For office use only	Team Control Number	For office use only
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T2 ________	Problem Chosen	F2 ________
T3 ________		F3 ________
T4 ________	**D**	F4 ________

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Summary Sheet

Optimizing the Passenger Throughput at an Airport Security Checkpoint

Abstract

In order to optimize the passenger throughput at an airport security checkpoint, the notions of multilayered network and queuing theory is adopt to establish a Multilayered Dynamic Queuing Network Model to simulate the flow of passengers and an Optimization Model is built to select optimum solution.

For task 1, at the beginning, the Multilayered Dynamic Queuing Network Model is constructed to explore the flow of passengers vividly, which contains three layers. Then passengers are divided into pre-check passengers and ordinary persons. Afterwards a complete security route is chose to simplify calculation. After adding average time-delay effects of pre-check passengers to Loosely Coupled Inter-Organizational Work Flows model (LCIOWF) , generalized stochastic Petri net (GSPN) is gained. To achieve the stable situation, Iterative method is proposed to solve Markov chain . Finally, two problem areas of pre-check passengers' routes are identified and three problem areas of ordinary persons' routs are certain.

For task 2, to optimize passenger throughput and reduce variance in wait time, we take measures to improve work efficiency of the five problem areas. Variable-controlling approach is adopted to help analyse the changes. Then an optimization model is built to select optimum solution. The improvement measures for the routs provided for pre-check passengers are increasing efficiency in C Zone by **35.68%** and that in D Zone by **59.92%**. And the improvements for ordinary routs are raising work efficiency in Zone B, C, D respectively by **55.87%, 54.05%, 51.95%**. Throughput of the two kinds of passengers are soaring to **128.76%**, **138.57%**.

For task 3, sensitivity analysis is made by considering a slower traveler, Chinese culture and Swiss culture. For slower traveler, when his sluggish degree is less than 0.04, deviation of T_s is tiny and the maximum deviation is approximate 5%. For Chinese culture and Swiss culture, Arena is used to simulative calculate throughput and variance directly. After simulating, the error of throughput between Chinese culture and Swiss culture is 710.22 and error of variance is 7.875. The large fractional errors is sensitive to culture differences.

For task 4, five suggestions are given for security managers to improve passenger throughput and reduce variance in wait time.

Key words: Multiplex Network; Queuing Theory; Optimization; Markov chain.

Contents

1 Introduction

1.1 Background

The September 11 attacks has become Americans' horrible lingering memory. After that airport security has been significantly enhanced throughout the world. And security checkpoints are set up to screen passengers and their luggage for explosives and other dangerous items.

This measure improves airport security, but with the development of economy and accretion of population, the time passengers spent waiting in the line at a security checkpoint and waiting for their flight is on the increase. As the saying goes, 'Time is money'. Not only is efficiency when checking in significant for passengers, airlines also have a vested interest in maintaining a positive flying experience for passengers. Therefore, it is quite necessary to built a model to maximize security while minimizing inconvenience to passengers.

Meanwhile, high efficiency do not only depend on security officials, but also relies on passengers themselves. Consequently, the model should consider about both airline factor and passenger factor so that we can provide valid suggestions to help security managers to optimize the airport configuration, that is to say, let our travel more convenient and positive.

1.2 Our Work

Initially, we are required to develop a dynamic model with bold assumptions to explore the flow of passengers through a security check point and identify bottlenecks. Referring to bibliography, we first analysis security process and build a multi-layered static network which contains three layers. After thinking about queuing situation, M/G/c/c queueing model is adopted to establish a dynamic queueing network on the basis of the three-layered static network. Then a complete security route is chose to simplify the problem. After wiping off the time-delay effects of each checkpoint, a special Petri net named LCIOWF could be gained. Taken into consideration the difference between the pre-check and the ordinary, bottlenecks and problem areas of the two kinds could be certain.

Secondly, we first reduce the service time in one problem area with fixed time interval while keeping the others to calculate the token value and availability of transition of all nodes. Then to certain the optimum measure, we build a optimization model with three optimizing index which are security, passenger throughput and Variance in wait time. Afterwards, we analyse the optimizing result which is selected from the huge amounts of data calculated in first step to analyse how our modifications impact the process.

Thirdly, sensitivity analysis is made by considering a slower traveler, Chinese culture and Swiss culture. For slower traveler, we analyse the relationship between deviation of throughput and sluggish degree. For Chinese culture and Swiss culture, Arena is used to simulative calculate throughput and variance directly.

Finally, based on our model, some policy and procedural recommendations are proposed for the security managers.

2 Assumptions

The following basic assumptions are made in order to simplify the problems and clear some vague concepts.

- Passengers entering security system only can exit through C zone.
- Passengers prefer checkpoints which is on waiting in line.
- When passenger have chosen a queuing, he will not change to another line.
- Any two passengers are independent with each other.

3 Symbol Description

In this section, we use a list of symbols (cf.table 1) for simplification of expression.

Table 1: Symbol Description

Symbol	Description
θ	passenger throughput
δ^2	Variance in wait time
T_s	average time one passenger spending in wait time
X	total passengers in the security system
P_n	probability of passenger x choosing checkpoint n
λ	checking rate of each checkpoint

P.s: Other symbols' instructions will be given in the text.

4 Multi-layered Dynamic Queuing Network Construction

4.1 Model Preparation: security process analysis

A comprehensive security flow chart describing the current process for a US airport security checkpoint is given by the security manager. It is drawn in Figure 1. It is significant to clear the security procedure before the construction of multi-layered dynamic queuing networks.

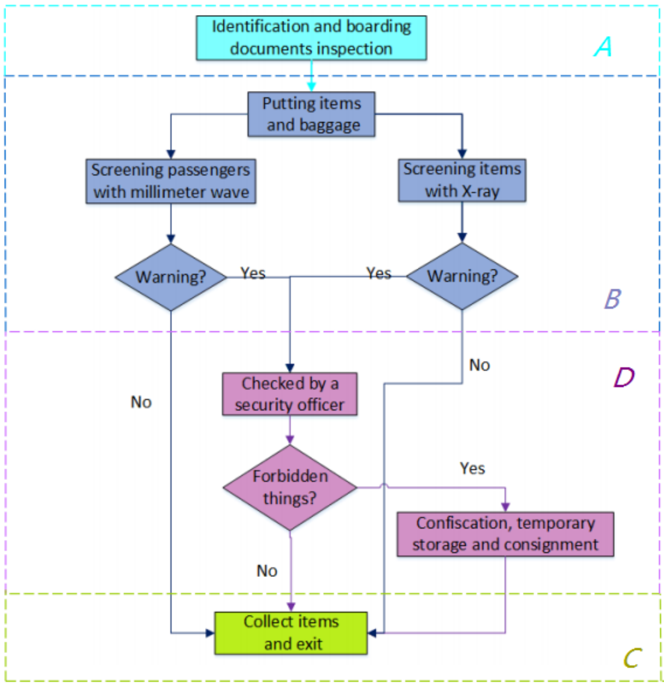

Figure 1: The security procedure.

From Figure 1, all the processes for airport security have been divided into four zones according to their geographic orientation and function.

4.2 Multi-layered Static Network Establishment

The concept of multiplex network[2] is introduced due to the consideration of security segments' properties. Because the time each passenger cost passing each checkpoint is at random, we define discrete time series $(t_{nx}, n \in N)$ to describe time passenger x spent in station n. We also define x_n as the quantity of passengers throughout node n in a period of time.

After digging into the reference and considering reality factors, the multiplex network contains three layers. α layer presents A zone.And γ layer stands for C zone.β layer contains two zone named βb and βd which stands for B zone and D zone respectively. Stations are selected as node and each node within the same layer is not connect to each other except for β layer, in which βb and βd is connecting. And the link between α layer and β layer is the flow of passengers from A zone to B zone. The link between β layer and γ layer is the flow of passengers from A zone to C zone. At the same time, the connection between βb and βd is the flow of passenger between B zone and C zone. The relation between the three layers is shown in Figure 2.

To avoid ambiguity, the detailed explanations about each layer list below.

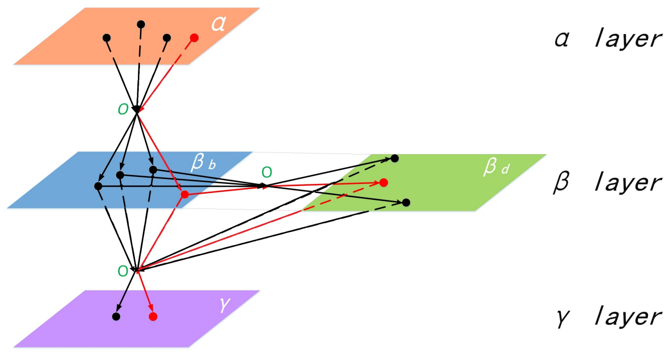

Figure 2: The multiplex network is made up on the basis of the reality security process. Besides, nodes in each layer represent checkpoints. The vector lines are the flow of passengers. Nodes with yellow means Pre-check lane. Red nodes and red lines present the flow of pre-check passengers; black nodes and black lines stand for the routs provided for ordinary persons.

α layer

There are several nodes contained in α layer and each layer stands for a checkpoint set in A zone. The number of passengers in each node presents the length of the queue before each station. Each node connect with the node in βb. What's more, passengers just can flow from α layer to βb.

β layer

β layer contains two parts, namely βb and βd. Individuals in βb zone is waiting for screening by a millimeter wave scanner or metal detector, at same time, their items are screened with X-ray. If they or their belongings are signed, they or their belongings would be send to βd zone to be checked by a security officer. Then passengers going to γ layer.

γ layer

Nodes in γ layer are stations set up for passengers who have been throughout α layer and β layer to pick up their baggages. The number of passengers in each node presents the length of the queue before each station in this zone.

Besides, the quantity of passengers in all of the nodes in the multi-layered network means the total number of individuals stranded in the entire security system. And the number of persons entering the network and the output of the network in a period of time is the throughput of the security system.

4.3 Dynamic Queuing Network Construction

As the flow of passengers have dynamic, blocking and random characteristics when existing queuing situation, analysis of queue can not base on multilayered static network. Considering about blockage effect and randomness and referring to bibliography, $M/G/c/c$ queueing model[3] is adopted. On the basis of the queueing model, a dynamic queueing network in a period of corresponding observation time could be established.

Referring to bibliography, we could obtain P_n which means the probability of passenger x choosing checkpoint n:

$$P_n = \left\{ \frac{[\lambda E[[T_1]^n]}{n! f(n) f(n-1) \dot{f}(1)} \right\} p_0 \tag{1}$$

Where:

$$\begin{cases} f(n) = exp\left[-\left(\frac{n-1}{\beta} \right)^{\gamma} \right] \\ \gamma = \frac{log\left[log\left(\frac{V_a}{V_1} \right) - log\left(\frac{V_b}{V_1} \right) \right]}{log\left(\frac{a-1}{b-1} \right)} \\ \beta = \frac{a-1}{(logV_1 - logV_a)^{\frac{1}{\gamma}}} = \frac{b-1}{(logV_1 - logV_b)^{\frac{1}{\gamma}}} \end{cases} \tag{2}$$

Where λ means arrival rate and it obeys Poisson distribution; $E[T_1]$ is average service time of the whole security system and it is calculated on the basis of the data provided by security manager and time the pre-checked cost is $27.3s$, time the other persons spend is $32.5s$; a and b is arbitrary value used to adjust exponential model and it obeys exponential distribution proposed by Mooly.

To obtain solution of P_n in a steady state, iterative method[5] is employed. After that, queuing situation of each individual in this security system could be acquired. Objective solution is the minimum total time passengers need to spend in wait time, which is named for T. And its calculation formula is listed below:

$$\begin{cases} minT = \sum_{n=1}^{N} \sum_{x=1}^{X} P_n \cdot x \cdot t_{nx} \\ \sum_{i=1}^{n} x_n = X \\ \sum_{i=1}^{n} P_n = 1 \end{cases} \tag{3}$$

Where P_n means the probability of passenger x choosing checkpoint n; x_n stands for the quantity of passengers throughout node n in a period of time.

Based on the equations given above, we could compute the steady solution of this dynamic queuing network. And on the basis of Dynamic Queuing Network, the queuing situation in each checkpoints and the flow of passengers could be obtained.

4.4 Bottlenecks and Problem Areas Identification

Based on the Dynamic Queuing Network, the queuing situation in each checkpoints and the flow of passengers could be obtained, at the same time, a complete security route can be chose to simplify the problem . After quantizing the Dynamic Queuing Network with data provided by security managers, bottlenecks and problem areas are certain.

Before the model quantization, data are preprocessed to to avoid ambiguity.

4.4.1 Data Preprocessing

According to the data provided by security managers, the time that passengers spend in each segments are computed with the following four measures.

Time spent inspecting passengers' identification and boarding documents

The time spent inspecting passengers' identification and boarding documents is donated to t_A. There exists two kinds passengers, which are Pre-Check passengers and ordinary persons and time Pre-Check passengers spent is less than the other. We compute the mean value on the data in the two columns respectively, compare numerical value and define the less value is spent by Pre-Check passengers and the other is cost by ordinary persons. After calculating, the less value is 10.19s and the other is 12.53s.

Time that the passengers and their items processing through B zone

The time that passengers processing through either a millimeter wave scanner or metal detector is donated as t_{Bp}. And t_{Bi} presents time their belongings and items through an X-ray machine, which is also separated as two parts. They satisfy the formula below respectively:

$$t_{Bp} = \frac{TI}{N} \tag{4}$$

Where TI is the sum of the time intervals of two adjacent passengers; N is the quantity of statistical data. t_{Bi} of Pre-Check passengers is calculated below:

$$t_{Bi} = \frac{TI}{N} + 20 \tag{5}$$

The number 20 *refers to bibliography.*

What's more, t_{Bi} of ordinary passengers is calculated below:

$$t_{Bi} = \frac{TI}{N} + 35 \tag{6}$$

The number 35 *refers to bibliography.*

After calculating, t_{Bi} of ordinary passengers is 41.85s and that of Pre-Check passengers is 27.75s.

Time spent in that passengers and items are checked by a security officer

Time spent in that passengers and items are checked by a security officer is presented as t_{Dp} and t_{Di} respectively. t_{Dp} is the difference between the maximum data and minimum data in H column. And referring to reality,$t_{Di} = t_{Dp} + 10$. After calculating, $t_{Dp} = 43.5s$ and $t_{Di} = 53.5s$.

Time spent in the process that persons collect their belongings and depart the checkpoint area

Time spent in this part is named as $t_C 1$. And t_{C1} of Pre-Check passengers is calculated below:

$$t_{C1} = \frac{TI}{N} \cdot 45\% \tag{7}$$

The number 45% *refers to the percentage of Pre-Check passengers.*

Meanwhile, t_{C2} of ordinary passengers is calculated below:

$$t_{C2} = \frac{TI}{N} \cdot 55\% \tag{8}$$

The number 55% *refers to the percentage of ordinary passengers.*

After calculating, t_C of Pre-Check passengers and ordinary passengers are both 11.4s.

Based on the computational method and computing result above, the Dynamic Queuing Network could be quantized.

4.4.2 Point out Bottlenecks and Problem Areas

LCIOWF construction and solution

Because of the mutual equivalence and parallelism among security lanes, a complete security route is chose from the dynamic queuing network to simplify the problem which requires writers to identify where problem areas exist in the current process clearly. After wiping off the time-delay effects of each checkpoint on the security route selected by us, a model of Loosely Coupled Inter-Organizational Work Flows (LCIOWF) could be got, which is a special Petri net[8]. And it could be donated as $LCIOWF = (L, T; F, M_0)$, where L stands for Place namely the queuing before each station, T is Transition which presents inspection procedure for each inspection site, F is the relation between L and T, and M_0 is the initial marking of chart.

Adding the average time-delay effects of each checkpoint to LCIOWF, generalized stochastic Petri net (GSPN) is obtained. And it is shown in Figure 3. Meanwhile, it is donated as $GSPN = (L, T; F, M_0, \lambda)$, where λ is average time of transition namely the checking rate of each checkpoint. λ calculated by following equation:

$$\lambda = \frac{1}{t} \tag{9}$$

Where t is the average time cost in each checkpoint namely work efficiency of each checkpoint.

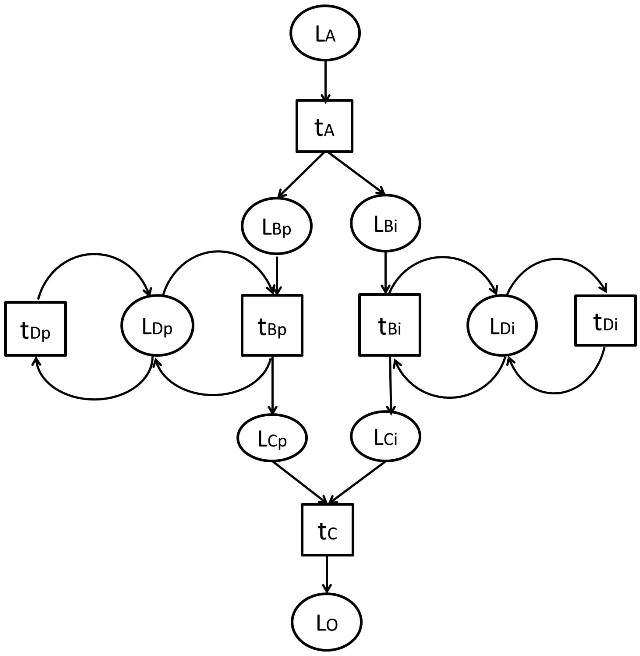

Figure 3: Generalized Stochastic Petri Net.Circles in the figure presents Place namely the queue before each checkpoint. Squares stands for specific security procedures and token means passengers who enter security system.

On the basis of security GSPN model, considering about the connected relation and transition delay-time, reachable marking table of security process could be obtained(cf.Table 2).

From Table 2, reachable marking graph is drawn in Figure 4. At the same time,

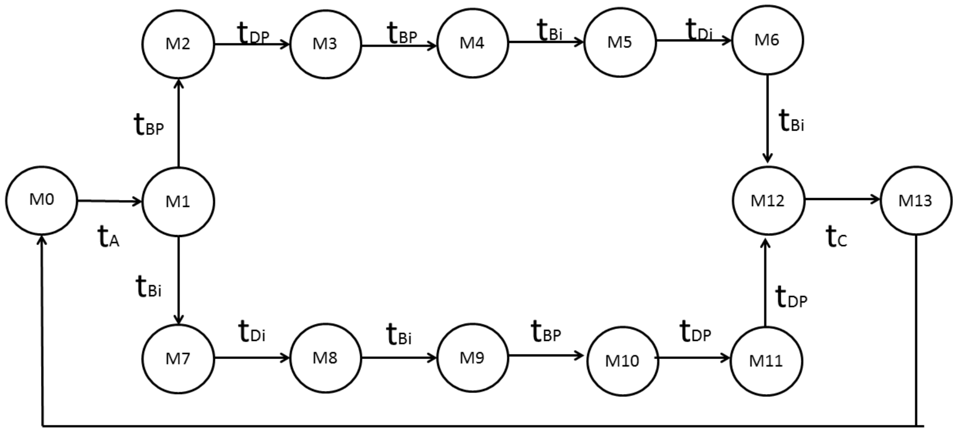

Figure 4: Reachable marking graph of Security Process.

isomorphic Markov chain of reachable marking graph is achieved. Iterative method is adopted to reckon state transition matrix of Markov chain. Then probabilistic equations of stable state of Markov chain are obtained. Due to the difference of costing between Pre-Check passengers and ordinary persons, the probabilistic equations are different. Then probability of occurrence of each state are calculated. What's more, availability of transition and Token value are computed.

Table 2: Reachable Marking Table of Security Process

	L_A	L_{Bp}	L_{Bi}	L_{Dp}	L_{Di}	L_{Cp}	L_{Ci}	L_O
M_0	1	0	0	0	0	0	0	0
M_1	0	0	1	1	0	0	0	0
M_2	0	0	0	1	1	0	0	0
M_3	0	0	0	1	1	0	0	0
M_4	0	0	0	1	0	1	0	0
M_5	0	0	0	0	1	1	0	0
M_6	0	0	0	0	1	1	0	0
M_7	0	0	1	0	1	0	0	0
M_8	0	0	0	0	1	1	0	0
M_9	0	0	1	0	0	0	1	0
M_{10}	0	0	0	0	1	0	1	0
M_{11}	0	0	0	0	1	0	1	0
M_{12}	0	0	0	0	0	1	1	0
M_{13}	0	0	0	0	0	0	0	1

Take into consideration about differences between Pre-Check passengers and ordinary persons, bottlenecks and problem areas may be different for these two populations. Consequently, we analyse the two populations respectively.

Bottlenecks and problem areas for ordinary persons

Based on GSPN established above, token and availability of transition can be computed. And the Equations 17 and 18 to calculate token and availability of transition are listed in Appendix A. The results of availability of transition and token value of normal passengers are shown in Figure 5 and Figure 6.

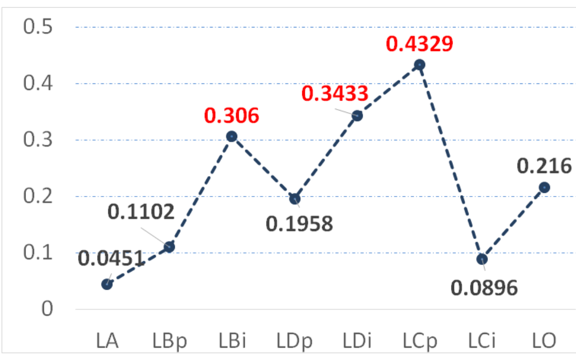

Figure 5: Token value of ordinary persons.

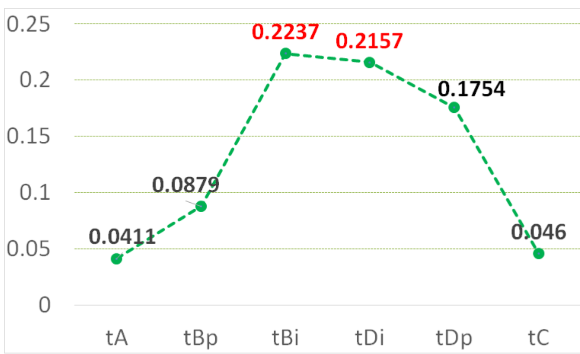

Figure 6: Availability of Transition of ordinary persons.

From Figure 5, the average token value of L_{Bi}, L_{Di} and L_{Cp} is more higher than others, which means there are a great probability of plenty of passengers passing through the three checkpoints. Meanwhile, the possibility of queuing before the three stations is extremely strong. Because of the correspondence between places and checkpoints, we can know **the three problem areas are the station X-ray screening of Zone B, the suspicious items' additional screening of Zone D and where persons collect their belongings in C zone for ordinary persons.** Referring to reality, checked in the three parts occupying too much time brings the great token value.

From Figure 6, the availability of transition of t_{Bi} and t_{Di} is much higher than others, which means the two parts are used frequently in security process. The results are consist with the conclusions got from token value. That is to say, there is a most possibility of that long queuing phenomenon appears before the two stations.

In conclusion, L_{Bi}, L_{Di} and L_{Cp} are three problem areas, where restrict throughput of security system. And L_{Cp} is the checkpoint in which passengers may wait for a long time, that is to say, **where persons collect their belongings in Zone C is the bottlenecks for ordinary persons of the security system.**

Bottlenecks and problem areas for Pre-Check passengers

Based on GSPN established above, token and availability of transition can be computed. And the Equations 19 and 20 to calculate token and availability of transition are listed in Appendix B. The results of availability of transition and token value of normal passengers are shown in Figure 7 and Figure 8.

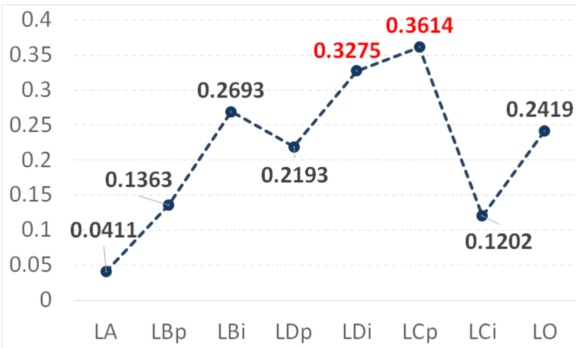

Figure 7: Token value of Pre-Check passengers.

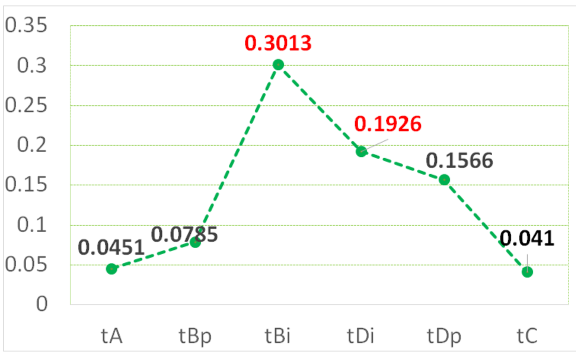

Figure 8: Availability of Transition of Pre-Check passengers.

From Figure 7, the average token value of L_{Di} and L_{Cp} is more higher than others, which means that passengers may queuing for a long time in the two stations. The token values indicate that **the repeat check of suspicious items by security officer in D zone and where persons collect their belongings in Zone C are problem areas**.

From Figure 8, the higher availability of transition is t_{Bi} and t_{Di}. While token value of L_{Bi} is normal. That is because the procedure in L_{Bi} is greatly simplified that Pre-Check passengers are not required to remove shoes, belts, or light jackets. Therefore, L_{Bi} is used frequently but no squeeze.

In conclusion, L_{Di} and L_{Cp} are two problem areas, where restrict throughput of security system. Due to the correspondence between places and checkpoints, we can know **the suspicious items' additional screening of Zone D and where persons collect their belongings in C zone for ordinary persons.** And L_{Cp} is the checkpoint in which passengers may wait for a long time, that is to say, **where persons collect their belongings in Zone C is the bottlenecks for ordinary persons of the security system.**

5 Task Two:Security System Optimization

The problem areas on the routes for ordinary persons and Pre-Checked passengers have been certain in above section. Consequently, potential modifications are provided for the two kinds of passengers respectively. To give optimizing measures, a security system optimization model is proposed.

5.1 Potential Modifications

In order to improve passenger throughput and reduce variance in wait time, we reduce the time consuming in the whole security system by improving efficiency (namely λ) of bottlenecks and problem areas.

In order to model these changes, variable-controlling approach is adopted to analyse how the throughput change when the efficiency of the problem area increases.

For the routes ordinary persons passing through, increasing the work efficiency (λ)of each problem area of the three problem areas with fixed time interval and computing token value and availability of transition of each node. The same measure is used to analysis the changes of routes Pre-checked passengers using. Afterwards, the model to reflect the relation between properties of the security system and the work efficiency of each nodes is gained. And the model is shown below:

$$\lambda \propto \lambda_z, \quad \lambda \propto \theta \tag{10}$$

$$\frac{\Delta\theta}{\Delta\lambda} \propto \frac{1}{\lambda} \tag{11}$$

Where λ_z presents the work efficiency of the whole security system.

When work efficiency of one checkpoint is in a great high level, improving λ makes little contribution to increase the value of θ.

Then, in order to obtain optimum solution, an optimization model is proposed.

5.2 Optimization Model Construction

In order to establish the optimization model, three optimizing indexes (that are security, passenger throughput and Variance in wait time) are took into consideration as below.

Security at airports

It is known to all that security at airports is relevant to the security segments passengers pass through. Therefore, to ensure stable security at airports, we assume that the security procedures individuals participate will never decrease. And the difference between the number of security segments before optimizing and that after optimizing is donated as ΔPR.

Passenger throughput

Passenger throughput is a notion to describe the quantity of persons passing through the security system in a period of time. And it is donated as θ. At the same time, it is equivalent to the average rate security system inspects passengers in a steady situation. The rate is expressed as V_s and it satisfies the equation following:

$$V_s = \frac{X}{T} = \frac{1}{T_s} \tag{12}$$

Where x is the number of passengers entering into the security system in a period of time and T is the time the stable system spent inspecting X persons; T_s presents the time took to check up one person.

From Equation 13, it is obvious that $\theta \propto \frac{1}{T_s}$. On the basis of the multi-layered dynamic queuing network built in Section 4, T could be calculated using following formula:

$$T = \sum_{y=\alpha}^{\gamma} \sum_{n=1}^{N_y} TK_{ny} \cdot X \cdot t_{ny} \qquad (y = \alpha, \beta, \gamma) \tag{13}$$

Where y is the mark of layer of the multi-layered dynamic queuing network; N_y stands for the number of checkpoints in layer y; TK_{ny} presents the token value of node n in layer y when the security system in a stable situation;t_{ny} express the average time passengers in node n spent transforming into another node in another layer.

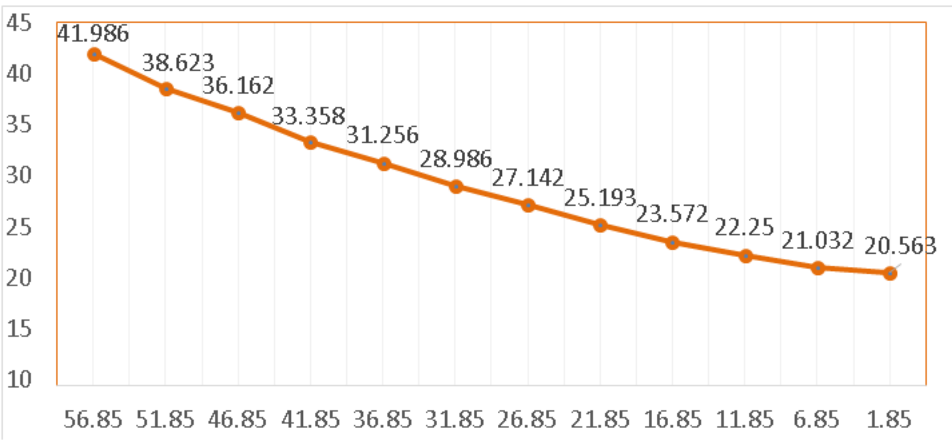

Figure 9: The decrease of T_s with the abatement of t_{Bi}.

In general, to obtain the maximum passenger throughput is equivalent to gain the minimum T_s. However, referring to reality and take into account financial expenses, personal management and site limitation, the improvement of efficiency that system inspect passengers have a threshold. That is to say, the improvement of rate brought by adding security officers, augmenting security equipment and expending area will tend to be a stable value. And when the improvement of the efficiency of a segment reaches the threshold, the impact brought by the segment on raising passenger throughput of whole system is petty. This phenomenon is shown in Figure 9. And it seems as a limitation brought by reality.

Variance in wait time

Analysis of variance in wait time contains two aspects as below.

- Time that different individuals spend passing through the same security route is variable and the difference may cause the variance increase. This index is donated as δ_1^2.

  The higher efficiency the security route have, T_s is less, which means that the queuing time of each individual reduce expect persons who do not need to queue. Consequently, variance in wait time is decreased. Hence, the relation between δ^2 and T_s is gained: $\delta \propto T_s$. And the object function (min δ_1^2) is equivalent to that of passenger throughput.

- Pre-check passengers and ordinary persons are inspected in different route and the time they spend is different. The variance increase caused in this situation is defined as δ_2^2 and it satisfies following formula:

$$\delta_2^2 = \sum_{i=1}^{X}\left(T_{spi} - \frac{\sum_{i=1}^{X} T_{spi} + T_{supi}}{2X}\right)^2 + \sum_{i=1}^{X}\left(T_{supi} - \frac{\sum_{i=1}^{X} T_{spi} + T_{supi}}{2X}\right)^2 \tag{14}$$

  On the basis of the multi-layered static network model, when the net is in a steady situation, the object function (min δ_2^2) is simplified as below:

$$\delta_2^2 = \left(T_{sp} - \frac{T_{sp} + T_{sup}}{2}\right)^2 + \left(T_{sup} - \frac{T_{sp} + T_{sup}}{2}\right)^2 \tag{15}$$

Based on detailed explanations above, two object functions and constraint conditions are abstracted, which is our optimization model and are listed below.

$$\begin{cases} min\delta_2^2 \\ min \sum_{y=\alpha}^{\gamma}\sum_{n=1}^{N_y} TK_{ny} \cdot t_{ny} \qquad (y = \alpha, \beta, \gamma) \\ s.t. \qquad \Delta \geqslant 0 \\ s.t. \qquad \dfrac{\Delta\theta}{\Delta\lambda} \geqslant 0.2 \end{cases}$$

5.3 Results Analysis

Based on the optimization model built in above section, optimum potential modifications are selected from the huge amounts of data calculated in Section 6.1.

The improvement measures for the routs provided for pre-check passengers are listed below:

- Increasing work efficiency in C zone by **35.68%**.
- Raising screening efficiency in D zone by **59.92%**.

The result is throughput improved by **28.76%** and variance reduced by 3.48%.

The improvement measures for the routs provided for ordinary persons are listed below:

- Improving work efficiency in B zone by **55.87%**.
- Increasing work efficiency in C zone by **54.05%**.
- Raising screening efficiency in D zone by **51.95%**.

The result is throughput improved by **38.57%** and variance reduced by 3.48%.

And Figure 10 and Figure 11 shows the token value and availability of transition of the best modification for ordinary security routes respectively.

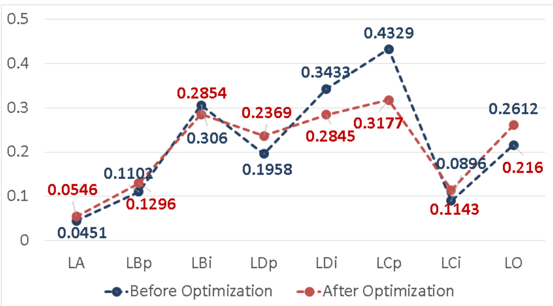

Figure 10: Comparison of token value.

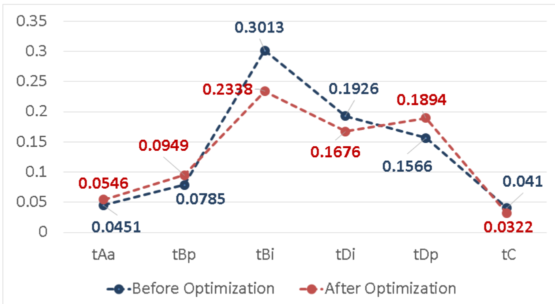

Figure 11: Comparison of availability of transition.

From Figure 10, before optimizing, the token values of the three problem areas, L_{Bi}, L_{Di}, and L_{Cp} are 0.306, 0.3433 and 0.4329. The values are all great high. While after optimizing, the token values drop down to 0.2854, 0.2845 and 0.3177. It shows that the long queues before L_{Bi}, L_{Di}, and L_{Cp} are shorten. From Figure 11, we can know the comparison of availability of t_{Bi} and t_{Di} change from 0.3013, 0.1926 to 0.2338 and 0.1676. Taking into consideration changes of token values and comparison of availability, the plight of the problem areas has been well improved and the bottlenecks are broken up.

The token value and availability of transition of the best modification for pre-checked security routes are drown in Figure 12 and Figure 13 respectively.

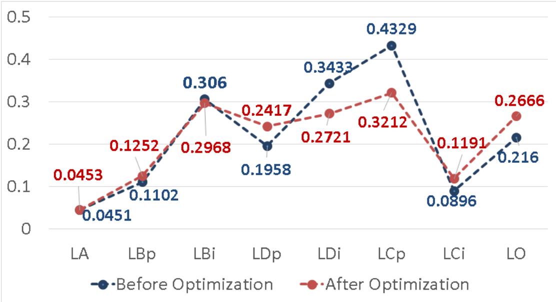

Figure 12: Comparison of token value.

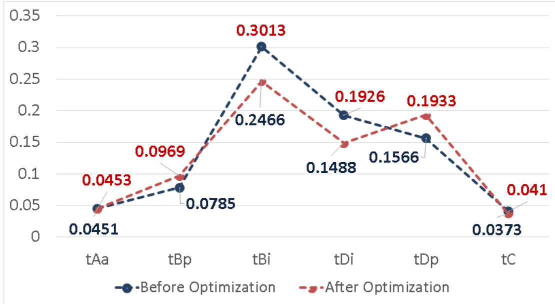

Figure 13: Comparison of availability of transition.

From Figure 12, before optimizing, the token values of the two problem areas, $L_{Di}$and L_{Cp}, are 0.3433, and 0.4329. The values are all great high. While after optimizing, the token values drop down to 0.2721 and 0.3212. It shows that the long queues before L_{Di} and L_{Cp} are shorten. From Figure 13, we can know the comparison of availability of t_{Bi} and t_{Di} change from 0.3013 and 0.1926 to 0.2466 and 0.1488. Taking into consideration changes of token values and comparison of availability, the plight of the problem areas has been well improved and the bottlenecks are broken up.

6 Task Three: Sensitivity Analysis

6.1 Multilayered Dynamic Queuing Network Model Sensitivity Analysis

Task three requires to conduct a sensitivity analysis on the multi-layered dynamic queuing network by considering cultural norms.

Swiss passengers and Chinese travelers are two typical passengers, of which the Swiss are known for their emphasis on collective efficiency, and the Chinese are known for prioritizing individual efficiency. Consequently, user equilibrium (UE) model referring to user optimum is adopted to measure Chinese passengers and system optimum (SO) model referring to overall cost minimization is used to measure Swiss travelers, which are proposed from a game theory based traffic assignment algorithm[4]. What's more, properties included in the multi-layered dynamic queuing network could be computed according to the following four formulas:

$$\begin{cases} p_q = P_r[N = q] \\ \theta = \lambda(1 - p_q) \\ L = E[N] = \sum_{n=1}^{q} n p_n \\ W = E[T] = \dfrac{L}{\theta} \end{cases} \tag{16}$$

Where p_q is the blocking probability; θ presents passenger throughput; L expresses average number of passengers in a security route; W means the mean service time.

Then Arena[6], which is a simulating software, is adopted. Afterwards, a simulation model of multi queue and multi service based on Advanced Process Panel and Common Panel of Arena is built. Add object functions of UE model and SO model to the simulation model, at the same time, the random probability of jumping the queue is assigned to each factors in UE model. After simulating, the stable situation of the dynamic queuing network is calculated and gain passenger throughput and variance in wait time which are both listed in table 4.

Table 3: Output of Simulation

	Passenger Throughput	Variance in wait time
SO	7231.58	28.98
UE	6521.36	36.855

In Table 3, the unit of passenger throughput is ten thousand per year and the unit of variance is s^2. From Table 3, for same security system, difference of throughput between Swiss culture and Chinese culture is great and variance is also significantly different. Therefore, the model is sensitive and unstable to the two culture.

6.2 GSPN Model Sensitivity Analysis

However, the sensitive analysis adopted is on the basis of simulating software which is black box analysis[7] and it is not explicit enough. Consequently, a further analysis on the method computing properties of the dynamic queuing network in a steady situation is made after taking into account the lower traveler.

Because passengers participate in the total security segments, the rate of persons' action has a direct influence on the security efficiency. For passenger throughput and variance in wait time of the whole security network, a slower traveler will raise the service time, that is to say, they may cause other passengers to wait for a longer time and reduce the efficiency of the whole system. For the purpose of concise writing, we make an assumption that the slower traveler is an ordinary passenger who is not pre-checked and select the segment they collect their belongs in C zone to describe in detail, note that choosing which segments does not impact the result.

Assuming that the sluggish degree of a slower person is D, which means the time he need to finish a behaviour is (1+D) times that of normal individuals. Consequently, the time for him to collect belongs in C zone is $(1 + D)t_{Cp}$. The model established in task two modeling how our modifications impact the process is used to compute the time for security system to inspect the slower person with various D, namely T_s, which is inversely with passenger throughput. The time with various D is shown in Figure 14.

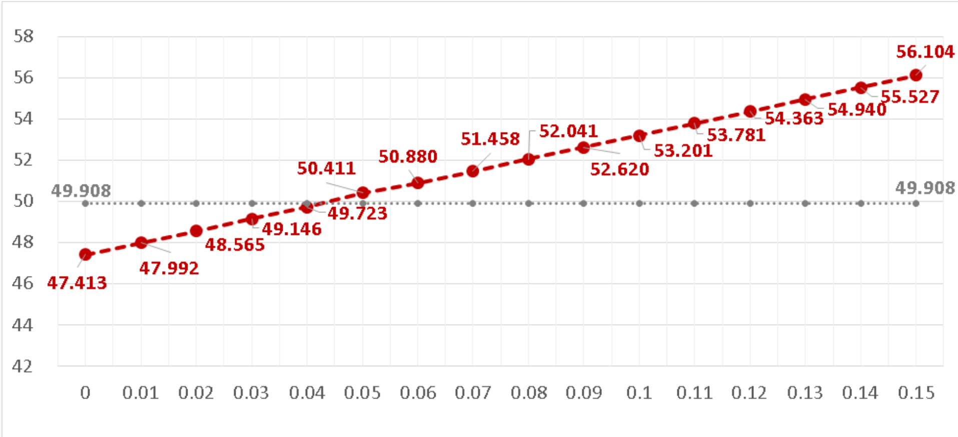

Figure 14: The variable T_s with the increase of D. The red nodes is the value of T_s and the grey horizontal is a boundary under which the difference between current T_s and initial value (that is 47.413) is less than 5%.

From Figure 14, T_s is increasing with the increase of D, which result is consist with reality. Because of the relation: $\theta \propto \frac{1}{T_s}$, when $D < 0.04$, deviation of θ is tiny and the maximum deviation is approximate 5%, that is to say, our model is low sensitive and

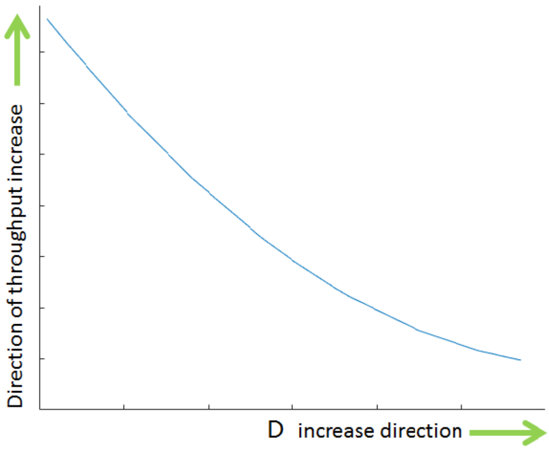

Figure 15: Tendency of throughput.

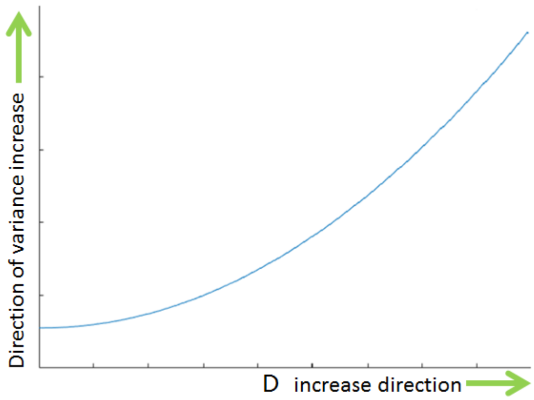

Figure 16: Tendency of variance.

stable enough in this situation. When $D > 0.04$, deviation of θ increases shapely with the raising of D. The result indicates that our model is sensitive sharply at this time, which leads to the result of our model is unstable. Then the optimization model built in task two is used to select the best result as the changes the security system need to make. According to the discussion in above section, we can know that, with the increase of D, the value of variance in wait time becomes more and more great and throughput is decreasing. And the changing rate of the two factors are raising with the increase of the value of D. The phenomenon is drawn in Figure 15 and Figure 16.

7 Task Four: Policy and Recommendations for Security Managers

Based on the conclusion of our model built above, some suggestions are given below.

Initially, for an airport security system, it is extremely convenient to adopt the he multilayered dynamic queuing network model and the consistent analysis proposed in task one to identify bottlenecks and problem areas. And it is a great solution that just taking a reasonable optimization on the problem areas and the bottlenecks of the airport security inspection system to the problem that passengersąŕ queuing time is too long.

Secondly, according to the analysis and compare on the pre-check passengers and ordinary persons in task two, we can know that time pre-check travelers consuming in waiting to screen belongings in B zone is much less than that of ordinary persons. Consequently, it is necessary for TSA to promote pre-check service vigorously.

Thirdly, based on the conclusion obtained in task two, we know that to improving the efficiency of any segment will indirectly improve the efficiency of the entire security system, thereby reducing waiting time. Therefore, taking into account stable security, passenger throughput and variance in wait time, our optimization model will give the optimal scheme. Then the area need to enhance work efficiency and the degree need to improve could be gained.

Finally, the discussion about culture of the Chinese and the Swiss, passenger throughput of Chinese habit is less than that of Swiss while variance in wait time for Chinese is much more that that for the Swiss. Hence, airport need to forbid jump the queue.

8 Model Improvement

On the one hand, considering in real life, passengers may choose a closer pass with a queue instead of a farther idle passageway because of different distance from the security lines to them. So to improve the model 's accuracy, we can add geographical coordinates of security lines and passengers entering the airport to the original model. And we add these two new messages to the original function of security line order selection as part of judging conditions.

On the other hand, we think about the connection among passengers. Passengers' choice is not only determined by environmental factors, but also impacted by their companies.

9 Strengths and Weaknesses

9.1 Strengths

- Our multilayered dynamic queuing model is constructed on the basis on the really security system at airport. Therefore, the model can describe the flow of passengers intuitively.
- Our models have been considered in two cases,

9.2 Weaknesses

- Calculating the stable solutions of the multilayered dynamic queuing network needs huge data.
- To reach steady situation, iterative method is used while this method may consume too much time.

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10 Appendix A

The formulas to calculate token and availability of transition.

$$
\begin{cases}
4.7885M_{p0} = M_{p13} \\
6.9383M_{p1} = 4.7885M_{p0} \\
1.3793M_{p2} = 5.5046M_{p1} \\
5.5046M_{p3} = 1.3793M_{p2} \\
1.4337M_{p4} = 5.5046M_{p3} \\
1.1215M_{p5} = 1.4337M_{p4} \\
1.4337M_{p6} = 1.1215M_{p5} \\
1.1215M_{p7} = 1.4337M_{p1} \\
1.4337M_{p8} = 1.1215M_{p7} \\
5.5046M_{p9} = 1.4337M_{p8} \\
1.3793M_{p10} = 5.5046M_{p9} \\
5.5046M_{p11} = 1.3793M_{p10} \\
5.2632M_{p12} = 1.4337M_{p6} + 5.5046M_{p11} \\
\sum_{i=0}^{13} = 1
\end{cases}
\tag{17}
$$

$$
\begin{cases}
L_A = M_{p0} \\
L_{Bp} = M_{p1} + M_{p7} + M_{p8} + M_{p9} \\
L_{Bi} = M_{p1} + M_{p2} + M_{p3} + M_{p4} \\
L_{Dp} = M_{p2} + M_{p3} + M_{p10} + M_{p11} \\
L_{Di} = M_{p5} + M_{p6} + M_{p7} + M_{p8} \\
L_{Cp} = M_{p4} + M_{p5} + M_{p6} + M_{p12} \\
L_{Ci} = M_{p9} + M_{p10} + M_{p11} + M_{p12} \\
L_O = M_{p13} \\
t_A = M_{p0} \\
t_{Bp} = M_{p1} + M_{p3} + M_{p9} + M_{p11} \\
t_{Bi} = M_{p1} + M_{p4} + M_{p6} + M_{p8} \\
t_{Dp} = M_{p2} + M_{p10} \\
t_{Di} = M_{p5} + M_{p7} \\
t_{Cp} = M_{p12} \\
t_{Ci} = M_{p12}
\end{cases}
\tag{18}
$$

A Appendix B

The formulas to calculate token and availability of transition.

$$\begin{cases} 5.8881M_{p0} = M_{p13} \\ 7.6668M_{p1} = 5.8881M_{p0} \\ 1.3793M_{p2} = 5.5046M_{p1} \\ 5.5046M_{p3} = 1.3793M_{p2} \\ 2.1622M_{p4} = 5.5046M_{p3} \\ 1.1215M_{p5} = 2.1662M_{p4} \\ 2.1662M_{p6} = 1.1215M_{p5} \\ 1.1215M_{p7} = 2.1662M_{p1} \\ 2.1662M_{p8} = 1.1215M_{p7} \\ 5.5046M_{p9} = 2.1662M_{p8} \\ 1.3793M_{p10} = 5.5046M_{p9} \\ 5.5046M_{p11} = 1.3793M_{p10} \\ 5.2632M_{p12} = 2.1662M_{p6} + 5.5046M_{p11} \\ \sum_{i=0}^{13} = 1 \end{cases} \tag{19}$$

$$\begin{cases} L_A = M_{p0} \\ L_{Bp} = M_{p1} + M_{p7} + M_{p8} + M_{p9} \\ L_{Bi} = M_{p1} + M_{p2} + M_{p3} + M_{p4} \\ L_{Dp} = M_{p2} + M_{p3} + M_{p10} + M_{p11} \\ L_{Di} = M_{p5} + M_{p6} + M_{p7} + M_{p8} \\ L_{Cp} = M_{p4} + M_{p5} + M_{p6} + M_{p12} \\ L_{Ci} = M_{p9} + M_{p10} + M_{p11} + M_{p12} \\ L_O = M_{p13} \\ t_A = M_{p0} \\ t_{Bp} = M_{p1} + M_{p3} + M_{p9} + M_{p11} \\ t_{Bi} = M_{p1} + M_{p4} + M_{p6} + M_{p8} \\ t_{Dp} = M_{p2} + M_{p10} \\ t_{Di} = M_{p5} + M_{p7} \\ t_{Cp} = M_{p12} \\ t_{Ci} = M_{p12} \end{cases} \tag{20}$$