rate of entering is decided by the passengers, so we should improve the efficiency of services, which reduces the $x_3$ and $x_4$.

Checking of people and baggage is carried out at the same time, so the effect on the total time depends on the longer one, that is, the time spent on checking people. But after the observation of the data, we found that the total time of passengers from the beginning the checkpoint was much more than the time of checking itself. We can easily figure out that the crux is the time spent on collecting items. So we give the corresponding feasible solution to this phenomenon.

First of all, we suggest that the airport should move the process of collecting items to another zone. The staffs help passengers transfer baggage, and passengers only need to reach the appropriate location to take their baggage. This can make the efficiency of exiting is not affected by personal efficiency, which can greatly reduce the congestion.

Secondly, the TSA can double the number of staff at checking channel, so that the checking efficiency, which is also known as the firing rate of $t_4$, can be doubled.

Furthermore, the TSA should add a separate zone E where is provide for passengers to pack their bags. And increase staff in the area to remove the baggage into the specific area. Thus we can reduce $x_5$ and increasing the leaving rate. The revised figure is:

Fig. 4 Illustration of thetas security screening process after modification

Finally, TSA should also horn the efficiency of internal processes to reduce $x_3$ and $x_4$, thereby reducing the $x_5$. That is, the TSA should focus on increasing staff in the place where staff check baggage and people, but also should pay attention to the occupational training.

Assume that after allocating another zone for storing luggage and doubling the checking efficiency, the firing rate is changed as below:

| Transition | Average Time/s | Firing Rate | Firing Rate Value |
|------------|---------------|-------------|-------------------|
| t1         | 11.225        | $\lambda_1$ | 5.35              |
| t2         | 11.225        | $\lambda_2$ | 5.35              |
| t3         | 5.76          | $\lambda_3$ | 10.41             |
| t4         | 11.345        | $\lambda_4$ | 10.58             |
| t5         | 28.62         | $\lambda_5$ | 6                 |
| t6         | 9.05          | $\lambda$   | 5.7               |
The steady-state probability of MC is changed into

\[
x_0 = 0.2176 \\
x_1 = 0.2176 \\
x_2 = 0.0555 \\
x_3 = 0.0546 \\
x_4 = 0.0564 \\
x_5 = 0.1940 \\
x_6 = 0.2042
\]  

(8)

In that sense, all of the process can stay balanced. The modified token number and transition utilization probability is shown in Chart.11, in which we can see the accumulation of passengers is sharply reduced.

Table. 11 Expected token of each place and transition utilization probability of each transition after modification

| Place | Expected token | Transition | Transition Utilization Probability |
|-------|----------------|------------|------------------------------------|
| i     | 0.2176         | t1         | 0.2176                             |
| P_1   | 0.2176         | t2         | 0.2176                             |
| P_2   | 0.1119         | t3         | 0.1119                             |
| P_3   | 0.1101         | t4         | 0.1101                             |
| P_4   | 0.2486         | t5         | 0.1940                             |
| o     | 0.2504         |            |                                    |
|       | 0.2042         |            |                                    |

5 Summary

This paper applies a simple Petri net model to American airport security system work flow, aiming at finding the bottleneck and give proposals. The calculation in Petri net model shows uncoordinated efficiency between X-ray scanner and millimeter wave scanner and passengers’ low luggage extraction rate is the main crux to the long queue. In this respect, we balance the places’ busy probabilities and the transitions’ utilization probability, finding that the addition of millimeter scanners and temporary luggage depositary at non-security area can horn the efficiency.

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