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2017

Mathematical Contest in Modeling (MCM/ICM) Summary Sheet

Modeling the Process of Airport Security : Modification and Evaluation

Summary

We build a Multistage Queue Model, based on but more general than the current process of Airport Security, and develop it to seek intelligent methods to expedite the checkpoints.

To begin with, to derive precise model, we process the given data and perform some observations and analyses. We conduct One-Sample Kolmogorov-Smirnov test and find that the arrival time and the baggage screening time satisfy exponential distribution and the time spent of ID Check satisfies the standard normal distribution. Furthermore, we utilize the results to generate big data for test in the succedent simulation processes.

Secondly, we design a basic model named Multistage Queue Model and list all these related parameters such as device numbers, service time and passengers' queue-select method, preparing for further developments.

Next, we specialize the based model and yield a realistic simulation with discrete optimization to identify the bottleneck. Using the given data and throughput statistics in reality, we figure out that the bottleneck occurs at the third stage, baggage waiting, the stage after body screening which has the maximum time expectation among three stages. In addition, waiting procedure of ID Check is the second nettlesome standstill.

Based on the above, we devise two schemes to modify the current process. In the first modification, we find the equilibrium point which minimize both the expectation of wait time and the cost of modification utilizing High-Dimensional Fit and Nonlinear Programming. In the second plan, we design an additional procedural system based on RFID technology, Data-based Classify-Methods and Dynamic Estimating Algorithm, to predict the expected scanning time and help passengers take an intelligent strategy.

To quantify the effect, we set up an evaluation system including Principal Component Analysis model,Factor Analysis. We find that the Select Function Modification has best effect because it observably reduce the wait time and is less sensitive to the increase of cost.

Finally, by varying behavior patterns of people, arrival frequency and service time, we derive a correlation between average wait time and the rate of changes of key factors. The results show our model has an stable performance in practical situations.

Keywords: Multistage Queue Model; Principal Component Analysis; Factor Analysis; Kolmogorov-Smirnov test; Nonlinear Programming; High-Dimensional Fit; Time Discreted Queuing Simulation;

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1 Introduction

1.1 Background

According to the Global Terrorism Database (GTD), more than 1177 terrorist attacks worldwide between 1970 and 2015 targeted airports and aircrafts, representing 1.3 percent of all attacks [1]. These figures highlight the vulnerability of airport security. As a response, more police and military personnel at major international airports all over the world go further into preventive measures, and travelers are being told to arrive earlier because of increased pre-flight security.

With airport security being tightened up, it is inevitable to bring passengers to a standstill. The congestion not only causes inconvenience, but itself presents an attractive target. Finding the right balance between security and inconvenience has been put into the high agenda of the U.S. Transportation Security Agency (TSA).

1.2 Problem Clarification

We are asked to build some models to explore the flow of passengers and identify potential bottlenecks. After that, we are supposed to provide some modifications schemes to the current process to improve passenger throughput and reduce variance in wait time and evaluate the effect of our changes. Our models should remain stable considering the differences of culture norms. Finally, based on our models, we need to put forward some suggestions for both global and specific situations.

1.3 Terminology and Symbols Description

Key concepts used in the process of Airport Security are as follows:

- **X-Ray Mchines**: X-ray machines are used to screen objects non-invasively. Luggage at airports is examined for possible weapons, including bombs. Prices of these Luggage X-rays vary from $50,000 to $300,000 [2].
- **Full-Body Scanners**: A full-body scanner is a device that detects objects on a person's body for security screening purposes, without physically removing clothes or making physical contact. Two distinct technologies are in general use: Backscatter X-ray and millimeter-wave. Backscatter body scanners subject you to a far gentler burst of X-rays than baggage X-ray. Millimeter wave scanners use non-ionizing electromagnetic radiation similar to that used by wireless data transmitters.TSA uses **millimeter wave scanners**.
- **Walk Through Metal Detector**: It detects any metal as a person passes through the detector, costing $30,000 [3]. It costs less time in comparison with Full-body scanners.[4]
- **Pre-Check**: Pre-Check is an expedited security screening program connecting travelers with smarter security and a better air travel experience.

The Global symbols and definition are listed in Table 1. The specialized definition of Basic Model will be defined in section 3.2.

Table 1: Notations

Symbol	Description
w_i	Wait Time (i = 1,2)
T_i	Service Time Distribution(i = 1,2,3)
S_i	Queue-Select Function (i = 1,2,3)
D_i	Arrival Time Distribution (i = 1,2)
$E[w_i]$	Expectation of Wait Time(i = 1,2)

1.4 Assumptions

According to the given information and TSA official website, we make some assumptions reasonably.

- The process of airport security consists of two steps: identity verification and security screening.
- Travelers who have enrolled in Pre-Check have their own separate lane for the whole process of Airport Security.
- There are three types of devices used as Screening Technology: full-body scanners, metal detectors for body and X-ray machines for baggage.
- Every process is working on without interruption, unless otherwise noted.
- Transit time between process stations is ignored.
- Once the passengers reach the front of the queue, they prepare all of their belongings for X-ray screening, that is, time for placing items on the belt is ignored.
- Metal detectors are as much as millimeter wave scanners in service.
- The passengers process through either a millimeter wave scanner or metal detector with the same probability 0.5.
- The time spent for passengers who remove all the items under regulations stepping through the metal detector smoothly is very short by comparison with the time spent on millimeter wave scanner.[5]
- The arrival time of the passengers and the service time have the memoryless property.

2 Data Processing

2.1 Arrival Interval Distribution

Based on the preliminary analysis of the arrival time of passengers, we assume the initial time when passengers arrive at the TSA Security Screening Process is memoryless.

That is to say, the distributions of time from now to the next passenger are exactly the same. According to this principle, we work out time intervals of passengers' arrival and apply One-Sample Kolmogorov-Smirnov test (K-S test) on them, including Normal Distribution (ND), Uniform Distribution (UD), Exponential Distribution (ED) and Poisson Distribution (PD). The results are shown in the Table 2.

Table 2: One-Sample K-S Test for Arrival Time

Passenger		PreCheck	Regular
N		57	46
Exponential parameter[a b]	Mean	9.1740	12.9459
Most Extreme Differences	Absolute	.181	.166
	Positive	.181	.166
	Negative	-.112	-.051
Kolmogorov-Smirnov Z		1.363	1.125
Asymp. Sig. (2-tailed)		.049	.159

[a] Test Distribution is Exponential.
[b] Calculated from data.

As can be seen from the test results, the 2-tailed Asymptotic Significance of the ND, UD and PD are not significant, so we reject the null hypothesis. In the K-S test of the exponential distribution (Table2), we can see that the Z value of the K-S test is 1.363 and 1.125 for both the PreCheck passengers and Regular passengers, with the probability of 0.049 and 0.159. They are respectively close to or greater than 0.05, so we accept the null hypothesis. Consequently, we consider the interval of arrival time to be exponentially distributed.

2.2 Service Time Distribution

Apart from the arrival time distribution of passengers meeting a certain Markov distribution, the service time for passengers and baggage to accept screening also meet a certain probability distribution. With the same assumption that the probability distribution is memoryless, firstly we draw the frequency distribution of different Service Time (Fig. 1).

As is shown in Fig. 1, both ID Check and Millimeter Wave Scan approximately meet the properties of the normal distribution, whereas the time interval frequency distribution of the X-ray scan is more similar to the exponential distribution. For further verification, we conduct One-Sample Kolmogorov-Smirnov Test on these Service Time Intervals using the SPSS software. The results of the tests are shown in Table 3.

As can be seen from the Table 3, the 2-tailed Asymptotic Significance for ID Check 1 and 2 reach 1.000 and 0.988, which are significantly larger than 0.05 and close to 1, indicating that the ID Check Interval sample of the normality is excellent. We can consider it to meet the normal distribution.

For inspection time of Millimeter wave scanner, after comparison, the progressive significance is less than 0.05. So we believe that the it does not meet the test of these four distributions. Reasons for such result may be that different passengers carrying different items will go through various situations. Furthermore, manual inspection is subjective, and thus it may not satisfy the condition of no memory.

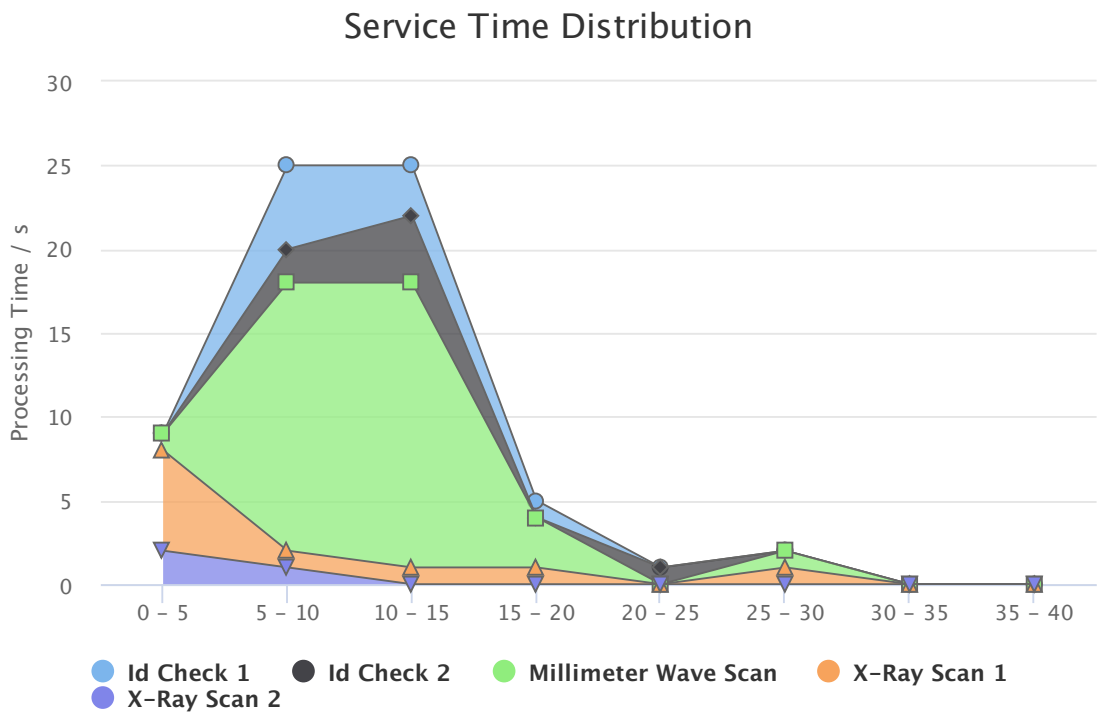

Figure 1: Distribution of Service Time

Table 3: One-Sample K-S Test for Millimeter Wave Scanner

Service Procedure		ID CHECK 1	ID CHECK 2	MILLIMETER WAVE SCAN	X-ray SCAN 1	X-ray SCAN 2
N		9	7	39	10	3
Normal	Mean	10.1967	12.5514	11.6372	7.5420	3.6700
Parameters[a b]	Std. Deviation	2.98144	4.54482	5.86876	8.24170	3.36613
Most Extreme	Absolute	.100	.169	.229	.304	.364
Differences	Positive	.098	.169	.229	.304	.364
	Negative	-.100	-.133	-.174	-.239	-.262
K-S Z[c]		.300	.447	1.433	.961	.631
Asymp.Sig.	(2-tailed)	1.000	.988	.033	.315	.821

[a] Test Distribution is Normal.
[b] Calculated from data.
[c] Kolmogorov-Smirnov Z

The time intervals of X-ray machines exhibit a good exponential distribution characteristic in course of the test. 2-tailed Asymptotic significance of two X-ray machines reach 0.507 and 0.877 (as is shown in Table4). Hence, the service time of X-ray machines can be considered to be exponentially distributed.

According to the above analysis, we can see that the arrival time of passengers and the detection time of X-ray machines satisfy exponential distribution, while the time spent of ID Check satisfies the standard normal distribution. We can derive the corresponding probability distribution function from the known data fitting. Succedent simulation processes will utilize the corresponding probability distribution function to generate big data for test.

Table 4: One-Sample K-S Test for X-ray Machines

Service Procedure		ID CHECK 1	ID CHECK 2	MILLIMETER WAVE SCAN	X-ray SCAN 1	X-ray SCAN 2
N		9	7	39	10	3
Exponential	Mean	10.1967	12.5514	11.6372	7.5420	3.6700
Parameters[a b]		2.98144	4.54482	5.86876	8.24170	3.36613
Most Extreme	Absolute	.412	.450	.411	.260	.341
Differences	Positive	.220	.196	.169	.260	.258
	Negative	-.412	-.450	-.411	-.201	-.341
K-S Z		1.236	1.190	2.567	.823	.590
Asymp.Sig.	(2-tailed)	.094	.118	.000	.507	.877

[a] Test Distribution is Exponential.
[b] Calculated from data.

3 Basic Model

3.1 Process Restatement

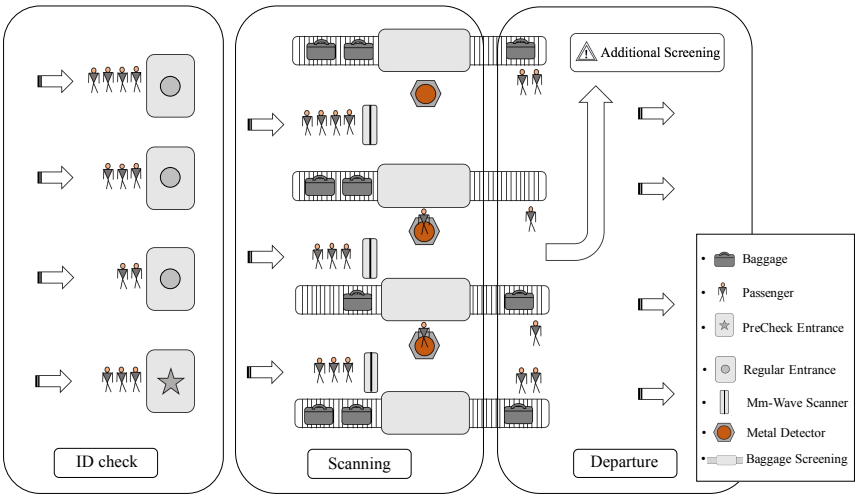

Figure 2: Illustration of Current Process

We establish a **Multistage Queue Model** to explore the flow of passengers and identify bottlenecks. In our model, process contains three stages: ID Check, Screening and Departure.

Due to the special process of PreCheck members, we will discuss passengers separately.

ID Check As is shown in Fig. 2, for every ID Check station, passengers arrive at the line in certain arriving time distribution D_1 and wait in the queue. We call the wait time in this stage w_1. For passengers who reach lobby, there are n_2 (for PreCheck members are n_1) alternative check lines, they will choose one of the ID Check stations using Queue-select method S_1, which is one of the factors influencing D_1.

The wait ends with the inspection of identification and other documents, and the check cost time, which is the service time in the first stage with distribution T_1.

Screening As soon as the passengers leave the check station, they move to a screening line utilizing an alternative selecting method S_2. In this stage, every Scanner has decided arriving time distribution D_3, determined by aforementioned factors D_1, w_1, S_1.

The moment passengers reach the front of the queue, both the baggage and body begin screening respectively. We call the service time distribution for people T_2 and for baggage T_3.

Departure In the third stage, there are two possible condition of departure:

- Those who fail either body or baggage screening will depart the normal process and receive an additional inspection.
- Passengers who pass the inspection smoothly then proceed to the conveyor belt on the other side of the X-ray machines to collect their belongings. There exists possible wait time w_3 for finished people to get their unfinished baggage.

3.2 Model Parameters

All parameters considered of our model are listed in Table 5. We will reify the basic model by setting these parameters.

Table 5: Parameters of Multistage Queue Model

Symbol	Parameter
n_1	the number of PreCheck Entrances in service
n_2	the number of Regular Entrances in service
n_3	the number of Millimeter Wave Body Scanners in service which equals to the number of Metal Detector in service
n_4	the number of X-ray Baggage Scanners in service
D_1	Arrival time distribution of Regular passengers
D_2	Arrival time distribution of PreCheck members
S_1	Queue-select function of people in check line
S_2	Queue-select function of people in screening line
S_3	Queue-select function of baggage
T_1	Service time distribution for ID Check
T_2	Service time distribution for Body Screening
T_3	Service time distribution for Baggage Screening

4 Identify Bottlenecks of Current Process

Definition 1. *Bottleneck : The bottleneck of the system occurs at the processor with the largest* $E[w_i]$.

4.1 Parameters Setting

We apply our Basic Model in a specific scenario and set parameters under following rules:

- $n_1 : n_2 = 1 : 3$: There is often one Pre-Check lane open for every three regular lanes.
- $n_3 = n_4$: Every screening line has a X-ray machine, a millimeter wave scanner and a metal detector.
- The distributions D_1, T_1, T_2, T_3 satisfy the analysis of data in Section 2.
- The Queue-select functions S_1, S_2 is a stochastic process.
- $S_2 = S_3$: Because every screening line has one X-ray machine, millimeter wave scanner and metal detector. The baggage has the same selecting method for lines.

4.2 Model Development

Aiming to let our model "Running", we implement a C++ program (as is shown in Algorithm **1**) to simulate the process of airport security in reality.

First of all, we generate a large number of Regular passengers conforming to certain distribution D_1 derived from Section 2.1. Likewise, we generate service time for ID Check, millimeter wave scanners and X-ray machines satisfying distribution T_1, T_2 and T_3.

In current process, passengers use a stochastic method to choose lines, which means that each ID Check entrance has a possibility of $\frac{1}{n_2}$ to be selected while each screening line has $\frac{1}{n_3}$.

In simulation, we operate time iteration for the continuation of events. The minimum unit of time interval is $0.01s$.

Algorithm 1: simulation process

```
Generate passengers a day ;
Put all passengers into arrival queue Q_arrival by arrival time order ;
T ← 00 : 00.00s // set the iteration start time
while exist passengers in queue do
    while the front passenger's arrival time equal to T do
        P ← passenger out of the front in Q_arrival;
        Q_ID ← the queue for ID Check selected by P though function S_1;
        put P into back of Q_ID;
        if Q_ID only has passenger P then
            start P's ID Check service
    foreach Q_ID for ID Checking do
        if the front passenger in Q_ID has finish his ID Check service then
            P ← passenger out of the front in Q_ID;
            if Q_ID ≠ ∅ then
                start the front's ID Check service
            Q_body ← the body screening line selected by P though function S_2;
            put P into the back of Q_body;
            if Q_body only has passenger P then
                start P's body scan service
            B ← the baggage of P;
            Q_baggage ← the baggage screening line selected by P though function S_3;
            put B into the back of Q_baggage;
            if Q_baggage only has baggage B then
                start B's baggage scan service
    foreach Q_body for passenage scanning do
        if the front passenger in Q_Body has finish his body scan service then
            let the front out of Q_body;
            if Q_body ≠ ∅ then
                start the front's scanning service
    foreach Q_baggage for baggage scanning do
        if the front passenger in Q_baggage has finish its baggage scan service then
            let the front out of Q_baggage;
            if Q_baggage ≠ ∅ then
                start the front's scanning service
    T ← the next Discretization time;
Calculate each passenger's wait time for their baggage
```

4.3 Computer Implementation

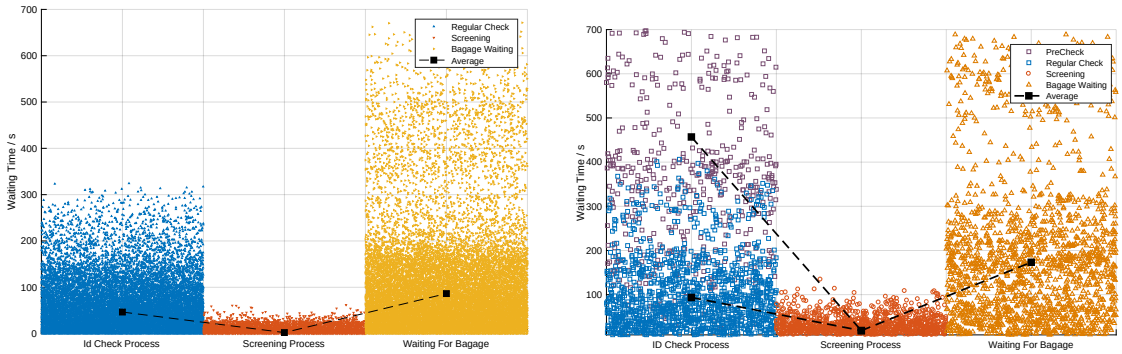

Figure 3: Results Comparison between two matching-finding methods

Figure 4: wait time for Regular and PreCheck passengers

According to the Fig. 4, we can observe visually that for Regular passengers (the image on the left), time spent expectation in baggage waiting is noticeably the most. It indicates that time spent for baggage screening is significantly higher than time for body.

As for PreCheck passengers (the image on the right), the most time spent expectation occurs in the first stage, waiting for ID Check.

Consequently, the bottleneck of Regular passengers occurs at the third stage. However, the bottle neck of PreCheck passengers occurs at the first stage. Besides, the first stage of Regular passengers also has a standtill second only to the bottleneck.

4.4 Improvement

We find that the complexity of our algorithm is $O(\#queues \times iteration\ times)$ with the minimum time unit 0.01s, indicating that we need process $24 \times 3600/0.01 = 8640000$ times iterations, which costs too much time. Thus, we discretize our data, so the iteration times reduce to $O(\#passengers)$. Every step we extract a discretized time with complexity $O(\log \#passengers)$ using the data structure, Priority Queue. As a result, the ultimate complexity of our improved algorithm is $O(\#queues \times \#passengers \times \log \#passengers)$

5 Modifications

In this section, we devise two modifications to the current process of Airport Security, *Layout Modification* and *Queue-select Function Modification*, and model the changes to demonstrate their effect. Fig. 5 shows the contrast of distribution and expectation of wait time among three schemes.

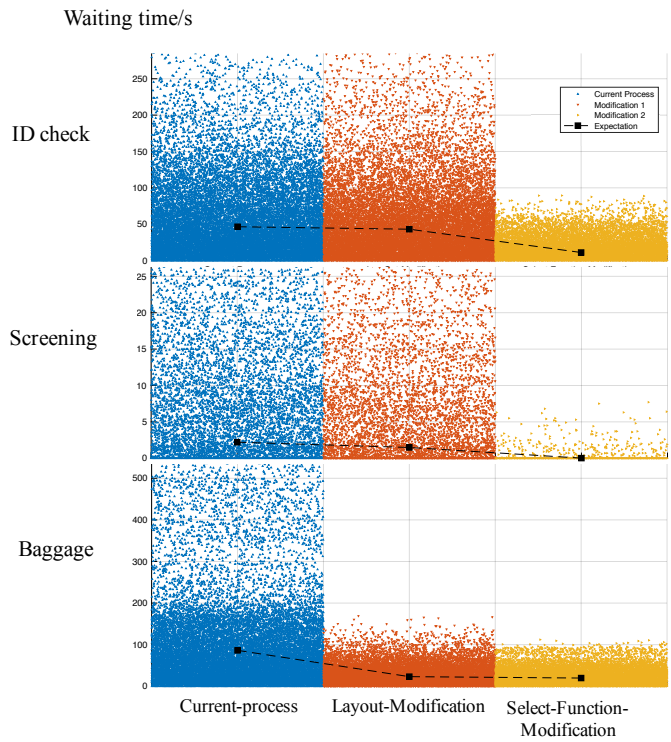

Figure 5: Contrast among current process and revisions

5.1 Modify Layout of Equipment

5.1.1 Revision Plan

In Section 4, we find out that the bottleneck for the Regular passenger is in the third stage where passengers wait for their baggage. For the PreCheck passengers, as is illustrated in Section 4, their bottleneck appears in the first stage, where they enter a queue after arrive.

Thus, we yield our first revision plan to increase the number of X-ray baggage scanners per screening line and increase the number of ID Check stations.

To determine the optimal number of X-ray machines and ID Check stations, we modify the Basic model to simulate the process when the numbers change. We analyze the data produced during the simulation process to obtain the optimal apportion.

5.1.2 Implementation

The main factors affect our optimal decision include both the general time passengers spend and the cost of the airport company to employ the modification.

In order to make our model have greater adaptation for different situations, we set the independent variables as the increase rate the ID Check and the X-ray Machines.

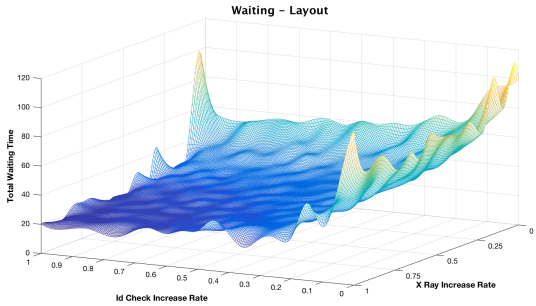

Figure 6: Expectation Distribution of wait time

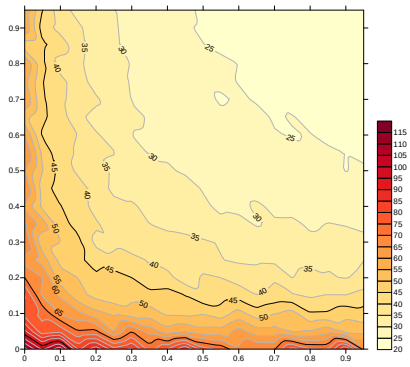

Figure 7: Contour Line Graph of wait time

The time passengers spend on the checkpoints can be calculated out during the programming simulation. We set the average time cost as the dependent variable. The output of the simulation program is a Matrix. The row is the rate of increase of the ID Check stations number and the column is the rate of increase of the X-ray Machines.

The distribution of the expectation of wait time in the flat is shown in Fig. 6

To demonstrate the trend of the expectation of wait time with the rate of increase of ID Check and X-ray Machine, we draw the contour line graph of wait time Fig. 7.

From the picture we can see that the largest wait time appears when $x = 0$ and $y = 0$, i.e. the current process of TSA. With the increase of ID Check stations and X-ray Machines, the wait time decreased observably. When the number increase by 50%, the wait time reduce to less than 30 seconds. The modification is efficient.

5.1.3 The Equilibrium Point Model

Definition 2. *The equilibrium point: The equilibrium point is the point that minimize both the expectation of wait time and the cost of modification.*

From the Distribution graph (Fig. 6) and the Contour Line Graph (Fig. 7), we can find that the equilibrium point must exist around the center area of the xoy flat. Because the wait time will be unsatisfied when x and y are too small and the cost will become unaffordable when they are too large.

To analyze the combined effect, we must figure out and standardize the price of the equipments and labor force.

We obtain the data from webpage of national association of airline passengers, Job informations of TSA, etc.[6] The possible cost in TSA security screening process is listed in Table 6:

According to the different value of x and y, the cost of the equipments and labor force will also vary. After calculation, the function of cost $G(x, y)$ is described as Equation 5.1:

$$G(x, y) = 82427.1x + 36418.0y + 118845.1 \tag{5.1}$$

Table 6: Cost and Service Period of Different Devices

	Metal Detector	Millimeter wave scanner	X-ray machine	Security Officer for ID Check	Security Screener
Price (USD)	7925	119025	40000	36418	32267
Service Period (yrs)	8	10	8	1	1

After standardization, we get Equation 5.2

$$G(x, y) = 0.6936x + 0.3064y + 1 \tag{5.2}$$

As for the wait time, We already have the distribution of expectation of wait time. We use Matlab to operate function fitting, set the fitting model as Equation 5.3:

$$\begin{aligned} f(x, y) =& p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + \\ & p_{02}y^2 + p_{30}x^3 + p_{21}x^2y + p_{12}xy^2 + p_{03}y^3 \end{aligned} \tag{5.3}$$

According to the Fitting Result, we can find that the R-Square value is 0.9525, indicating that the fitting is accurate enough. We substitute the value of variable p_{ij} into the fitting model. After standardization, the wait time can be described as Equation 5.4

$$\begin{aligned} f(x, y) =& 1 - 1.3771x - 2.2685y + 2.2636x^2 - 0.1464xy + \\ & 3.7996y^2 - 1.2113x^3 + 0.0128x^2y + 0.1103xy^2 - 2.0711y^3 \end{aligned} \tag{5.4}$$

Then the combined effect function is as Equation 5.5

$$\begin{aligned} f(x, y) =& -0.6835x - 1.9621y + 2.2636x^2 - 0.1464xy + \\ & 3.7996y^2 - 1.2113x^3 + 0.0128x^2y + 0.1103xy^2 - 2.0711y^3 \end{aligned} \tag{5.5}$$

Using the software Lingo, we operate the Nonlinear Programming to find the equilibrium point. According to the report of Lingo, the result of NLP is the point $(x, y) = (0.1875, 0.3742)$. It means when $x = 0.1875$ and $y = 0.3742$, the combined effect has the greatest value.

Consequently, our Layout Modification should increase the number of ID Check stations by 18.72% and increase the number of X-ray Machines by 37.42% to achieve the largest benefit.

5.2 Modify Queue-select Function

For the discrepancy between passengers and their baggage, different screening lines will spend different time on screening, even if they have the same queue length. Hence it will be a smart choice to select the queue which has the minimum expected wait time, instead of selecting randomly.

But the problem is, how to identify the queue with minimum expected wait time. People may not smart enough, but the computer programs can achieve that.

5.2.1 Revision Plan

We introduce a kind of new equipment to predict expected service time for baggage screening using Radio Frequency Identification (RFID) technology [7].

In the current process, passengers are asked to remove shoes, belts, jackets, metal objects, electronics, and containers with liquids, placing them in a bin to be X-rayed separately. For the discrepancy of inspection complexity between varieties of items, service time is also different. We classify all the items according to required service time, which is determined by collected data in database containing the past records. The airport is supposed to embed different RFID chips in the bottom of bins so that they can be identified automatically through radio frequency signals and access to relevant data by the new equipment without human intervention. It can simultaneously identify a number of bins, the operation is fast and convenient.

In our revision plan, as soon as the passengers arrive at the screening line, they are asked to classify their baggage. Our rule says that items should be put into corresponding bins. The new equipment is placed at the tail of the conveyor belt, serving as a **counter** for the bins to be scanned.

According to the counts of each kind of bins and its service time distribution, it can predict the expected service time and provide guidance for passengers.

5.2.2 Computer Implementation

To quantify the modification, we simulate the predictor and implement it to choose an intelligent strategy.

Fig. 5 present basic results to demonstrate the functionality of our new equipment and select function modification.

5.3 Simple Comparison

As is shown in Fig. 5, we can conclude that both of our revision plan take effect. The Queue-select modification has a better results on decreasing the expectation of wait time. Further evaluations will be discussed in the following section.

6 Models for Evaluation

6.1 Model to Quantify and Unify Convenience of Passengers

By implementing the C++based simulation method of the TSA Security Screening Process to simulate the process with large-scale data of passengers, we can get the spatial position of passengers in the process of security detection, as well as the time spent in each spatial location, resulting in a large amount of detail data. We process these details and summarize the following factors related to passengers convenience: the maximum, minimum, expectation, variance of customs total clearance time, and the maximum, expectation, variance of wait time. Apparently, we want all these factors to be as small as

possible. For example, the smaller expected clearance time shows that the overall speed of customs clearance is faster which facilitates the travel of passengers. Besides, by minimizing the maximum wait time we can ensure that the worst lucky passenger will not get impatient, etc. We extract 100 sets of data for further analysis.

The correlation coefficient matrix (Table 7) is obtained using SPSS.

Table 7: Correlation Matrix

Correlation		**Total Time(s)**				**Wait Time(s)**		
		Max	Min	$\mathbb{E}$	Var	Max	$\mathbb{E}$	Var
Total Time(s)	Max	1.000	.209	.567	.766	.999	.568	.766
	Min	.209	1.000	-.007	-.031	.213	-.005	-.030
	Expectation	.567	-.007	1.000	.919	.566	1.000	.920
	Variance	.766	-.031	.919	1.000	.768	.920	1.000
Wait Time(s)	Max	.999	.213	.566	.768	1.000	.567	.768
	Expectation	.568	-.005	1.000	.920	.567	1.000	.920
	Variance	.766	-.030	.920	1.000	.768	.920	1.000

From the correlation coefficient matrix (Table 7) we can see the there is a very significant relationship between the maximum clearance time and the maximum wait time, with the correlation coefficient reached 0.999. Additionally, there is a significant relationship between the minimum clearance time and maximum wait time, expectation of clearance time and variance of wait time, variance of maximum wait time and wait time. It suggests that there is an overlap of information among these variables.

Table 8: Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of SL[1]		
	Total	% of Var	Cumulative %	Total	% of Var	Cumulative %
1	5.027	71.821	71.821	5.027	71.821	71.821
2	1.208	17.259	89.080	1.208	17.259	89.080
3	.699	9.988	99.068			
4	.064	.914	99.982			
5	.001	.018	100.000			
6	1.095E-5	.000	100.000			
7	9.304E-6	.000	100.000			

[1] Squared Loadings
Extraction Method: Principal Component Analysis.

The principle of extracting the number of principal components is that we extract the first few principal components whose principal components correspond to the eigenvalues greater than 1. Therefore, we use the eigenvalues greater than 1 as the criteria for inclusion. Through the variance decomposition principal component extraction analysis Table 8, we can see that we should extract the two principal components, and divide them into the first principal component and the second principal component (set to M_1 and M_2), according to their eigenvalue.

From the initial load factor matrix (Table 9), it can be seen that the maximum time, expectation, variance and waiting maximum time, expectation and variance of customs clearance have higher load on M_1, indicating that M_1 basically reflects the information of these variables. The minimum clearance time has a high load on M_2, indicating thatM_2 basically reflects the minimum clearance time information. So the distinction between the two components can basically reflect all the indicators of information.

Table 9: Component Matrix

Component	Total Time(s)				Wait Time(s)		
	Max	Min	$\mathbb{E}$	Var	Max	$\mathbb{E}$	Var
1	.844	.071	.913	.982	.845	.913	.982
2	.393	.854	-.261	-.129	.396	-.258	-.129

Calculation of Principal Component Expression We multiply the standardized data by the feature vector, then we get the expression of the two principle components, Equation 6.1 and Equation 6.2.

$$F_1 = 0.376x_1 + 0.032x_2 + 0.407x_3 + 0.438x_4 + 0.377x_5 + 0.407x_6 + 0.438x_7 \tag{6.1}$$

$$F_2 = 0.358x_1 + 0.777x_2 - 0.237x_3 - 0.117x_4 + 0.360x_5 - 0.235x_6 - 0.117x_7 \tag{6.2}$$

Then, we use the eigenvalues of the two principle components divided by the total eigenvalues as the weight to calculate the combined evaluation model with Equation 6.3.

$$F = \frac{k_1}{k_1 + k_2}F_1 + \frac{k_2}{k_1 + k_2}F_2 \tag{6.3}$$

We achieve the combined evaluation model with Equation 6.4.

$$F = 0.364x_{+}0.175x_2 + 0.273x_3 + 0.320x_4 + 0.365x_5 + 0.274x_6 + 0.320x_7 \tag{6.4}$$

We can use this evaluation model to evaluate the current plan of TSA Security Screening Process and our two revision plans. Because the unit of every variable haS been unified to second(s), we don't need to standardize our data when using this evaluation model.

Utilizing the evaluation model above, we calculate the combined index of the three plan as is shown in Table 10.

Table 10: Combined Index

Current Process	Modification 1	Modification 2
600.4537	391.104	166.7357

Then in the last evaluation index, we know that the Queue-select Function Modification can reduce the cost of wait time and maximize convenience. The Layout Modification ranks the second.

6.2 The Cost Model of Airport

In Section 5.1.3, we have figured out the price of different equipments and labor force. According to the information in the webpage of O'Hare Airport[8], and the modified model in our prework, we conclude the number of equipments and officers in Table10.

In the Select Function Modification, the price of RFID tag is very cheap, which can be ignored. We only need to consider the maintenance personnel and the price of the

Table 11: The Number of Equipments

Equipment Kind	Metal Detector	Millimeter wave scanner	X-ray Machine	ID Check Security Officer	Security screener
Current Process	10	10	10	10	20
Modification 1	10	10	14	12	24
Modification 2	10	10	10	10	25

RFID Reader, which is about $1500. To apply this modification, we will install one RFID reader for every checkpoint.

Then the cost of our revision plans is estimated in Table 12.

Table 12: Cost of plans

Current Process	LayOut Modification	Select Function Modification
1188500	1410400	1457600

6.3 The Combined index

We define the Combined Index by Equation 6.5

$$CI = \frac{F \times cost}{standard\ cost} \tag{6.5}$$

So the Combined Index of the three plan is in Table 13

Table 13: Combined Index of plans

Current Process	LayOut Modification	Select Function Modification
600.4537	464.1254	204.4880

From Table 13 we can see that the Combined Index of the Select Function Modification is the lowest. It means that the Select Function Modification can observably reduce the wait time and less sensitive to the increase of cost. Consequently, The Select Function Modification is the most reasonable plan.

7 Sensitivity Analysis

In this section,we perform sensitivity analyses allowing for different behavior patterns adhered to culture discrepancies to demonstrate flexibility. In addition, we tune the two parameters : arrival frequency and service time, to test the robust.

7.1 Influence of Cultures

We figure out the influences reflected on our model, to be preciseïijŇby behavior patterns of people in different culture and analyze the implementation results.

Americans Americans are known for deeply resecting and prioritizing the personal space and privacy. To some extent, the millimeter wave scanner invade the privacy of passengers.[9] The Full-Body Scanner displays nude pictures of the passenger to an employee, thus, some passengers who care about personal privacy, may request to have a pat-down in private.[10] To quantify this influence, we set 5% passengers more willing to accept a pat-down screening. Those passengers will be taken to a separate room, not occupy the screening service time. Instead, they will spend more personal time in checking, and we call the distribution of pat-down time T_2'

Swiss Swiss are known for their emphasis on collective efficiency, they may spend more personal time to make sure the society security, thus, we set a new rule for the situation in Swiss, that passengers are supposed to take both millimeter wave scanning and mental detector inspection.

Chinese Chinese are known for prioritizing individual efficiency. In some special case, they may choose to cut in others line for some moral reasons which are difficult to refuse, such as for the convenience of old people or pregnant women in the family. Thus, in oder to test this situation in our model, we set 5% passengers, who will cut into to a random position of the queue when they arrive a line.

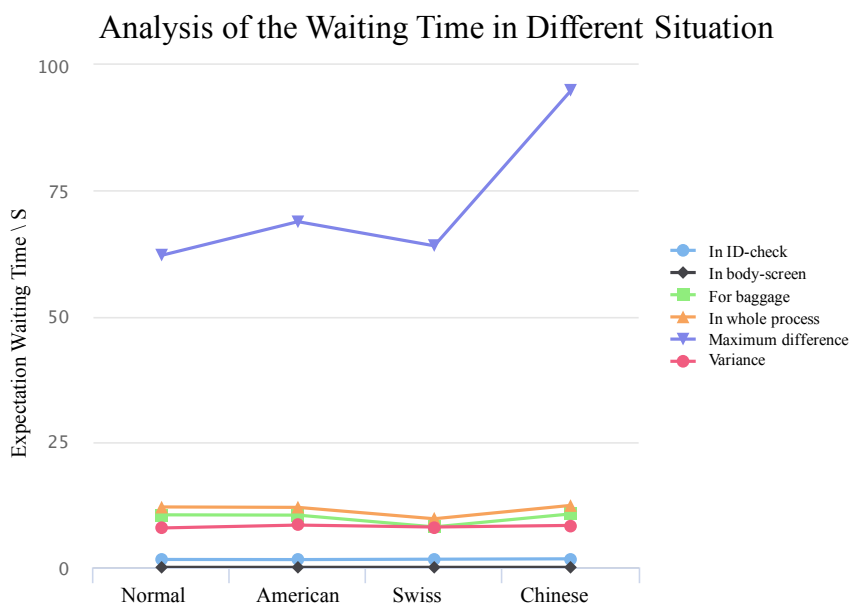

Figure 8: Analysis of the Waiting Time in Different Situation

Analysis As Fig. 8 shows, the wait time in every stage remain fairly consistent, but there still exists some minor changes.

Because Swiss pass both millimeter wave scanner and metal detector, they will spend more time on body screening, which lead to a slight increase on the waiting time for body-screen and a decrease on the waiting time for baggage.

Because some of the Americans will choose pat-down inspection, some passengers can directly pass the screening queue, which decrease the wait time for body screening. Actually, in our model the expectation time for body screening is pretty small, thus, it will not have notable effect, but the time for passing the whole process will be longer.

The behavior 'cut-in' of Chinese will increase the wait time of others and has the possibility to cause dispute. It enlarge the maximum D-value of waiting time. However, it will not affect the average wait time.

7.2 Influence of Arrival Frequency and Service Time

To test the Robustness of our model, we additionally design situations, where passengers arrive at a more quick frequency and go through slower service speed, that is, longer service time. We draw two figures to show system response using proportional control.

As the Fig. 10 shows, when the rate of total service increase (rate of frequency increase $\times$ rate of service time increase) is smaller than 10%, our model shows its stability with a small range of growth. However, when the rate grows beyond 10%, the growth apparently accelerate, indicating that the total service time exceeds the maximum service capacity our system can provide. The 3D image Fig. 9 more accurately reflect this rule.

We make an estimate on the rate of total service increase in reality and find that its range is within 10%, which shows that our model has an stable performance in practical situations. Besides, this sensitivity test also find our worst situation without any additional device and id-check officer.

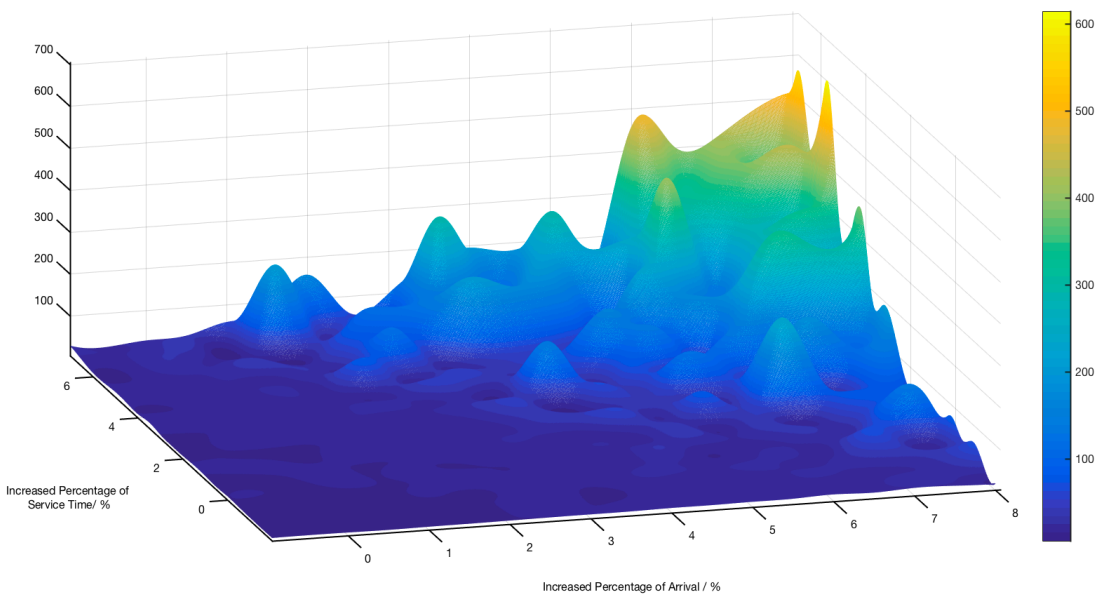

Figure 9: Influence of Arrival Frequency and Service Time

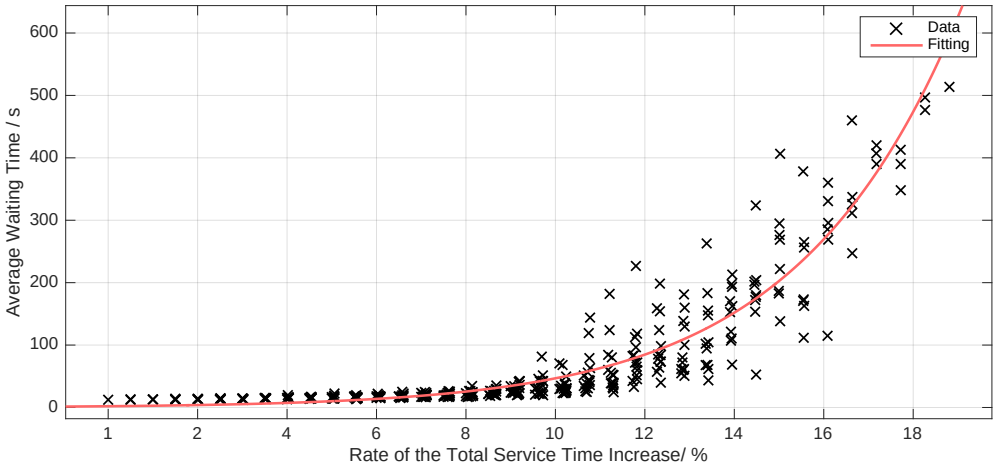

Figure 10: Influence of total service time increase rate

8 Strengths and Weaknesses

8.1 Strengths

- **Generality** : The greatest strength of our model is generality, allowing for a wide range of parameter customization, from objective conditions like equipments layout to the subjective factors like behavior patterns.
- **Practicality**: The model incorporates effect of both given data and additional information, yielding a realistic simulation.
- **Flexibility**: The straightforward implementation of simulations make it flexible to take a variety of tests of parameter sensitivity.
- **Comprehensiveness** The numerical model of evaluation allows for the possibility of expanding the simulations into a multidimensional model, which provided a comprehensive assessment of our modifications.
- **Data extension** By the disposal of data discretization, we enhance the ability of our simulation to proceed large-scale data.

8.2 Weaknesses

- **Limited data**: The scale of given data is not big enough for an accurate distribution estimation. Additionally, some data like average time spent on pat-down is hard to find. There will be some error by assumptions.
- **Unrealistic assumptions**: There are some simplifications and ignorance in order to simplify and generalize our model which we would like to expand upon if given more time and data.

8.3 Future Work

- In the sensitivity test for arrival frequency and service time (Section 7.2), we find a service capacity limited by devices and facilities condition. Our model shows its stability within the capacity but didn't provide solutions for worst situation. We can propose some measures for unpredicted emergency.
- To eliminate the limitation of data, we need the more strong-related and larger scale data to operate further analysis.
- Our model can combine some knowledge of Artificial Intelligence, to precisely predict the flight density and the tidal property of passengers' flow.

9 Proposals and Recommendations

(1) As is shown in Section 4, the bottleneck of PreCheck procedure is in the queue before ID Check. So we recommend that the percentage of PreCheck passengers should reduced to a lower rate, or the PreCheck Passengers should be guided to other CheckPoints when CheckPoints of PreCheck are congested, or the ID Check Entrances for PreCheck Passengers should be employed more.

(2) The bottleneck of Regular passengers is the process of waiting for baggage from the X-ray Machines. So we propose that more X-ray Machines should be employed per screening line.

(3) We propose a procedural addition to introduce a RFID equipment to predict the expected screening time for better strategy to select screening line after ID Check. We ask passengers to classify their baggage with baskets of different size with RFID labels once arriving at the X-ray Machines. Then we can estimate the scanning time by mathematical model precisely and guide the following passengers.

10 Conclusion

We analyze the distribution of the given data and build a Multistage Queue Model. By the simulation program, we find the bottleneck of PreCheck is in the waiting procedure of ID Check. The bottleneck of Regular Passengers appears in the third stage, baggage waiting.

Two models modified. The Layout Modification increases the ID Check by $18.72\%$and increases the X-Ray Machine by 37.42%. For the Function Selecting Modification, the RFID system is employed and we design a Dynamic Estimating Algorithm to implement it.

We construct a evaluation model based on Principle Component Analysis and Factor Analysis. The evaluation result shows that the Function Selecting Modification have the best performance. Finally, by varying behavior patterns of people, arrival frequency and service time. We analyze the culture effects and simulate the corresponding process.In the Sensitivity Analysis, the result shows that our model has an stable performance in most practical situations.

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