For office use only
T1 ________________
T2 ________________
T3 ________________
T4 ________________

Team Control Number
56381

Problem Chosen
D

For office use only
F1 ________________
F2 ________________
F3 ________________
F4 ________________

2017
MCM/ICM
Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)

Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

Since the significant enhanced airport security impacts people' traveling, finding the way to maximize security while minimizing inconvenience to passengers has been a critical issue. Thus based on the given data sets, this paper presents a descriptive queuing network model which elegantly describes the flow of passengers through the security check point. Having considered the difference of Pre-Check and regular passengers, the model introduces Erlang distribution to accurately depict the different number of bins being scanned. After carefully analyzing the data sets, this paper makes effective modifications to optimize the throughput and reduce the waiting time remarkably. A steady and secure system is designed to accommodate the culture differences, making passengers more convenient and safe.

In Task A, this paper developed a queuing network model which describes the flow of the passengers. The model creatively import Erlang Distribution to reflect the situation where one passenger has more than one bins to be scanned, which well demonstrates the difference between Pre-Check and Regular lane because the passengers in Pre-Check do not need to put off wearing and has less bins to be scanned.

In Task B, some modification are implemented such as merging the procedure of Document Check into the procedure of Baggage and Body Screening to decrease the number of queues in system. With parallel processing the two procedures, the throughput and waiting time have been well optimized.

In Task C, we make sensitivity analysis on how the parameters impact the average time each passenger take and the system throughput. Since different parts of the world share different culture, the model will be influenced by modifying the parameters. And sensitivity analysis indicates how important role each parameter plays.

In Task D, comprehensive proposals are presented to improve the throughput while minimizing waiting time, including globally applicable suggestions and tailored for specific cultures suggestions.

The model validation is implemented and the strengths and weaknesses of the model are analyzed to illustrate the model is effective and capable for Problem's demand.

Contents

1 Introduction 3

2 Preliminaries 3

2.1 Queuing Theory and Queuing Network . . . 3

2.1.1 $M/M/1$ Model . . . 3

2.1.2 $M/M/C$ Model . . . 3

2.2 $M/E_k/1$ Model . . . 4

2.3 Jackson Queuing Network . . . 5

2.3.1 Description of the Jackson Network . . . 5

2.3.2 The Open Jackson Network . . . 5

3 Task A 6

3.1 Data Analysis . . . 6

3.1.1 Pre-Processing of the Raw Data Sets . . . 6

3.1.2 Analyze the Arrival and Departure Distribution . . . 6

3.2 Model Developing . . . 7

3.2.1 Assumption . . . 7

3.2.2 Model Establishment . . . 8

3.2.3 Parameter Calculation . . . 8

3.2.4 Model validation . . . 9

3.3 Problem Detection . . . 10

4 Task B 12

4.1 Model Modification . . . 12

4.2 Data Collection . . . 13

4.3 Model Validation and Comparison with Original Model . . . 14

5 Task C 14

5.1 Culture Influences . . . 14

5.2 Sensitivity Analysis . . . 15

5.3 Accommodation Measures . . . 15

6 Task D **16**

6.1 Propose Policy and Procedural Recommendations 16

6.1.1 Globally Applicable Suggestions 16

6.1.2 Tailored for Specific Cultures Suggestions 17

7 Evaluate of the Model **17**

7.1 Strengths 17

7.2 Weaknesses 17

Appendices **18**

Appendix A Program **18**

1 Introduction

Airport security has always been a major issue to both people and airline companies. With the security screen process being increasingly strict, passengers(Pax) are more likely to be stuck at the security screen check point(SSCP), which brings a lot of inconvenience for traveling. Many passengers complain about spending too much time waiting in the queue of inspection, alarming the airline companies to update and modify their security control system. However, it is necessary that when increasing the checkpoint throughput and reduce variance in waiting time, the safety and security should be maintained at the same time. Only analysis and modification of the current security system is under suitable framework or models, can there be satisfying solutions.

Queuing theory is a powerful tool to analyze the process of stochastic service system. Single queuing nodes are usually described using Kendall's notation in the form $A/S/C$ where A describes the time between arrivals to the queue, S the server efficiency in the queue and C the number of the servers. This paper deploys the queuing network to analyze the passengers flow in the SSCP. An elegant model is established in this paper which can accurately describe the behaviour of every node in the system.

2 Preliminaries

2.1 Queuing Theory and Queuing Network

2.1.1 $M/M/1$ Model

The basic queuing model is proposed by Jackson [4] in 1963. $M/M/1$ model queuing model is a queuing model in which the input process obeys Poisson flow and the service time obeys a negative exponential distribution. The average number of customers in a queuing system denoted as $E(N)$ can be calculated using Eq.1.The cycle time $E(T)$ an entity spends in an M/M/1 system can be calculated using Eq.2.

$$E(N) = \frac{\lambda}{\mu - \lambda} \tag{1}$$

$$E(T) = \frac{1}{\mu - \lambda} \tag{2}$$

Where λ is the arrival rate, and μ is the service rate,and $\rho = \lambda/\mu$ is called utilization factor or traffic.

2.1.2 $M/M/C$ Model

$M/M/C$ model is built on the basis of the $M/M/1$ model, in the system there are C parallel servers. Where C is the number of servers in the system, and each server can serve only one customer at a time. When the customer arrives, if there is no available server, the queue will be formed according to Blanchard and Fabrycky [1]. Mark [7] used the $M/M/1$ model and the principle of universal relations to obtain the $M/M/C$ model. The expressions of the parameters in the model are as shown in Eq.3 to Eq.6 .And the P_Q represents the probability that all servers are in a busy state.

$$\rho = \frac{\lambda}{c\mu} \tag{3}$$

$$P_Q = \frac{1}{1 + (1-\rho)(\frac{c!}{(cp)^c}) \sum_{k=0}^{c-1} \frac{(cp)^k}{k!}} \tag{4}$$

$$E(N) = \frac{\rho}{1-\rho} P_Q + c\rho \tag{5}$$

$$E(T) = \frac{P_Q}{c\mu - \lambda} + \frac{1}{\mu} \tag{6}$$

2.2 $M/E_k/1$ Model

Considering the number of bags carried by passengers, every bag receives X-Ray detection service independently, subject to Exponential Distribution. Therefore, the sum of bags of one passenger receiving X-Ray detection service follows the Erlang Distribution. $M/E_k/1$ denotes the Poisson process arriving at the arrival rate λ, the k-order Erlang distribution service time and only 1 server. The service rules are first-come-first-served and service times are independent from customer arrival. Griffiths et al. [3] established the $M/E_k/1$ queuing model, and used the probabilistic function to study the queue and customer waiting time in the model. The expressions are shown in Eq.7 to Eq.10. Where $E(T_q)$ represents the average queuing time of the customer and $E(T)$ represents the average time that the customer stays in the system.

$$\rho = \frac{\lambda}{\mu} \tag{7}$$

$$E(N) = \rho + \frac{(k+1)\rho^2}{2k(1-\rho)} \tag{8}$$

$$E(T_q) = \frac{(k+1)\rho}{2k\mu(1-\rho)} \tag{9}$$

$$E(T) = \frac{(k-1)\rho}{2k(1-\rho)} \tag{10}$$

2.3 Jackson Queuing Network

2.3.1 Description of the Jackson Network

The Jacksonian network is a queuing network in which the balanced distribution is particularly easy to compute because the network has a product form solution. If a queuing network is defined as a Jackson queuing network, then it must satisfy the following conditions:

- All customers outside the system, regardless of which server to visit first, obey the Poisson distribution.
- Regardless of which server, all the service time is subject to exponential distribution.
- All servers can accept an unlimited number of customers.
- When a customer is finished with a service, the probability of moving to another server is independent of the process the customer receives the service, regardless of the server on which the other service is located.

The Jacksonian network diagram can be open or closed. The open Jackson network diagram allows customers outside the system to access the system and customers can leave. The closed Jackson networks do not accept visits from outside customers and no passengers leave the network.

2.3.2 The Open Jackson Network

As shown in Fig.1 is an open Jackson network, it has the following characteristics:

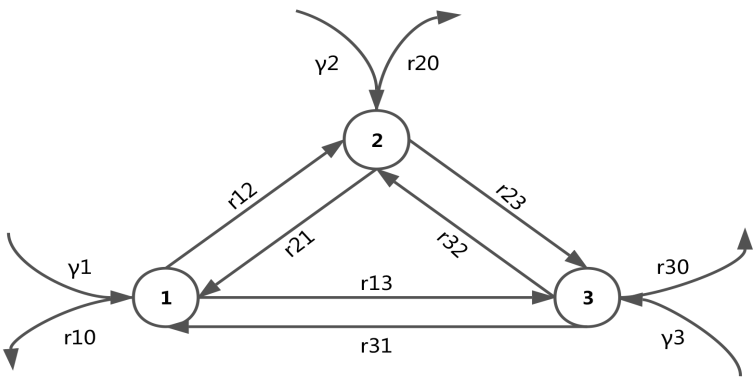

Figure 1: The open Jackson network

- The network has k nodes.
- Each node has c_i servers, and each server's service time average $1/\mu_i$, subject to exponential distribution.

- The customer arrives at node i at γ_i rate
- When the customer completes the service of the node i, enters the node j with probability r_{ij}, leaves the queuing network with probability r_{i0}.
- The capacity of the node queue is infinite.

The arrival rate of the customer is given by Eq.11, and the average number of customers for node i is shown in Eq.12, where $\rho_i = \lambda_i/\mu_i$. The average time that a customer visits an average stay at node i is shown in Eq.13. According to the Little's Law of Little and Graves [6], we can calculate the average time spent on the whole network is shown in Eq.14.

$$\lambda_i = \gamma_i + \sum_{j=1}^{k} \lambda_j r_{ji} \tag{11}$$

$$L_i = \frac{\rho_i}{1-\rho_i} \tag{12}$$

$$W_i = \frac{L_i}{\lambda_i} \tag{13}$$

$$E(T) = \frac{\sum_{i=1}^{k} L_i}{\sum_{i=1}^{k} \gamma_i} \tag{14}$$

3 Task A

3.1 Data Analysis

3.1.1 Pre-Processing of the Raw Data Sets

The column A and B are collections of time stamps as individuals entering the pre-check queue which is random and hard to analyze. The pre-processing to the first two column is to calculate the time interval in each column which will give insight to the probability information about the people's arrival.

The second pre-processing is to neglect the data sets in the column F and G because these data reflect the time stamps as the bags exited the X-Ray screening which is included in the time taking people from arriving at the belt to place items to be scanned, until they retrieved from the post-xray belt. In other words, the data set in column H includes the data set in column F and G.

3.1.2 Analyze the Arrival and Departure Distribution

The processed data sets are analyzed from Exponential distribution hypothesis testing and the results are shown in Fig.2 and Table.1.

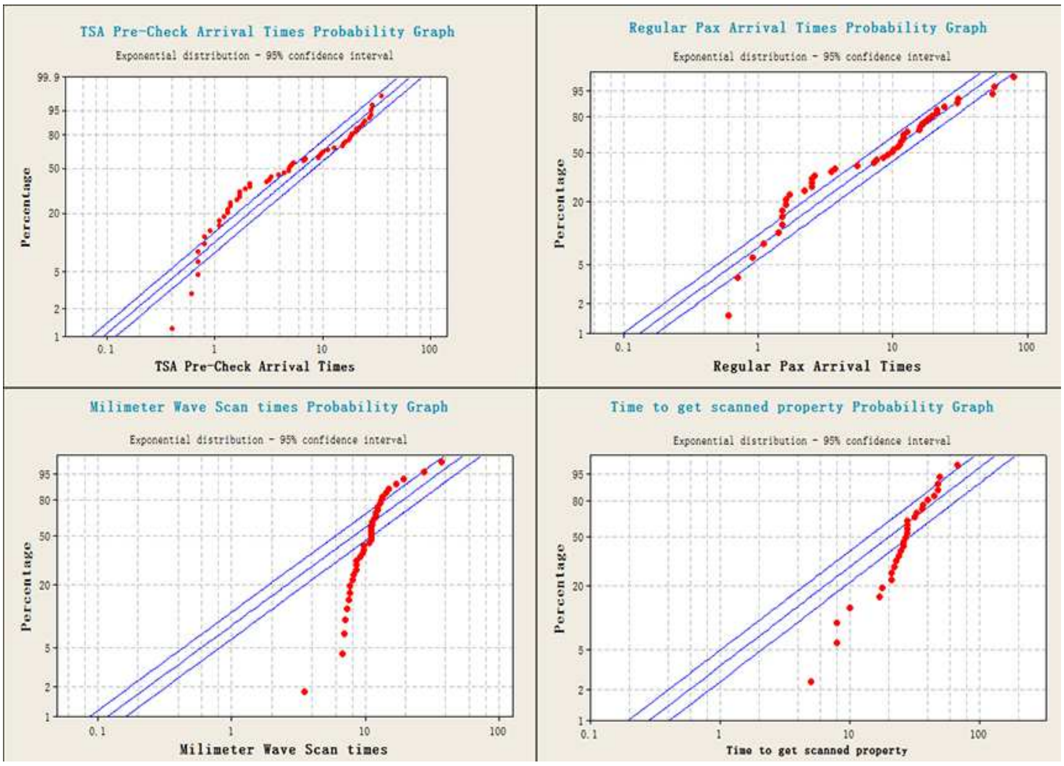

Figure 2: Analyze the individual distribution
Exponential distribution - 95% confidence interval

Table 1: Results of data set under exponential distribution testing

Data	P value	Decision
Pre-Check Arrival Time	0.005	Accept
Regular Arrival Time	0.079	Accept
Millimeter Wave Scan Time	0.003	Accept
Time to get scanned property	0.003	Accept

As shown in Table.1, the arrival of passengers, Milimeter Wave Scan times and Time to get scanned property are accepted to be subject to exponential distribution.

3.2 Model Developing

3.2.1 Assumption

- The number of TSA agent for document check in every lanes is determined by the passengers' arrival rate. There can be more than one TSA agents in one lane.
- Only the time that takes people from arriving at the belt to place items to be s-canned, until they retrieved their items off the post-xray belt will be considered as the service time in the second queue, for it is longer than the time gets pas-senger pass through the millimeter wave scanner and both events are parallel processed.

- All queues and process are modeled as fist-in-fist-out(FIFO) rule.
- Assume the efficiency of TSA officers who do the same job is equal.
- The external factors defined by Wetter et al. [8] are not investigated in the model.
- The number of open lanes are dynamic according to the person arrival rate but the number of Pre-Check and number of regular lanes are always maintain $1:3$ with regards to the Problem Statement.

3.2.2 Model Establishment

Consider there are two kinds of lanes and four regions, a queuing network model consisting of 5 queuing system is established as Fig.3. The average number of passengers and average time per passenger costs in the queue network are defined by Eq.15 and Eq.16 :

$$E(N) = \sum_{i=0}^{2} \frac{\rho_i}{1-\rho_i} P_{Qi} + c_i\rho_i + \sum_{j=0}^{1} \rho_j + \frac{(k_j+1)\rho_j^2}{2k_j(1-\rho_j)} \tag{15}$$

$$E(T) = \frac{E(N)}{\lambda_1 + \lambda_2} \tag{16}$$

where i represents the node in $M/M/C$ queues and j represents the node in $M/E_k/1$ queues.

The $M/E_k/C$ in the model can actually be regarded as C number of parallel $M/E_k/1$ model, for there is always the same number of lanes and X-ray scanners. But the $M/M/C$ queue in the model can not be regarded in the same way, for this paper assume there always have two lanes and each lane may have more than 1 STA agents.

3.2.3 Parameter Calculation

The customer arrival rate of the pre-check channel λ_1 and Regular Pax Arrival Times λ_2 is calculated from the time interval in the column A and B respectively. This

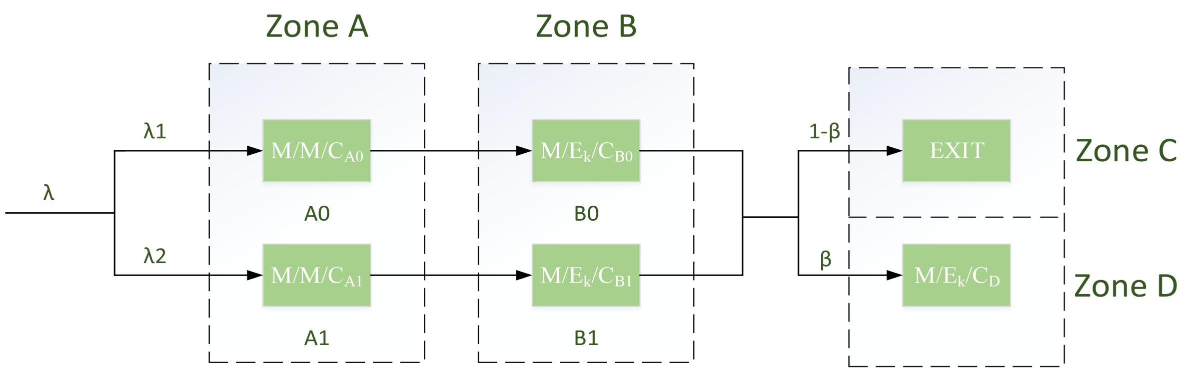

Figure 3: The established model consisting of 5 queuing system

paper takes the document identification time in the Pre-Check channel and regular channel equally denoted as μ_1. Since Millimeter Wave Scan times and X-Ray Scan time traveled less than the time to get scanned property, the average time to get scanned property is calculated and denoted as μ_2.

Dorton [2] presents a discrete distribution about the number of bags each person carried, as shown in Fig.7. The bag number is actually the bin number. Any passengers should put their wearing in a bin and carried electronic devices should be put in another bin. Therefore the Pre-Check passengers usually have less bins being scanned. A passenger will not leave until he/she retrieves all his/her bags(bins) and server time for every bag(bin) follows Exponential distribution, thus the whole time for a passenger in the region B follows the sum of K independent Exponential distribution if he/she has k bags(bins), which is known as Erlang distribution. Hence the server time in second queue follows the k_{th} order Erlang distribution as shown in Fig.3.

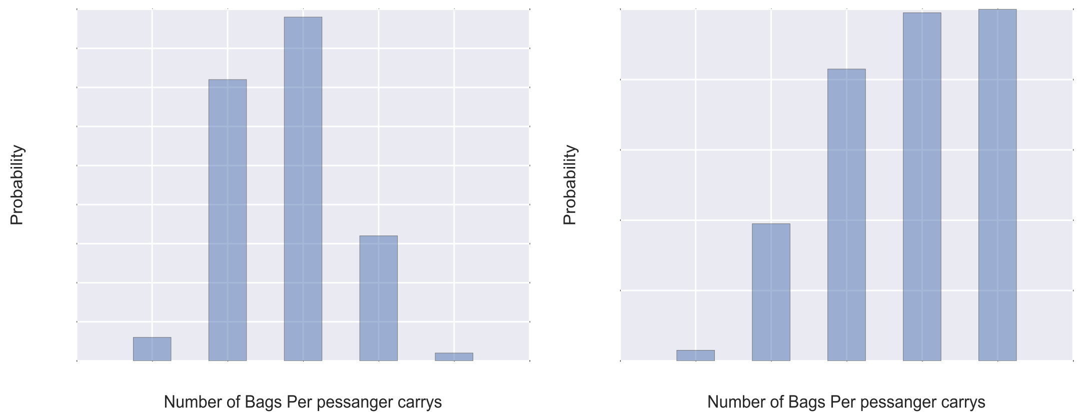

Figure 4: Density probability distribution and Cumulative probability distribution of bag number[2]

Alarm rate for region B process were taken from the data reported by Leone and Liu [5]. The data records over 11.000 bags from different sized airports at peak times. The mean values are shown in Table 2.

Leone and Liu [5] also reported a sample of over 500 manual searches with a uniform time between 120 and 300 seconds per baggage.

The number of numbers of server in the queue system is determined by the stable equation. All results are shown in Table 3.

3.2.4 Model validation

In this section λ_1 and λ_2 will be used to validate the model. In the real world, with the increase of passenger arrival rate, the queue will be busy and everyone spends more time waiting in the queues. Hence if the waiting time output of the model corresponds to this situation, the validity of the model will be proved. Change the arrival

Table 2: Alarm Rate in SSCP operations[5]

Sample	Npax	Mean Time(S)	Percent Passed	Nfailed	Percent Failed
1	1149	6.64	91	109	9
2	1223	7.64	89	158	11
3	1247	6.59	88	165	12
4	1264	6.84	94	80	6
5	976	6.92	95	52	5
6	994	6.42	92	92	8
7	1194	7.87	91	111	9
8	1136	6.83	97	41	3
9	1064	6.69	88	149	12
10	1043	6.71	88	136	12
Total	11290	6.93	91	1093	9

Table 3: The results of parameter calculation

Constant	Mean Value(s)	Parameter calculation(\PAX/min\)
TSA Pre-Check Arrival Times	9.189474	$\lambda_1 = 60/9.189474 = 6.53$
Regular Pax Arrival Times	12.94565	$\lambda_2 = 60/12.94565 = 4.63$
ID Check Process Times	11.21250	$\mu_1 = 60/11.2125 = 5.35$
Time to get scanned property Times	28.62069	$\mu_2 = 60/28.62069 = 2.10$
Mannual baggage search Times	210	$\mu_3 = 60/210 = 0.2857$
Average bag number individual carrays in Regular Queue	2.76	$k_1 = 2.76$
Average bag number individual carrays in Pre-Check Queue	2.26	$k_2 = 2.26$
Alarm Rate	0.09	$\beta = 0.09$
The server number of Pre-Check in region A	2	$C_{A0} = 2$
The server number of Regular in region A	1	$C_{A1} = 1$
The server number of Pre-Check in region B	4	$C_{B0} = 4$
The server number of Regular in region B	12	$C_{B1} = 12$
The server number in region D	4	$C_D = 4$

rate λ_1 and λ_2 from 0 to the value in the Table 3, the average time per passenger costs is shown in Fig.5.

As shown in Fig.5, the model is valid because the average time increases with λ_1 and λ_2, which corresponds to the actual situation.

3.3 Problem Detection

The paper believes there exists two bottlenecks.

- More and more passengers join the Pre-Check programme but there is only one Pre-Check lane open for every three regular lanes. According to the λ_1 in Table 3, in order to meet demands of people who is in Pre-Check, the airport should open 12 regular lanes according to the rule. Assuming the passenger's arrival rate at the regular lane is fixed, when the arrival rate at the Pre-Check lanes increase, the open lanes increases quickly while the passenger throughput increases slowly, as

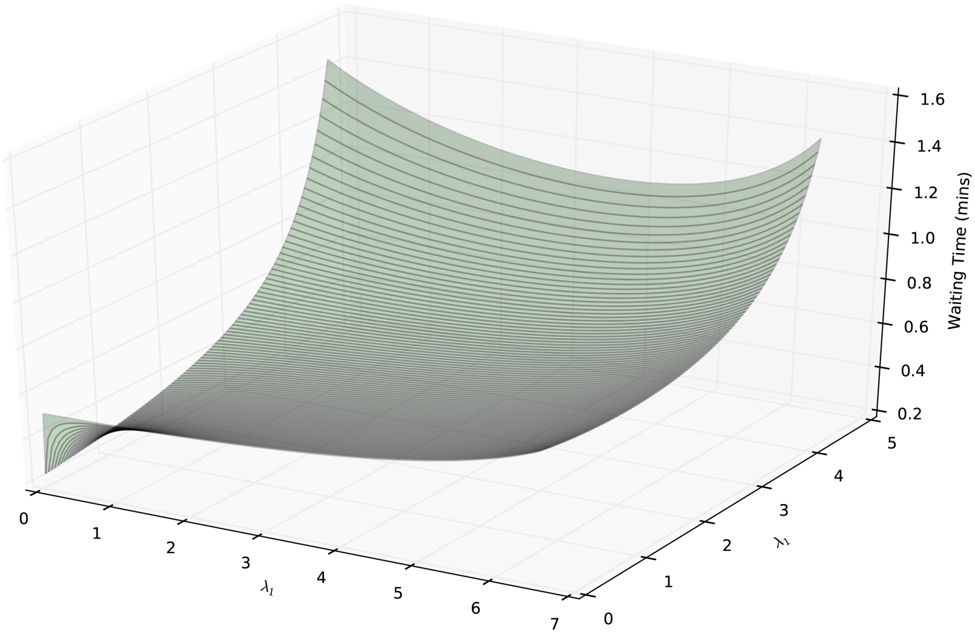

Figure 5: Average time per passengers costs in the queue system while arrival rates change

shown in Fig.6. However, limited to the space of the airport, the number of lanes are finite. If there could open no more than 10 lanes, the capability of servers could not even meet the current demand $\lambda_1 = 6.53$ at all.

- Actually though the Pre-Check programme could decrease the number of bins being screened, the Pre-Check lane could not shorten the waiting time too much. When the number of bins increases, the waiting time increases very lowly even more passengers arrive at the check point, as shown in Fig.7.

In summary, if members in the Pre-Check programme is in a small number, the programme will do a little help for reducing the waiting time. However if the number is large, the limited space can not open so many lanes to meet the Pre-checkers' demand, for the decrease of bins cannot decrease the screen time too much and many regular lanes are wasted.

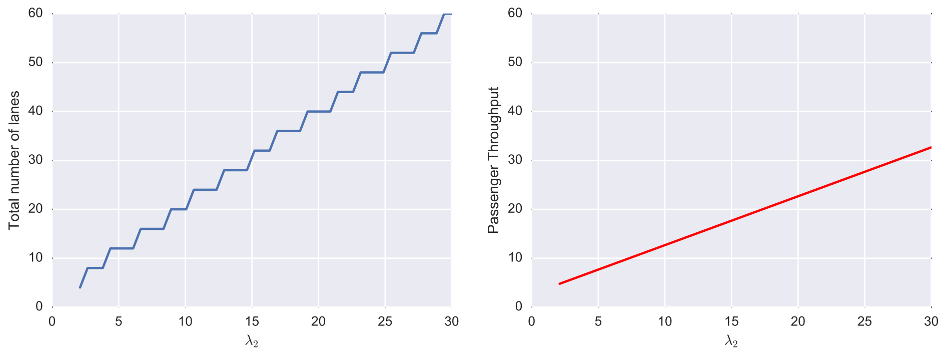

Figure 6: The number of lanes and passenger throughput change with λ_2

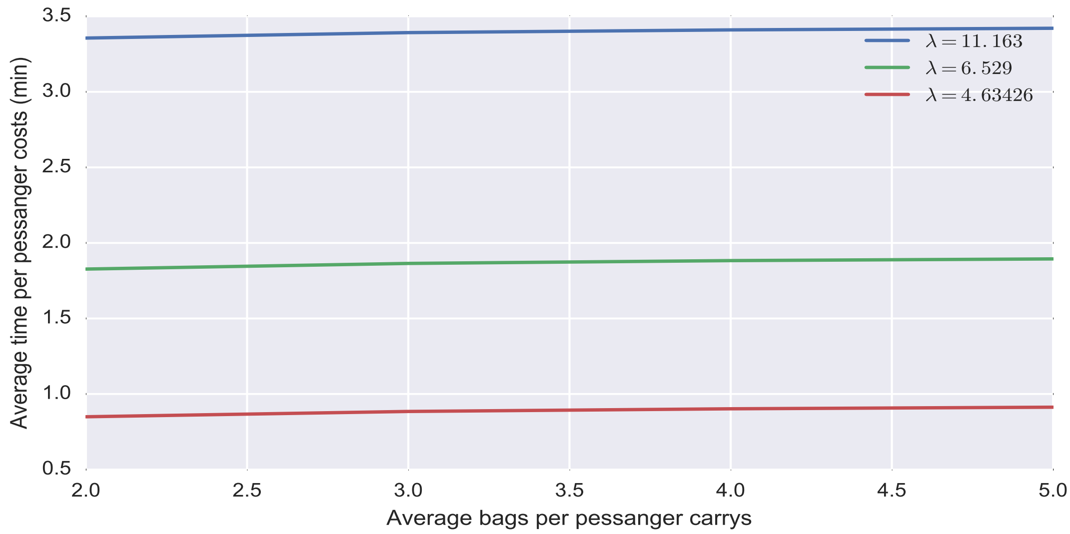

Figure 7: The influence of baggage number on waiting time

4 Task B

4.1 Model Modification

In this section, Some modifications are made to increase the throughput and reduce the waiting time.

- Firstly, the document check will be processed when passengers step into the millimeter wave scanner. In another word, before people step into the scanner, the identification document should be delivered to the TSA officer and be retrieved back when passengers exit the scanner. The process of checking the document is occurred simultaneously when people receive millimeter wave scan. Hence the original Zone A is combined with Zone B, denoted as Zone $A + B$, as shown in Fig.8. The TSA agents check the passenger's identification and boarding documents, while passengers put their luggage on the conveyor belt and step into the millimeter wave scanner. Unless these processes all meet the airport requirements at the same time, passengers can reach Zone C. If passengers are checked for suspicion or his/her luggage alarmed by the X-Ray scanner, passengers are required to go to the Zone D for manual inspection.

- Secondly, the number of Pre-Check lanes no longer depends on regular lanes number. Therefore, the number of servers can be adjusted according to the arrival rate of each kind of passengers. Though the Pre-Check programme does little help for improving the throughput and reducing the waiting time as Section 3.3 states, it can still be retained because it can protect individual's privacy in some way and many people have joined it.

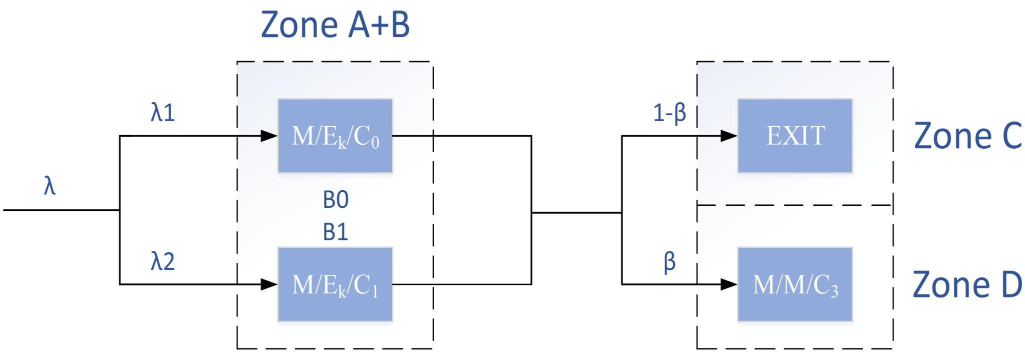

Figure 8: The modified model for SSCP

The average number of passengers and average time per passenger costs in the queue network are defined by Eq.17 and Eq.18 :

$$E(N) = \frac{\rho_D}{1-\rho_D} P_{QD} + c_D \rho_D + \sum_{j=0}^{1} \rho_j + \frac{(k_j+1)\rho_j^2}{2k_j(1-\rho_j)} \tag{17}$$

$$E(T) = \frac{E(N)}{\lambda_1 + \lambda_2} \tag{18}$$

4.2 Data Collection

Because the identification processes are happened simultaneously when people and their baggage are scanned in the Zone $A+B$. Comparing the time interval of document checking and time to put and retrieve bags from belt, the servers' efficiency depends on the latter one since it costs more time than checking the document. Therefore the parameters for the modified model are shown in Table 4.

Table 4: The results of parameter calculation

Constant	Mean Value(s)	Parameter calculation($\backslash PAX/min\backslash$)
TSA Pre-Check Arrival Times	9.189474	$\lambda_1 = 60/9.189474 = 6.53$
Regular Pax Arrival Times	12.94565	$\lambda_2 = 60/12.94565 = 4.63$
Time to get scanned property Times	28.62069	$\mu_2 = 60/28.62069 = 2.10$
Mannual baggage search Times	210	$\mu_3 = 60/210 = 0.2857$
Average bag number individual carrays in Regular Queue	2.76	$k_1 = 2.76$
Average bag number individual carrays in Pre-Check Queue	2.26	$k_2 = 2.26$
Alarm Rate	0.09	$\beta = 0.09$
The server number of Pre-Check in region $A+B$	4	$C_{B0} = 4$
The server number of Regular in region $A+B$	3	$C_{B1} = 3$
The server number in region D	4	$C_D = 4$

4.3 Model Validation and Comparison with Original Model

This section will firstly test the validity of the modified model and then show the improvement when comparing to the model in Task A. The arrival rates λ_1 and λ_2 are ranged to see if the modified model can get correct output and compare the modified model with original model.

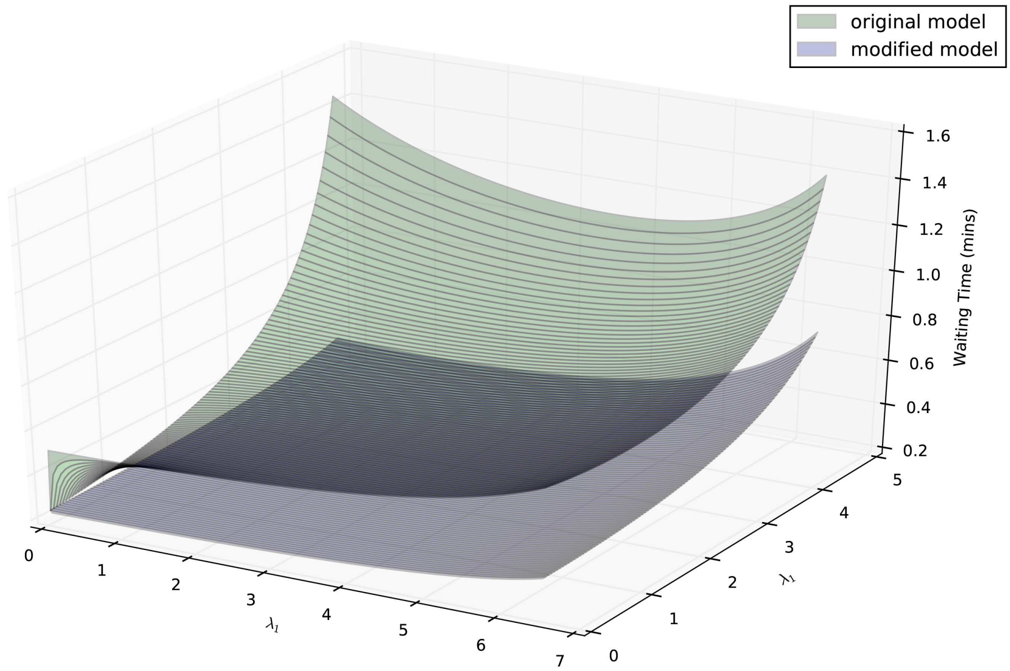

Figure 9: Validity and Improvement of modified model

As shown in Fig.9, the waiting time produced by the modified model increases with λ_1 and λ_2. Comparing with the original model, the waiting time graph in the modified model is under the surface of the original model, which clearly illustrates the improvement of reducing waiting time and passengers throughput.

5 Task C

5.1 Culture Influences

Considering different regions have unique cultures and lifestyles which shape the rules of social interaction, we can't neglect the impact of some factors, for instance travel habits, rhythms of life, education levels, working personnel, levels of technology, terrorism and rebellion, the general state of economy, and the size of population. These all affect the whole airport security control system more or less through impacting the three parameters: μ, β, k.

- μ **:** Whether the equipments are advanced or not directly have an influence on the parameter μ. Developed countries, commanding advanced equipments and technology, generally hold a higher μ than developing countries. The use of state-of-art equipment can not only result in less manual baggage inspections, which, in turn, might be beneficial for throughput, but also speed up the whole process. (Despite the reference consider the enthusiasm of the working personnel as a factor, here we only consider the advanced degree and efficiency of the equipments.)

- β **:** The alarm rate is relative to the frequency of terrorism and rebellion. Countries which have high rate of terrorism and rebellion, such as those in the Middle East, may have a higher alarm rate, because passengers there may have higher risk exposing to prohibited goods such as knives and drugs.

- k **:** The amount of the baggage per person carry is to do with travel habits difference and the percentage of Pre-check passengers. Someone prefer to travels lightly while others tend to be better equipped with abundant supplies. It can be assumed that travel habits difference in productivity are due to travellers carrying more items at certain times, naturally slow down the whole security process. Obviously, the percentage of passengers who choose Pre-check need to remove less items so the k will be lower. This will also speed up the process meanwhile adding throughput.

5.2 Sensitivity Analysis

Fig.10 indicates that when the alarm rate is pretty low, the increase of the alarm rate does little impact to average waiting time in the queue network. However, when the alarm rate reaches a threshold, the average time cost has a steep rise. Hence, it is unsteady for a system which holds a high current density.

On the other hand, the baggage number does not have a significant influence on the average waiting time. When the number of bags increases, the waiting time just has a slight increase, which means the model is not sensible to the baggage number, as shown in Fig10.

5.3 Accommodation Measures

As mentioned above, due to every country's different situation, the three parameters are unstable. The model must be able to accommodate these differences. Whether μ is high or low decides the amount of baggage screening equipments. The airport can improve μ by setting more baggage screening equipments or importing more advanced equipments which have high efficiency. In countries where alarm rate is higher, as discussed in the previous paragraphs, the increase of β will result in much more manual inspections, thus,there parameter C should be adjusted to a proper amount. Last, when it comes to the issue of k, though the increase of k do not have too much influence on the model, many people joined the Pre-Check programs for the convenience and privacy. Hence the Pre-Check lanes should open more than scheduled according to the actual situation. The proposed model have the ability for adjusting the change of these values. In another word, the model can well accommodating the changes.

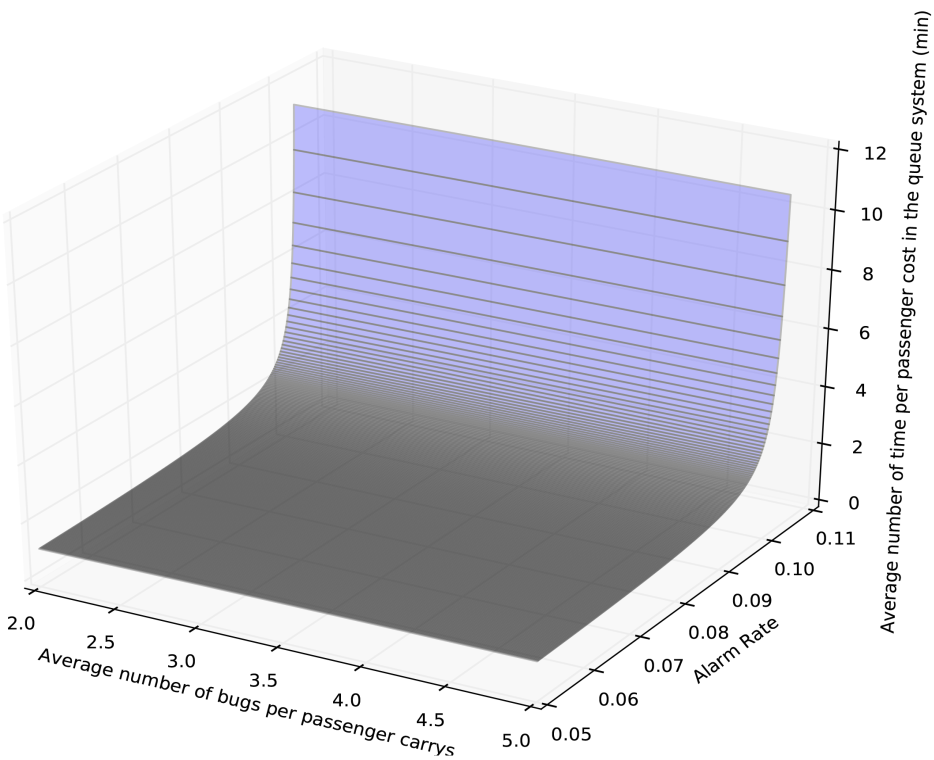

Figure 10: Sensitivity Analysis for Baggage Number and Alarm Rate

6 Task D

6.1 Propose Policy and Procedural Recommendations

We can draw a conclusion that the key to optimize the security control system is to coordinate the relationship between the three parameters and local situations. Generally, when ensuring the security maximizing throughput, the less cost scheme is preferred. So, the most important thing is to get the value of the three parameters, then take measures to change the influencing factors. At the same time, cutting the cost is an important issue.

6.1.1 Globally Applicable Suggestions

- **Merge Zone A and Zone B into Zone A+B.** Since time to get scanned property is always greater than the sum of the Milimeter Wave Scan time and X-Ray Scan Time in Zone B, and Zone A is an individual zone from that, we assume to merge Zone A and Zone B into Zone A+B, making the checking documents step and the scanning step proceed in parallel, to get the process facilitated.

- **Update scanning equipments.** μ should be increased to achieve a higher throughput. An interesting domain is modern technology, e.g dual-view x-ray machines, which could contribute to facilitation. The use of state-of-art equipment can result in less manual baggage inspections, which, in turn, might be beneficial for throughput. If working personnel is strengthened and the modern technology is better adapted, the μ will be much higher and thus optimize the throughput.

6.1.2 Tailored for Specific Cultures Suggestions

- **Arise passengers' consciousness** For those countries which have high rate of violence and terrorism, the government is supposed to burden the responsibility of arising citizens' conscious of observing the rules made by the airline companies to reduce β.
- **Set up policies of Pre-check.** Pre-check do not have a significant effect, for there are too few lanes open for the Pre-Check while too many people have joined the program. Hence there should be some regular to optimize the situation. More lanes should be open if the airport has a high density of Pre-Check passengers.

7 Evaluate of the Model

Model validation has been addressed in Task A and Task B respectively. In this section, the strengths and weaknesses of the model will be analyzed.

7.1 Strengths

- The theory used in the model is very mature and can easily be programmed and calculated.
- The model imports the Erlang distribution to describe the situation where bags being scanned, which makes the model capable for simulating the actual environment.
- The model has an excellent compatibility. One can fix the parameter in the model to accommodate the situation in any airlines. In another word, this model can be applied to different sizes of airports in various parts of the world, despite of culture difference.

7.2 Weaknesses

- The enthusiasm of the working personnel differs in every lane. But this paper does not consider this difference.
- The arrival of the passengers flow is random, thus λ may not always obey exponential distribution. Only at certain times it does.
- According to the Dorton [2], considering the diversity of the passengers' identity, there is inevitably a group of kids or the disabled. However, there is no conclusive evidence as to how small children and the disabled have on the throughput and cycle time. Actually, if the statistics are available,the rate of this group's arrival can be figured and be put into consideration.

References

[1] Benjamin S. Blanchard and W. J. W. Fabrycky. Systems Engineering And Analysis. 76(9):151–183, 1981.

[2] Stephen Louis Dorton. Analysis of Airport Security Screening Checkpoints using Queuing Networks and Discrete Event Simulation: A Theoretical and Empirical Approach. In *Dissertations and Theses*, page 47, 2011.

[3] J. D. Griffiths, G. M. Leonenko, and J. E. Williams. Time-Dependent Analysis of Non-Empty M/Ek/1 Queue. *Quality Technology & Quantitative Management*, (3): 309–320, 2008.

[4] James R Jackson. Jobshop-Like Queueing Systems. *Management Science*, 10(1):131–142, 1963.

[5] Kelly Leone and Rongfang Liu. Improving airport security screening checkpoint operations in the us via paced system design. *Journal of Air Transport Management*, 17(2):62–67, 2011.

[6] John D. C. Little and Stephen C. Graves. *Little's Law*. Springer US, 2008.

[7] L Mark. *Factory physics:Second Edition*. Irwin/McGraw-Hill, 2001.

[8] O. E Wetter, M Lipphardt, and F Hofer. External and internal influences on the security control process at airports. In *IEEE International Carnahan Conference on Security Technology*, pages 301–309, 2010.

Appendices

Appendix A Program

Input Python source:

```
#!/usr/bin/env python2
# -*- coding: utf-8 -*-
"""
Created on Sun Jan 22 11:32:03 2017
"""

from sympy import *
from numpy import *

def  sscp(x0,x1,u0,u1,u2,m0,m1,m2,m3,m4,alra,k):
    x=array([x0,x1])
    u=array([u0,u1,u2])
    m=array([m0,m1,m2,m3,m4])
    i=Symbol('i')
    Pa=x/(m[0:2]*u[0])
```

```
    Pb=x/(m[2:4]*u[1])
    Pd =sum(x)*alra/(m[-1]*u[2])
# x is the vector of average passengers arrival rate
# u is the vector of average server time
# alra represents the alarm rate
# k is the average number of bags per passenger brings
# m is the vector of number of servers
    c0=1/(1+(1-Pa[0])*(factorial(m[0])/(m[0]*Pa[0])**m[0])*\
    (Sum((m[0]*Pa[0])**i/factorial(i),(i,0,m[0]-1)).evalf()))
    c1=1/(1+(1-Pa[1])*(factorial(m[1])/(m[1]*Pa[1])**m[1])*\
    (Sum((m[1]*Pa[1])**i/factorial(i),(i,0,m[1]-1)).evalf()))
    c2=1/(1+(1-Pd)*(factorial(m[-1])/(m[-1]*Pd)**m[-1])*\
    (Sum((m[-1]*Pd)**i/factorial(i),(i,0,m[-1]-1)).evalf()))
    c=array([c0,c1,c2])
# c is the erlang c equation,
# wq is the time of the passengers waiting in the queue
    if m[0]==1:    # if servers of node A is equal to 1, the  m/m/1 adopted
        Wa0=x[0]/(u[0]*(u[0]-Pa[0]))
    else:
        Wa0=c[0]/(m[0]*u[0]-Pa[0])+1/u[0] # else the m/m/c adopted
    if m[1]==1:
        Wa1=x[1]/(u[1]*(u[1]-Pa[1]))
    else:
        Wa1=c[1]/(m[1]*u[1]-Pa[1])+1/u[1]

#    if m[2]==1:
    Wb0=(k-1)*Pb[0]/(2*k*(1-Pb[0]))
#    else:
#        Wb0=wq1+1/u[1]
    Wb1=(k-1)*Pb[1]/(2*k*(1-Pb[1]))
#    Wb1=wq2+1/u[1]

    if m[-1]==1:
        Wd=Pd/(u[-1]-sum(x)*alra)
    else:
        Wd=c[2]/(m[-1]*u[-1]-Pd)+1/u[-1]

# w is the average time of a passenger cost in the sscp process
    if m[0]==1:
        Na0=Pa[0]**2/(1-Pa[0])
    else:
        Na0=(Pa[0]/(1-Pa[0]))*c[0]+3*Pa[0]
    if m[1]==1:
        Na1=Pa[1]**2/(1-Pa[1])
    else :
        Na1=(Pa[1]/(1-Pa[1]))*c[1]+3*Pa[1]

#    if m[2]==1:
    Nb0=Wb0*Pb[0]
#    else:
#        Nb0=x[0]*wq1+x[0]/u[1]

    Nb1=Wb1*Pb[1]

    if m[-1]==1:
        Nd=Pd/(1-Pd)
    else:
        Nd=(Pd/(1-Pd))*c[-1]+3*Pd
```

```
# N is the average number of passenger in the system
    Nt=Na0+Na1+Nb0+Nb1+Nd if Nd>=0 else inf
    Wt=Nt/(x[0]+x[1]) if Nt!=inf else inf
    N=array([Na0,Na1,Nb0,Nb1,Nd,Nt])
    W=array([Wa0,Wa1,Wb0,Wb1,Wd,Wt])
    return Wt

#def sscp_vec():
#Wb1    return vectorize(sscp)
```