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# Methodologies For The Analysis Of Checked Baggage Inspection Systems

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# METHODOLOGIES FOR THE ANALYSIS OF CHECKED BAGGAGE INSPECTION SYSTEMS

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by

Nela Blejcharova

2012

## **Dedication**

To my family, especially to my grandmother Věra who encouraged me to study in U.S.A. and passed away in November, 2011 when I was here.

METHODOLOGIES FOR THE ANALYSIS OF CHECKED BAGGAGE INSPECTION  
SYSTEMS

by

NELA BLEJCHAROVA, Bc.

THESIS

Presented to the Faculty of the Graduate School of  
The University of Texas at El Paso  
in Partial Fulfillment  
of the Requirements  
for the Degree of

MASTER OF SCIENCE

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## **Declaration**

This thesis is an output of the Transatlantic Dual Masters Degree Program in Transportation Science and Logistics Systems, a joint project between Czech Technical University, Czech Republic, The University of Texas at El Paso, USA and University of Zilina, Slovak Republic.

This thesis is jointly supervised by the following faculty members:

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## Abstract

To enhance the security of the aviation system it is necessary to have a Checked Baggage Inspection System (CBIS) that is effective (that is, the highest possible detection probability or minimum false clear probability) yet efficient (that is, minimize the false alarm probability that causes inconvenience to passengers).

The first objective of this thesis is to review passenger, carry-on and checked baggage inspection procedures at airports

The second objective of this thesis is to develop a methodology using the optimization approach to set the optimal values of the sensitivity of the screening devices to minimize the total cost of inspecting each baggage. The methodology is developed for the two-device screening system. The sensitivity threshold is given by the value of  $\mu_1$  and  $\mu_2$ , for the primary and secondary screening machine, respectively. The output signal of each screening device is modeled by the Beta distribution. The outputs are compared to  $\mu_1$  and  $\mu_2$  to obtain the system's response (clear or alarm). The total cost considered is the expected costs of wrong inspection decisions for each baggage: false clear and false alarm. In this research four different screening technologies are compared. Each technology differs in the baggage screening throughput and the accuracy of the screening process.

Another important aspect which has to be considered for an efficient baggage screening system is the system capacity. A badly designed CBIS can cause delays in baggage screening which could in worst case lead to the delay of the aircraft departure or in need of using another flight to deliver the baggage to the requested destination. The third objective of this thesis is to calculate of the average waiting times, average queue length and number of devices needed for the baggage screening using the  $M/G/m$  queuing model. The probabilities



obtained in the precedent work are used for the calculation of the number of baggage sent to the secondary screening. First the equations of the  $M/G/m$  queuing model are described. Then two different examples are created to help to illustrate the calculations.

The queuing theory does not allow an analyst to consider higher arrival rate than the system can handle even for a short duration. The arrival rate at the airport varies according to the number of departing flights. The number of baggage that has to be screened sometimes exceeds the capacity of the system which can create a queue. This queue may not last long but can occasionally cause significant delay. This scenario can be analyzed by simulation. The fourth objective of this thesis is to evaluate how well the VISSIM microscopic traffic simulation software may be used to model CBISs. The arrangement of four screening devices in primary screening and two devices in secondary screening is modeled using the VISSIM software. The output data were compared with the results from queuing theory: the number of bags, the delay of bags, the queue length, and travel times.

**Key words:** aviation, security, checked baggage inspection system , queuing theory, false clear, false alarm

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# **Chapter 1: Introduction**

## **1.1 Background**

Since the International Civil Aviation Organization's Chicago Convention in 1944 (ICAO) the security and safety requirements of air transportation have changed. Demands on safety and reliability are constantly increasing. Nowadays air transport is a part of life of many people and economy and therefore, aircrafts have become the targets of terrorist attacks. Both airports and airlines are trying to prevent unlawful interference by using modern technologies as their budget allows. To be able to provide a certain level of safety, an efficient system of security controls is needed. The turning point of aviation security was the terrorist attack on 11th September 2001. On that day, nearly 3,000 people from 90 countries lost their lives due to the tragic events. After this incident strict measures were implemented for the security system. Some of them were, of course, related to security controls at the airports. Each passenger has to provide not only his carry-on baggage for inspection but also for example his/her shoes if asked for. Also the list of prohibited items for both carry-on and checked baggage has been extended. For example one cannot take on board liquids with a volume over 100 ml except those purchased in duty free shops at the airport.

Due to the new security requirements there is a need not only to develop new screening technologies but also to search for the most efficient way to implement these new devices. Several approaches have been proposed to find the most cost effective solution with a given limited budget (Jacobson et al, 2006; Jacobson et al, 2003; Feng, 2007; Feng et al, 2009; and Feng, Q., Sahin H. and Kapur K. C., 2009). But none of them combines the optimization and the queuing theory to optimize the design and operation of Checked Baggage Inspection Systems (CBISs).

Checked baggage inspection systems can be divided into two main categories: stand-alone CBIS, which is not used at international airports, and in-line CBIS. The in-line CBIS is more complex and involves the process of screening from the baggage drop at the check in desk, through the screening device, to the area where the baggage is sorted before boarding. The procedure includes three levels of screening which are described later in Chapter 2 (TSA, 2011).

## **1.2 Objective and Scope**

There are several objectives of the thesis. The first objective is to review passenger, carry-on and checked baggage inspection procedures at airports. The subsequent objectives are to develop or demonstrate three methodologies for the analysis of CBIS. The first analysis methodology is to recommend the optimal values for the sensitivity settings (parameters) of the checked baggage screening devices so as to meet the targets of minimizing the cost of wrong inspection decisions. Four different screening technologies are compared. The second analysis methodology uses the  $M/G/m$  queuing model to analyze the steady state average number of baggage in the system and the average delay of the CBIS, so that the number of devices may be deployed to meet the customer demand. Two examples of such system are presented to demonstrate how the optimization methodology for the sensitivity parameters and  $M/G/m$  queuing model may be used in a two-step procedure to design CBISs at the airports. The third analysis methodology uses the VISSIM microscopic traffic simulation model to estimate the time-varying queue length and delay of a CBIS. The feasibility of using VISSIM to simulate CBIS is evaluated.



### **1.3 Organization of Thesis**

Chapter 1 contains the introduction to the baggage screening problems. The literature review in Chapter 2 covers the introduction to the aviation security issues and briefly describes different kinds of the standard security procedures commonly used at international airports all over the world. In Chapter 3 the optimization methodology is described and the concrete values of false alarm, false clear, and costs are obtained. The number of devices needed, the average waiting time in the system, and the average queue length are calculated using the  $M/G/m$  queuing theory in Chapter 4. In Chapter 5, the VISSIM software is used to simulate the process of checked baggage screening and estimate the average delay.

## **Chapter 2: Literature Review**

The aim of this chapter is to review the procedures of passenger and carry-on baggage screening, checked baggage screening and technologies used to implement this processes at airports within U.S. The description below is based on information provided by the Transportation Security Administration (TSA) website, and equipment vendors' websites. TSA is an agency under the U.S. Department of Homeland Security (DHS) and was created in 2001 to take the responsibility for the security at more than 450 of U.S. airports and enforce all commercial airline passenger and baggage screening.

### **2.1 Aviation Security**

Aviation security deals with acts such as sabotage, unlawful seizure of aircraft or the use of civilian aircraft in terrorist attacks. One of its purposes is to implement security programs to protect people and the property both in the aircrafts and at the airports against such acts. Aviation security covers issues such as passenger screening, carry-on baggage screening, checked-in baggage screening, employee's inspection, and cargo and catering screening (Bina and Žihla, 2011). In this thesis only passenger screening, carry-on baggage screening and checked-in baggage screening are reviewed, but the focus of analysis methodologies is on checked-in baggage screening. Table 1.1 shows an overview of procedures and technologies used for different screening processes at airports.

### **2.2 Passenger and Carry-on Baggage Screening**

The passenger and carry-on baggage screening procedures are described separately in sections 2.2.1 and 2.2.2. However, they are connected as can be seen in Figure 2.1.

Table 1.1: Review of types of controls at the airport

	Type of control	Who is responsible?	How does it work?
Passenger	Secure Flight	TSA	Collecting passenger's data provided during the booking process
	Travel Document Checker (TDC)	TSA	Checking passenger's documentation including identification and boarding passes
	Walk-through Metal Detector		Looking for any metallic items
	Hand-Wand Inspection		Additional personal screening by TSA officer using Hand-Wand
	Advanced Imaging Technology (AIT)		Millimeter Wave Unit – uses harmless electromagnetic waves to create 3D black and white image
			Backscatter Unit – uses low level X-ray beams to create a reflection of the body viewed on the monitor
	Same-Gender Screening	TSA	Additional personal screening by TSA officer using his/her hands or second alternative for passengers who deny walk through the AIT machine
	Behavior Detection Officers (BDO)	TSA	Trying to identify potentially dangerous passengers according to their behavior
	CastScope		Screening of casts or prosthetics in case of finding any prohibited items
	Federal Air Marshals (FAMs)	TSA	Additional independent security supervision. Help to find out the reason the metal detector was alarmed
Carry-on	X-ray machine		Screens baggage, electronics and shoes of passenger
	Physical Inspection	TSA	Addition screening done by TSA officer
	Bottled liquids scanner (BLS)	TSA	Detects potential dangerous liquid threats in carry-on baggage especially for amount larger than three ounces
	Explosives Trace Detection (ETD)		Technology used for detection of explosives. The officer swabs the baggage or passenger hands and puts the sample into the ETD device
Check-in baggage	Explosive Detection System (EDS)		Millimeter wave technology machines screen the baggage in order to find both metallic and non-metallic dangerous items
	Backscatter X-ray (BX)		Objects with a high atomic number, such as metallic weapons, absorb X-rays, while explosives, containing, for example, nitrogen and carbon, which have a low atomic number, scatter X-rays.
	Dual-energy X-ray (DX)		Digital radiology imaging algorithm (enables to differentiate between organic and inorganic materials)
	Multiview tomography (MVT)		Multiple independent X-ray sources, each with a different viewing angle to provide the best possible visibility
	Inspection of the image by the officer	TSA	The officer examines the images from explosive detection system machine when the alarm is activated
	Physical Inspection	TSA	Additional physical search for the cause of alarm
Employee	Handheld Metal Detectors		
	Random Inspections		

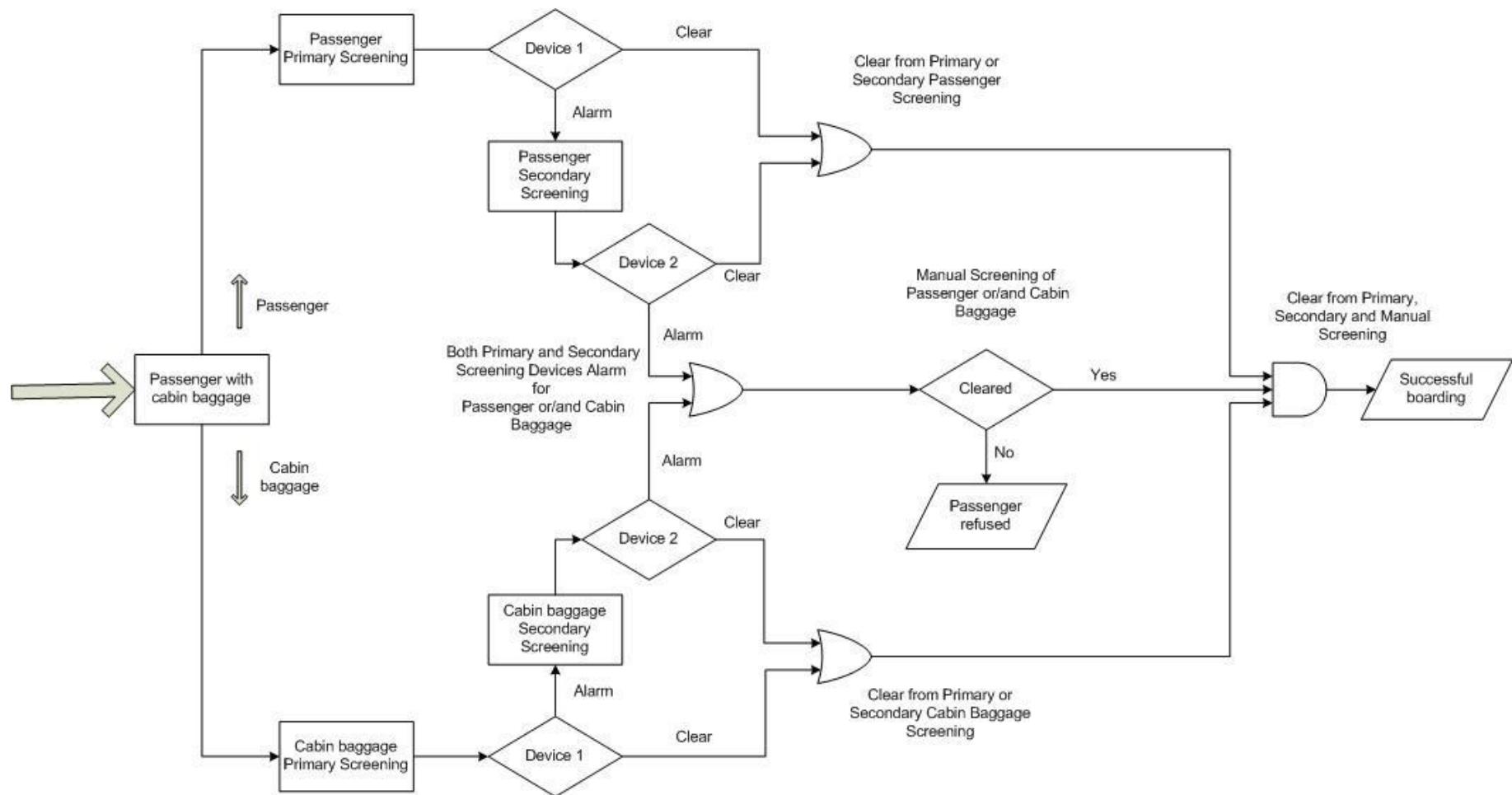


Figure 2.1 Passenger and carry-on baggage screening procedure

### 2.2.1 Procedure of Passenger Screening

The procedure of passenger control starts during the reservation of the air ticket. Every passenger has to provide full information including name, date of birth and gender. The Transportation Security Administration then compares this information with a government watch list. The purposes of comparing passenger names with the watch list are to identify known and suspected terrorists, to prevent individuals on the No Fly List from boarding an aircraft, and to identify individuals on the Selectee List for enhanced screening. Figure 2.2 illustrates the whole procedure (TSA, 2011). After finishing this procedure passengers are allowed to print their boarding passes.



Figure 2.2 Secure Flight process before passenger buys a ticket (TSA, 2011)

All the other security procedures take place at the airport. The first place where the passenger should go is the check-in desk. Here the passenger shows his/her boarding pass, passport and, if it is necessary, visa. At this point the checked baggage screening starts. The passenger takes his/her carry-on baggage and continues the process of boarding. On the way to the appropriate gate he/she undergoes several security screening procedures. Before he/she walks through the first step of screening, the passenger has to show his passport and boarding pass again because he/she is entering a restricted area where people without boarding passes are not allowed to go. Immediately after having his/her identification and boarding pass are checked he/she has to go through a Walk-through Metal Detector. The passengers have to take out all metallic items. If it is necessary the TSA officer can do an additional Hand-Wand

Inspection to find out the reason the metal detector alarmed. After this step the screening procedure continues with Advanced Imaging Technology (AIT). This technology is able to take an image of the passenger's whole body, including all items under the clothes. The passenger must also take off his shoes to avoid additional screening. When there is any suspicious item on the image, the passenger can be asked for Same-Gender Screening. That means additional personal screening by a TSA officer using his/her hands. This kind of screening can also be substituted for going through the AIT. If the passenger passes the screening he/she is allowed to continue to the appropriate gate. In special cases passenger may be asked to go through the CastScope machine, which screens casts or prosthetics in case of finding any prohibited item.

### **2.2.2 Procedure of Carry-On Baggage Screening**

This carry-on baggage screening is closely connected to the passenger screening because this baggage is carried by the passenger onto the plane. The procedure starts with an X-ray scanner while the passenger goes through a metal detector and the AIT machine. If the passenger has any electronics in his/her carry-on baggage he/she has to take them out and let them go through the X-ray machine separately. The officer examines the image from the X-ray device and when there is any suspicious item, a physical inspection of the baggage is required. When physical inspection is needed, the passenger is asked to open the baggage. The officer then physically examines the baggage.

If any prohibited item is found, the item is removed from the baggage and is not allowed to be taken on board. If the prohibited item is a liquid (passengers are not allowed to have liquid in an amount over 3 ounces or 100 ml), it has to be scanned in bottled liquid

scanner. On the other hand if no prohibited item is found or physical inspection is not required the carry-on baggage continues to the following and last screening. The last step of screening is Explosives Trace Detection (ETD). This technology is used for detection of explosives. The officer swabs the baggage to take a sample and put it into the ETD device.

More information about screening process can be found online at TSA's website (<http://www.tsa.gov/index.shtm>).

### **2.3 Checked-in Baggage Screening**

The process of checked-in baggage screening has three separate levels and can be described as follows. Figure 2.3 is the flow chart that illustrates the checked-in baggage screening procedure. The passenger comes to the check-in desk to drop off the baggage. The airline officer at the desk measures the weight of the baggage and prints a barcode which contains information about the owner and the flight. Then the baggage is sent to be screened in Explosive Detection System (EDS) machines. This is called Level 1 screening. The machine captures an electronic image of the baggage and after the analysis of the image evaluate if there is a possible threat in it. If there is any suspicious item inside the baggage is usually sent to be screened once more by another device. If the second screening results without an alarm the baggage is loaded onto an aircraft.

If the second device sounds an alarm, the image is transmitted to the officer who inspects the image and has to consider if any additional physical inspection is required. This step (which involves an officer examining the electronic image) is called Level 2 screening.

If additional physical inspection is required, the bag is sent to a separate room where a TSA officer physically examines if the baggage contains any prohibited items. The procedure is called Level 3 screening. The barcode is used to link the bag with an X-ray image. This helps them to detect the possible threat item and the cause of alarm. Inspection of each bag is recorded on video. After the inspection the officer has to put an announcement into the bag to inform the passenger when and where his bag was physically checked. If additional physical inspection is not required, the bag is sent to be loaded into the aircraft.

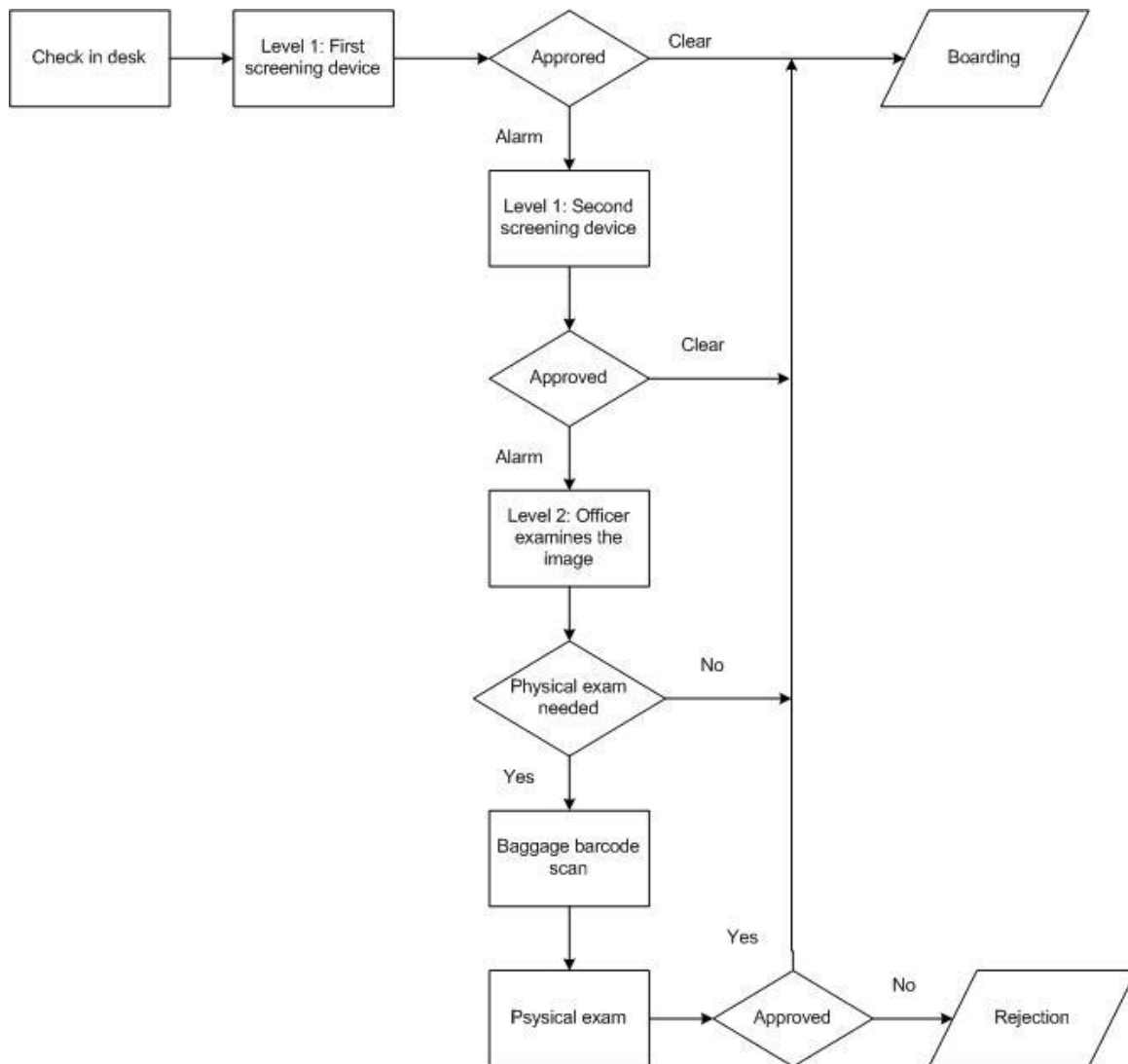


Figure 2.3 Checked baggage screening process



## **2.4 Technologies in Screening Process**

There are several different technologies which are used for both passenger and baggage screening. These technologies differ in the type of electronic waves they use, and materials they are able to detect. This research is mainly focused on checked baggage screening and therefore the following section describes four types of technologies currently used in CBISs at airports.

The most widespread technology is EDS. Explosive Detection System is based on Computer-Aided Tomography (CAT scan) technology and is taken from the medical field (InVision Technologies, 2002). The EDS machine includes a CAT scanner which rotates around the baggage and takes hundreds of pictures from different angles. As the result of the scanning the cross-sectional digital images of the density and mass of the objects inside the baggage are obtained. Explosive detection system devices are fully automated and do not need any manual handling. For the purpose of checked baggage inspection, a specially developed software compares the density of all objects inside the baggage with the densities of known explosives. If there is any suspicious item found inside, the EDS device sounds an alarm. The EDS does not identify the chemical composition but is able to recognize both metallic and non-metallic items.

Another technology used in CBIS, also included in this research, is Dual-energy X-ray (DX). The DX technology utilizes a combination of low-energy and high-energy X-rays. Different objects inside the checked baggage have different characteristics in terms of DX energy absorption and transmission. According to these characteristics the software in the DX device can provide a picture of the screened baggage. The absorption depends on the density of the object. The items with high densities are darker in the image. The energy absorption is influenced by the effective atomic number of the material and also the thickness

of the object. Certain kinds of materials can only be identified by comparing images obtained from low-energy and high-energy X-ray scans. Modern dual-energy baggage screening software provides color images obtained from the low-energy and high-energy scans. With this combination the software can estimate the atomic number of material. There are specific colors for different types of materials - orange for organic materials, green for soft inorganic materials (such as glass), and blue for "hard" inorganic (metallic) substances (Vidisco).

Backscatter X-ray (BX) measures the radiation that is reflected from the target unlike classical X-ray imaging technology which detects the value of the rays transmitted through the object. This technology was mainly used for passenger screening but can also be used for baggage screening. The BX technology creates 2D image and provides good imaging results for organic materials.

MultiView Tomography (MVT) is the technology with the highest screening throughput rate. A MVT device can screen up to 1,800 bags per hour (L3 Communications). This technology works on the basis of multiple independent X-ray sources scanning from different viewing angles, from which 3D images of the objects inside a baggage may be visualized. The algorithm detects and displays the presence and the position of a threat item according to the material density, context, size, and effective atomic number.

Explosive trace detection (ETD) is a technology mostly used for the carry-on baggage and passenger screening. It can be used in the Level 3 screening of the checked baggage. (InVision Technologies, 2002). The screening of each baggage takes less than four seconds. The EDS operates based on thermodynamics and does not require a substance library. It contains spectrometer technology and searches for unique heat signatures indicating the traces of explosives.

## **Chapter 3: Optimization Methodology for Checked Baggage Screening**

### **3.1 Chapter Introduction**

To enhance the security of the aviation system it is necessary to have a CBIS that is effective (that is, the highest possible detection probability or minimum false clear probability) yet efficient (that is, minimize the false alarm probability that causes inconvenience to passengers). The methodology developed in this chapter uses the optimization approach to set the sensitivity parameters of the screening devices to minimize the total cost of inspecting each baggage. The total cost considered are the expected costs of wrong inspection decisions for each baggage: false clear and false alarm.

### **3.2 Literature Review for the Chapter**

In Feng (2007) the objective of the model is to find out which screening technology has an acceptable ratio of the annual costs and the probability of false clear and false alarm. Both, single-device and two-device systems, are studied in this paper. For the cost estimation the total system cost was analyzed. The cost model includes purchasing cost of the device, maintenance cost per year of a device, inspection or screening cost per baggage, cost of a false alarm, cost of a false clear, cost of a true alarm, and cost of a true clear. The model is based on annual system costs. Because each type of device has a different processing rate, the purchase cost has to be multiplied by the number of devices needed at the airport. The problem is defined by the constrained nonlinear multivariable function and solved using the sequential quadratic programming method. Input parameters for the model are divided into two groups: system parameters and device parameters. System parameters are the costs of the device's respond which are cost of a false alarm, cost of a false clear, cost of a true clear

(these are set as zero), cost of a true alarm, probability that baggage contains a threat item, and the pre-specified false clear probability. There are several parameters associated with the devices such as the purchase cost, the maintenance cost, the operating cost, the lifetime of each device, processing capacity, and the number of devices which was calculated through the processing rate of each technology. After running this model and performing sensitivity analysis, Feng (2007) came up with the conclusion that the two-device system (each alarmed baggage is subjected to screening by two devices) is more accurate and cost effective compared to the single-device system. The optimal solution for the single-device system is MVT, which has significantly lower costs than second most cost effective technology which is EDS. The MVT technology has lower accuracy than the EDS device but the processing capacity is almost 10 times higher. The most cost-effective choice for the two-device system is provided by the combination of MVT and EDS where MVT is placed first in the sequence.

Feng et al. (2009) studied CBIS from the view of system capability and reliability. The formulation of the problem includes two scenarios that had different rules of producing false alarms. In both scenarios, each baggage was subjected to screening by two devices. In the first scenario, the system indicates an alarm when both devices signal alarms on a threat item. In the second scenario the system results in an alarm when any one of the two devices signals an alarm on an item. In addition, Feng et al. (2009) included a switching mechanism after the first device. The switch represents a TSA officer checking the images of the alarmed baggage obtained from Level 1 screening. The TSA officer decides whether the baggage needs to be screened by the second device or can be classified as cleared and sent to be loaded to the plane. To solve this problem a minimization of life-cycle cost is applied. The model consists of four types of parameters: the cost parameters, the probability parameters, the volume parameters, and time parameters. The cost parameters comprise three main components: deployment cost, operating cost, and system decision cost. The deployment cost is related to the type of device and covers the initial purchase cost, and the maintenance cost

both given by the manufacturer of the screening device. The inspection cost and the switching cost are a part of the operating cost. The results show that using the MVT technology in the first device is the most cost-effective solution with satisfactory false clear and false alarm probabilities. The lowest life-cycle cost is obtained by using the MVT in the first device followed by EDS in the second device. The same combination was also obtained from the previous research (Feng, 2007) which did not include the probability of switching.

In another paper, Sahin and Feng (2009) take into consideration whether the passenger is on the selectee or non-selectee list. This approach divides the screening into two different procedures based on the result of passenger prescreening by the Computer-Assisted Passenger Prescreening System. If the baggage is cleared by the first device and the passenger owning the bag is on the selectee list the baggage has to go to the switch where a TSA officer will decide if a secondary inspection is needed. When the bag triggers an alarm and the passenger is on selectee list the whole system alarms. However, if the passenger is not on the selectee list the baggage goes to the switch. For the optimization the same sequential quadratic programming method was solved by MATLAB. As for the combinations of technologies for primary and secondary screening the best solution remains the same as in previous simpler research.

The simulated annealing is used to design the optimal aviation baggage screening strategies by Kobza et al. (2004). The cost function of the problem consists of four components: total purchase cost, total false alarm cost, total false clear cost, and total operating cost. The total purchase cost is a function of the number of devices needed at each level to screen the expected number of baggage per hour. The total operating cost is a function of the number of devices needed at each level to screen the expected number of baggage per hour and the annual operating cost per device. The total false alarm and false clear cost are functions of the probability of threat, the expected number of baggage screened

per year and the cost of the false alarm/false clear. The model is applied to 40 different samples of devices and up to ten different levels of screening. The probability of the false clear and false alarm for each device is given in a table. The source of these probabilities is not specified and the distribution function neither. The objective of this model is to select a low cost baggage screening strategy. Three different cooling schedules for the simulated annealing algorithm were run for cases involving high and normal levels of security. To see if there is any difference between the two security scenarios and three simulated annealing variations an analysis of variance test was performed. The results from this analysis suggest that there is no interaction between the choice of cooling schedule and the level of security. There was a big difference in cost between the two levels of security regardless the cooling schedule used.

### **3.3 Methodology Formulation**

This chapter concerns with the detection accuracy of two-device systems for Level 1 CBIS. Before describing the analysis methodology it is necessary to define the probabilities of false clear and false alarm. False clear means that a baggage has a threat item, but passes through the Level 1 CBIS undetected and is allowed to board the plane. In some cases this error can have catastrophic consequences. That is why the cost of false clear has to be set very high. After conducting sensitivity analysis, Feng 2007 estimated that the cost of false clear was \$30 billion. The second error which can be resulted from the screening device and causes extra cost is false alarm. In this case the baggage does not have any threat item but the two-device system declares an alarm. This means that the baggage needs to be sent to Level 2 screening which in substance is not necessary. Besides the extra cost of screening device and personnel at Level 2 screening this experience can be stressful and unpleasant for the passenger. In the case of baggage it can cause a queue of baggage waiting to be screened

again which can lead to the need of more devices. The cost of false alarm was calculated at \$9.16 per alarm per bag.

The methodology covers only the Level 1 screening as it is shown in the Figure 3.1. Level 2 and Level 3 screenings are not processed fully automatically and the precision and the probabilities of rejection are not easy to predict because there is human factor involved.

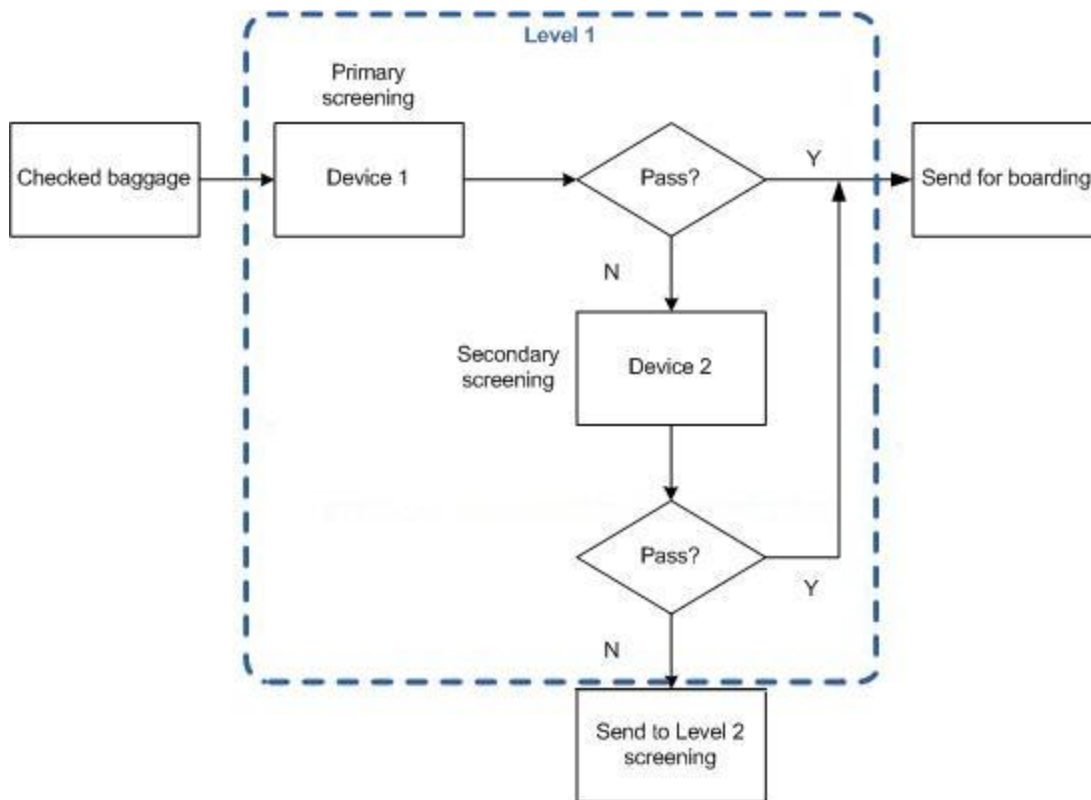


Figure 3.1 Flow chart of the Level 1 screening for checked baggage

The purpose of the methodology is to find the detection or alarm thresholds of the screening machines. The thresholds are given by the value of  $\mu_1$  and  $\mu_2$ , for the primary machine and secondary machine, respectively, in a Level 1 system.

When the output value from the device is smaller than  $\mu_1$  (primary screening) or  $\mu_2$  (secondary screening) the response of the machine will be “clear”. On the other hand when the output value is greater than  $\mu_1$  or  $\mu_2$  the response is “alarm”. The baggage is cleared to board the plane when the response from first device is clear or after triggering an alarm on the first device the baggage is cleared at the secondary screening. A false clear occurs if the baggage contains a threat item but is cleared anyway. On the other hand the baggage is sent to the Level 2 of CBIS when alarms occur on both, primary and secondary screening devices successively. This response can be classified as false or true alarm depending on whether the baggage contains prohibited item.

To find the thresholds the minimization of the cost function is used as the objective. This methodology does not take into account the purchase and operating costs because the main objective is to find values of  $\mu_1$  and  $\mu_2$ . First the equations for probabilities of the four different scenarios have to be derived. The first equation is for true clear. This represents the right case when the passenger does not have any threat item and is allowed to board the plane. The closer is the probability of true clear to 1 the better and more accurate is the screening device. The second correct decision, called true alarm, occurs when the passenger has a threat item and the device detects it and alarms. False clear and false alarm were as described above.

Table 3.1 shows the summary of all the possible threat (input) and outcome (screening decision) scenarios.  $Z=0$  represents baggage without any threat item and  $Z=1$  otherwise.



Table 3.1 Possible combinations of the device respond

System response	Z=0	Z=1
Clear	Ok (1- $\alpha$ )	False clear $\beta$
Alarm	False alarm $\alpha$	Ok (1- $\beta$ )

The screening decision is the security response from the image-based screening device which is based on comparing the output signal  $x_1$  and  $x_2$  with a given threshold represented by  $\mu_1$  and  $\mu_2$ , respectively. The output signal from the screening device follows the Beta distribution. The shape of the curve of the Beta distribution is not only dependent on the input parameters but also on the baggage screened. If the baggage contains threat item the shape is different than shape of baggage without threat item.

The probability density function of the Beta distribution is described in following equation:

$$f(X = x, \rho, \tau) = \frac{\Gamma(\rho+\tau)}{\Gamma(\rho)\Gamma(\tau)} x^{\rho-1} (1-x)^{\tau-1}, \quad (3.1)$$

where  $\Gamma(\cdot)$  is a gamma function,  $0 \leq x \leq 1$ ,  $\rho > 0$ ,  $\tau > 0$ .

The Beta distribution requires two parameters ( $\rho$ ,  $\tau$ ). These two parameters determine the shape of the Beta distribution. One curve is needed for a baggage with threat item (T) and one for a baggage without threat item (N). But for one device,  $\rho_T = \tau_N$ . One of the parameters is always equals to 1 and the second parameter value changes according to the device used for screening. The higher the parameter value the more accurate is the screening device.

The probability of false alarm is calculated as

$$\alpha = P(A|Z = 0) = P(x_1 \geq \mu_1|Z = 0) * P(x_2 \geq \mu_2|Z = 0) = [1 - P(x_1 < \mu_1|Z = 0)] * [1 - P(x_2 < \mu_2|Z = 0)] \quad (3.2)$$

where  $x_1$  and  $x_2$  are the output values of the screening devices 1 and 2, respectively.

The probability of true clear is calculated as

$$(1 - \alpha) = P(C|Z = 0) = P(x_1 < \mu_1|Z = 0) + [1 - P(x_1 < \mu_1|Z = 0)] * P(x_2 < \mu_2|Z = 0), \quad (3.3)$$

$P(x_1 < \mu_1|Z = 0)$  means that the result from the first device is clear and  $[1 - P(x_1 < \mu_1|Z = 0)] * P(x_2 < \mu_2|Z = 0)$  covers the case when the first machine alarms but the second one responds as clear.

The probability of false clear is

$$\beta = P(C|Z = 1) = P(x_1 < \mu_1|Z = 1) + [1 - P(x_1 < \mu_1|Z = 1)] * P(x_2 < \mu_2|Z = 1) \quad (3.4)$$

The probability of true alarm is

$$(1 - \beta) = P(A|Z = 1) = [1 - P(x_1 < \mu_1|Z = 1)][1 - P(x_2 < \mu_2|Z = 1)] \quad (3.5)$$

The unconstraint objective function can now be set using the probabilities of false alarm and false clear.

$$\min C = \beta * C_\beta + \alpha * C_\alpha \quad (3.6)$$

where  $C_\beta$  expresses the costs of false clear and  $C_\alpha$  expresses the costs of false alarm.

Using the formulas for false clear and false alarm the objective function can be rewritten as follows:

$$\begin{aligned} \min C = & \{P(x_1 < \mu_1|Z = 1) + [1 - P(x_1 < \mu_1|Z = 1)] * P(x_2 < \mu_2|Z = 1)\} * C_\beta + \\ & \{[1 - P(x_1 < \mu_1|Z = 0)] * [1 - P(x_2 < \mu_2|Z = 0)]\} * C_\alpha \end{aligned} \quad (3.7)$$

The next step is to rewrite the Equation (3.7). The function  $f$ , the output of screening devices, is expressed as probability density function of the Beta distribution.

$$\begin{aligned} \min C = & \left[ \int_0^{\mu_1} f(x_1|Z = 1)dx_1 + \int_{\mu_1}^1 f(x_1|Z = 1)dx_1 * \int_0^{\mu_2} f(x_2|Z = 1)dx_2 \right] * C_\beta \\ & + \left[ \int_{\mu_1}^1 f(x_1|Z = 0)dx_1 * \int_{\mu_2}^1 f(x_2|Z = 0)dx_2 \right] * C_\alpha \end{aligned} \quad (3.8)$$

### 3.4 Experimental Method

Four different technologies, namely EDS, BX, DX, and MVT as reviewed in Chapter 2, can be used for the two-device screening system in Level 1 which creates 16 possible combinations. For each combination of devices, the sensitivity parameters  $\mu_1$  and  $\mu_2$  can take values from 0.1 to 0.9. This means that 81 values of false alarm, false clear, and cost of errors for each combination. To compute the results for each combination of  $\mu_1$  and  $\mu_2$  the MATLAB software was used. Together, there are  $81 \times 16 = 1296$  points for true alarm, false alarm, true clear, false clear, and costs of wrong decisions. Values of all variables needed for the calculation are listed in the Table 3.2. These same values of  $\rho_T$ ,  $\rho_N$ ,  $\tau_T$ ,  $\tau_N$ , were used in Feng (2007), Feng et al. (2009) and Sahin & Feng (2009).

Table 3.2 Parameters for the Beta Distribution

		Threat item	Non-threat item
Primary screening	$\rho_1$	4, 5, 6, 7	1
	$\tau_1$	1	4, 5, 6, 7
	$\mu_1$	0.1, 0.2, 0.3, ..., 0.9	
Secondary screening	$\rho_2$	4, 5, 6, 7	1
	$\tau_2$	1	4, 5, 6, 7
	$\mu_2$	0.1, 0.2, 0.3, ..., 0.9	

For the primary and secondary screening the conditions of  $\rho_{1,T} = \tau_{1,N}$ ,  $\rho_{2,T} = \tau_{2,N}$ ,  $\rho_{1,N} = \tau_{1,T} = 1$ , and  $\rho_{2,N} = \tau_{2,T} = 1$  has to be followed. How the shape of the probability density function of the Beta distribution changes according to the change of the parameters can be seen in Figure 3.2.

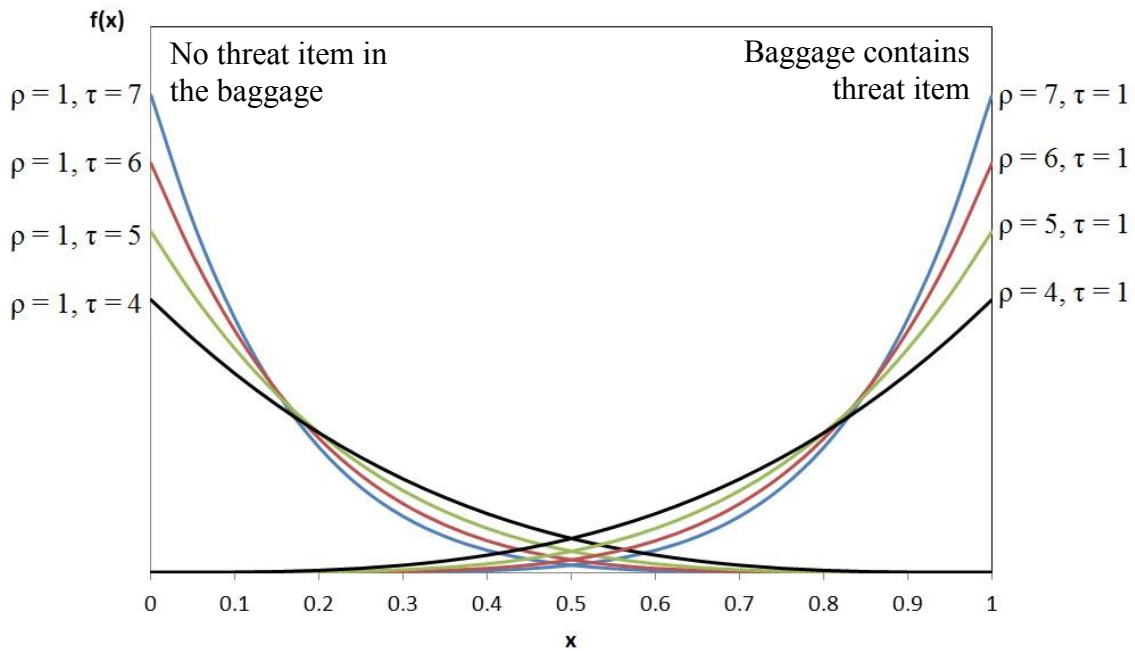


Figure 3.2 Graph of the Beta Distribution with different parameters

### 3.5 Results and Discussions

All the results given by the MATLAB program were processed in Microsoft Excel and put into figures and tables. Figure 3.3 shows the data for true alarm or correct detection ( $1-\beta$ ) against false alarm ( $\alpha$ ). The different types of data points in the figure represent different types of screening technologies used for the primary and secondary screening. These values are 4, 5, 6, 7 for DX, BX, MVT, and EDS technologies, respectively. The most important and useful points are on the top edge of the data points. These data points are connected and the envelope is highlighted in Figure 3.4. The curve is called Operating Characteristic Curve (OCC) which shows the optimal trade-off between false alarm and correct detection.

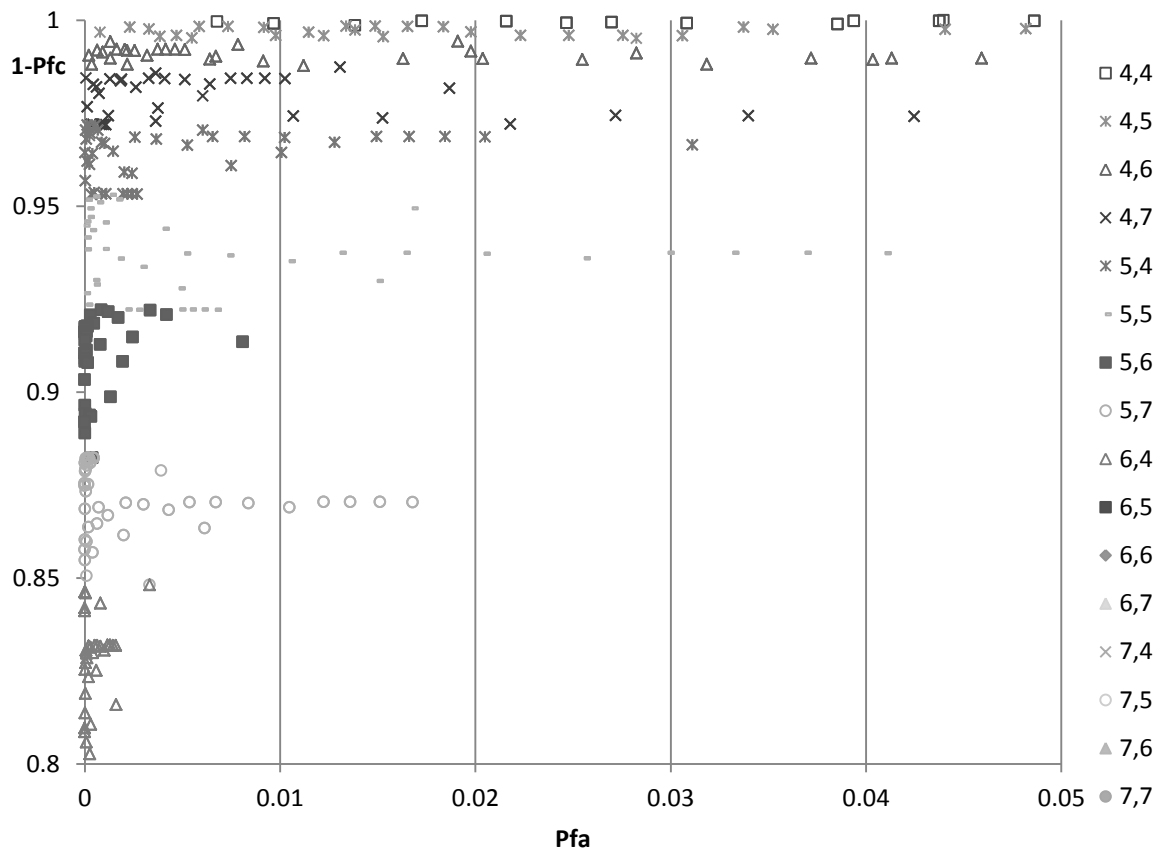


Figure 3.3 True alarm ( $1-\beta$ ) against false alarm ( $\alpha$ )

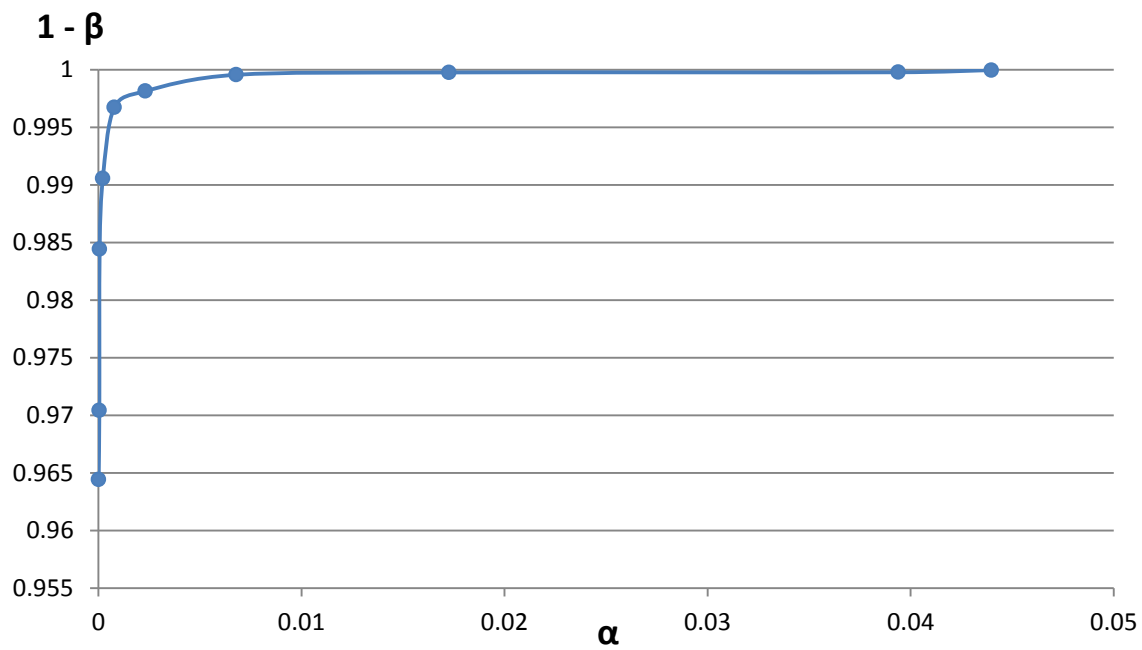


Figure 3.4 Operating characteristic curve (OCC)

These ten points that form this OCC curve are listed in Table 3.3. It is obvious that EDS provides the best results for the false and true alarm probabilities and it is the most accurate technology within all four used for the calculations.

Table 3.3 Data points for the OCC

$\alpha$	$1-\beta$	Device 1	Device 2	$\mu_1$	$\mu_2$	$Z$
1.28E-05	0.964413	EDS	EDS	0.5	0.6	1.07E+09
4.59E-05	0.970414	EDS	EDS	0.4	0.6	8.88E+08
6.1E-05	0.984436	EDS	EDS	0.5	0.5	4.67E+08
0.000219	0.990562	EDS	EDS	0.4	0.5	2.83E+08
0.000784	0.996726	EDS	EDS	0.4	0.4	98223469
0.002305	0.998143	EDS	EDS	0.3	0.4	55702250
0.006782	0.999563	EDS	EDS	0.3	0.3	13120565
0.017271	0.999769	EDS	EDS	0.2	0.3	6944916
0.03939	0.999781	EDS	EDS	0.1	0.3	6564000
0.04398	0.999974	EDS	EDS	0.2	0.2	767995.5

The closer the  $1-\beta$  to 1 the lower is the number of false clear baggage. On the other hand there is also a need to reduce the false alarm probability because otherwise this can lead to high number of rejected baggage and increase in need of more screening devices in secondary screening in Level 1. The following tables show the best results according to the value of false alarm  $\beta < 0.0001$  in (Table 3.4) and  $\beta < 0.001$  in (Table 3.5) if they exist.

How the values of  $\alpha$ ,  $\beta$ , and  $C$  change according to the change of  $\mu_1$  and  $\mu_2$  is shown in the 3D plots in Figure 3.5, Figure 3.6, and Figure 3.7, respectively. Different colors on the surface of the 3D plots represent different values of  $\alpha=P_{fa}$ ,  $\beta=P_{fc}$ , and  $Z$  on the vertical axis, respectively. These figures correspond to arrangement of two EDS devices in both primary and secondary screening.

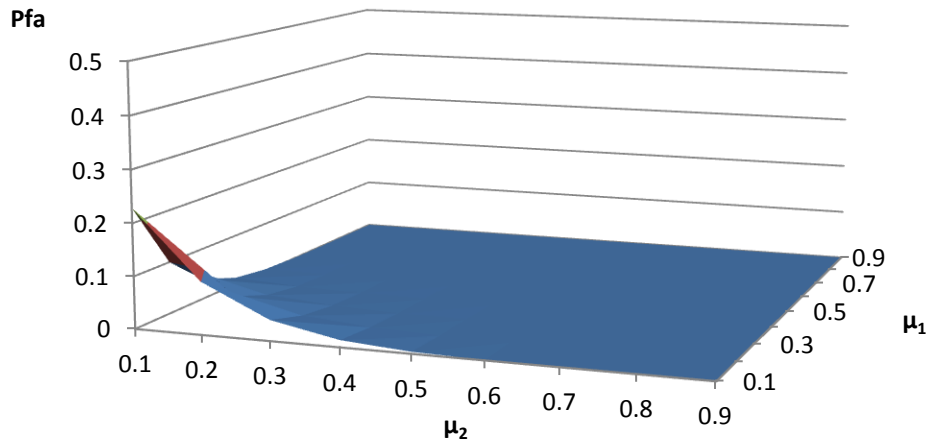


Figure 3.5 Probability of False Alarm for  $\mu_1$  and  $\mu_2$

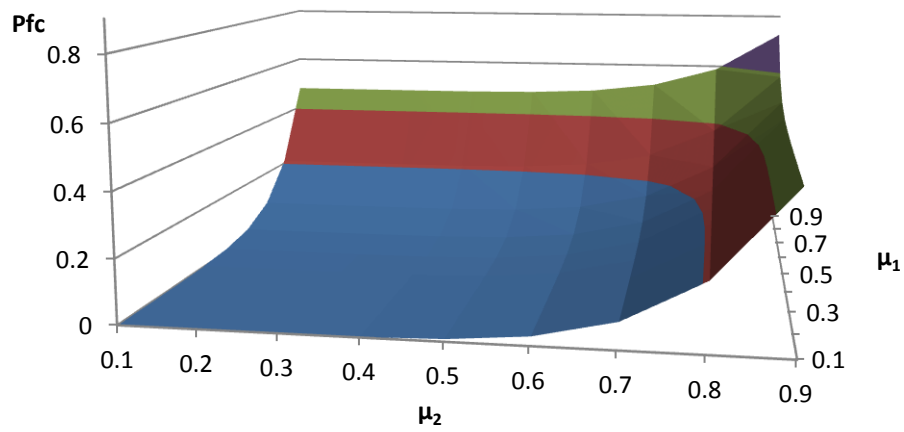


Figure 3.6 Probability of False Clear for  $\mu_1$  and  $\mu_2$

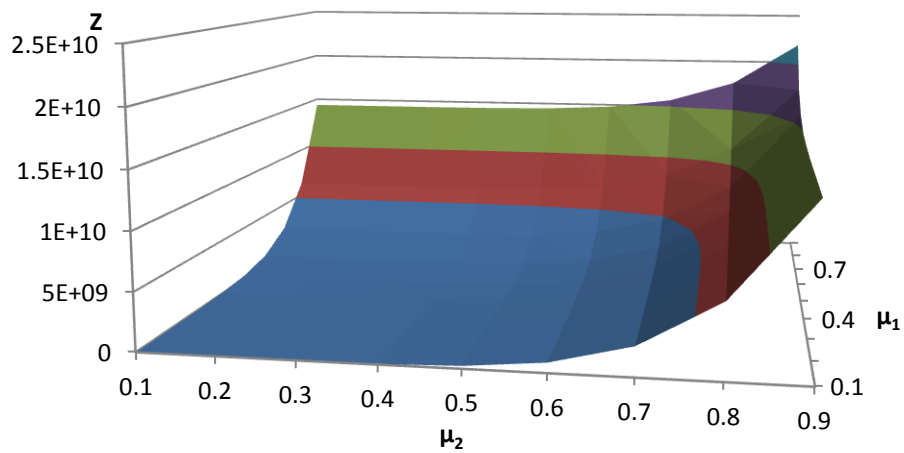


Figure 3.7 Total cost of error per bag for different  $\mu_1$  and  $\mu_2$





Table 3.4 Best results of true alarm for the value of false clear  $\beta < 0.0001$ 

D 1	D 2	$\rho_{1,0}$	$\tau_{1,0}$	$\rho_{1,1}$	$\tau_{1,1}$	$\rho_{2,0}$	$\tau_{2,0}$	$\rho_{2,1}$	$\tau_{2,1}$	$\mu_1$	$\mu_2$	Pfa ( $\alpha$ )	1-Pfc (Pta)	Pfc ( $\beta$ )	1-Pfa (Ptc)	Z
BX	MVT	1	5	5	1	1	6	6	1	0.1	0.2	0.154793	0.999926	7.40E-05	0.845207	2219982
BX	EDS	1	5	5	1	1	7	7	1	0.1	0.2	0.123835	0.999977	2.28E-05	0.876165	683997.3
MVT	BX	1	6	6	1	1	5	5	1	0.2	0.1	0.154793	0.999926	7.40E-05	0.845207	2219982
MVT	MVT	1	6	6	1	1	6	6	1	0.2	0.1	0.139314	0.999935	6.50E-05	0.860686	1949999
MVT	EDS	1	6	6	1	1	7	7	1	0.2	0.2	0.054976	0.999923	7.68E-05	0.945024	2303976
EDS	BX	1	7	7	1	1	5	5	1	0.2	0.1	0.123835	0.999977	2.28E-05	0.876165	683997.3
EDS	MVT	1	7	7	1	1	6	6	1	0.2	0.2	0.054976	0.999923	7.68E-05	0.945024	2303976
EDS	EDS	1	7	7	1	1	7	7	1	0.2	0.2	0.04398	0.999974	2.56E-05	0.95602	767995.5

Table 3.5 Best results of true alarm for the value of false clear  $\beta < 0.001$ 

D 1	D 2	$\rho_{1,0}$	$\tau_{1,0}$	$\rho_{1,1}$	$\tau_{1,1}$	$\rho_{2,0}$	$\tau_{2,0}$	$\rho_{2,1}$	$\tau_{2,1}$	$\mu_1$	$\mu_2$	Pfa ( $\alpha$ )	1-Pfc (Pta)	Pfc ( $\beta$ )	1-Pfa (Ptc)	Z
DX	DX	1	4	4	1	1	4	4	1	0.1	0.1	0.430467	0.9998	2.00E-04	0.569533	5999704
DX	BX	1	4	4	1	1	5	5	1	0.1	0.2	0.214991	0.99958	0.00042	0.785009	12599042
DX	MVT	1	4	4	1	1	6	6	1	0.1	0.3	0.07719	0.999171	0.000829	0.92281	24867814
DX	EDS	1	4	4	1	1	7	7	1	0.1	0.3	0.054033	0.999681	0.000319	0.945967	9560344
BX	DX	1	5	5	1	1	4	4	1	0.2	0.1	0.214991	0.99958	0.00042	0.785009	12599042
BX	BX	1	5	5	1	1	5	5	1	0.2	0.2	0.107374	0.99936	0.00064	0.892626	19196929
BX	MVT	1	5	5	1	1	6	6	1	0.1	0.3	0.069471	0.999261	0.000739	0.930529	22169782
BX	EDS	1	5	5	1	1	7	7	1	0.2	0.3	0.026986	0.999461	0.000539	0.973014	16158901
MVT	DX	1	6	6	1	1	4	4	1	0.3	0.1	0.07719	0.999171	0.000829	0.92281	24867814
MVT	BX	1	6	6	1	1	5	5	1	0.3	0.1	0.069471	0.999261	0.000739	0.930529	22169782
MVT	MVT	1	6	6	1	1	6	6	1	0.2	0.3	0.030841	0.999207	0.000793	0.969159	23788601
MVT	EDS	1	6	6	1	1	7	7	1	0.3	0.3	0.009689	0.999052	0.000948	0.990311	28426217
EDS	DX	1	7	7	1	1	4	4	1	0.3	0.1	0.054033	0.999681	0.000319	0.945967	9560344
EDS	BX	1	7	7	1	1	5	5	1	0.3	0.2	0.026986	0.999461	0.000539	0.973014	16158901
EDS	MVT	1	7	7	1	1	6	6	1	0.3	0.3	0.009689	0.999052	0.000948	0.990311	28426217
EDS	EDS	1	7	7	1	1	7	7	1	0.3	0.3	0.006782	0.999563	0.000437	0.993218	13120565

### 3.6 Chapter Conclusions

This methodology was developed to help the analyst to find the sensitivity threshold values for the existing technologies used in the CBIS. To obtain the results two approaches were considered. In the first approach the thresholds were selected according to the OCC curve without applying the minimum cost requirement. The optimal solution for this approach is using the EDS devices for both primary and secondary screening. In the second approach the optimal threshold values were chosen in addition to have satisfactory value of probability of false clear and the highest value of probability of true alarm at the same time. For the value of false clear at  $\beta < 0.0001$ , the best device combination is BX and EDS regardless the order; and for the value of false clear at  $\beta < 0.001$  the optimal solution is to have two DX devices. If the CBIS designer would like to set the thresholds only according the costs of wrong decisions, the values of  $\mu_1$  and  $\mu_2$  would be much lower than 0.1.

## Chapter 4: Queuing Model for Checked Baggage Screening

### 4.1 Chapter Introduction

Another important aspect which has to be considered for an efficient baggage screening system is the system capacity. Badly designed CBIS can cause delays in baggage screening which could in the worst case lead to the delay of the aircraft departure or in need of using another flight to deliver the baggage to the requested destination. This always creates extra cost to the airlines and frustration to the passenger. This chapter deals with the calculation of the average waiting times, average number of baggage in the system and number of devices needed for the baggage screening using the  $M/G/m$  queuing model. The probabilities obtained in the previous chapter will be used for the calculation of the number of baggage sent to the secondary screening device. First the equations of the  $M/G/m$  queuing model are described. Then two different examples were created to help to illustrate the application of the  $M/G/m$  queuing model.

### 4.2 $M/G/m$ Queuing

Hokstad (1978) introduced the equations for the  $M/G/m$  queuing. First it is necessary to explain what  $M/G/m$  means. M (memoryless) defines the Poisson arrival process with an average arrival rate  $\lambda$ . G (general) represents the arbitrary distribution of service time per server. The number of servers (in this case screening device) is given by the integer value of  $m$ . The capacity of the system is not limited. There is always only one queue which the newly arriving baggage joins.

Figure 4.1 shows the layout of the queue and servers for a Level 1 two-device screening system, with  $m$  devices for primary screening and 1 device for secondary screening. The variables  $W_1, W_2$  in the figure represents average waiting time during the primary and secondary screening, respectively, of Level 1 screening. Similarly,  $L_1, L_2$  represents the average number of baggage in the primary and secondary screening, respectively. For a baggage that is sent to the secondary inspection, the average total waiting time is  $W_1 + W_2$ .

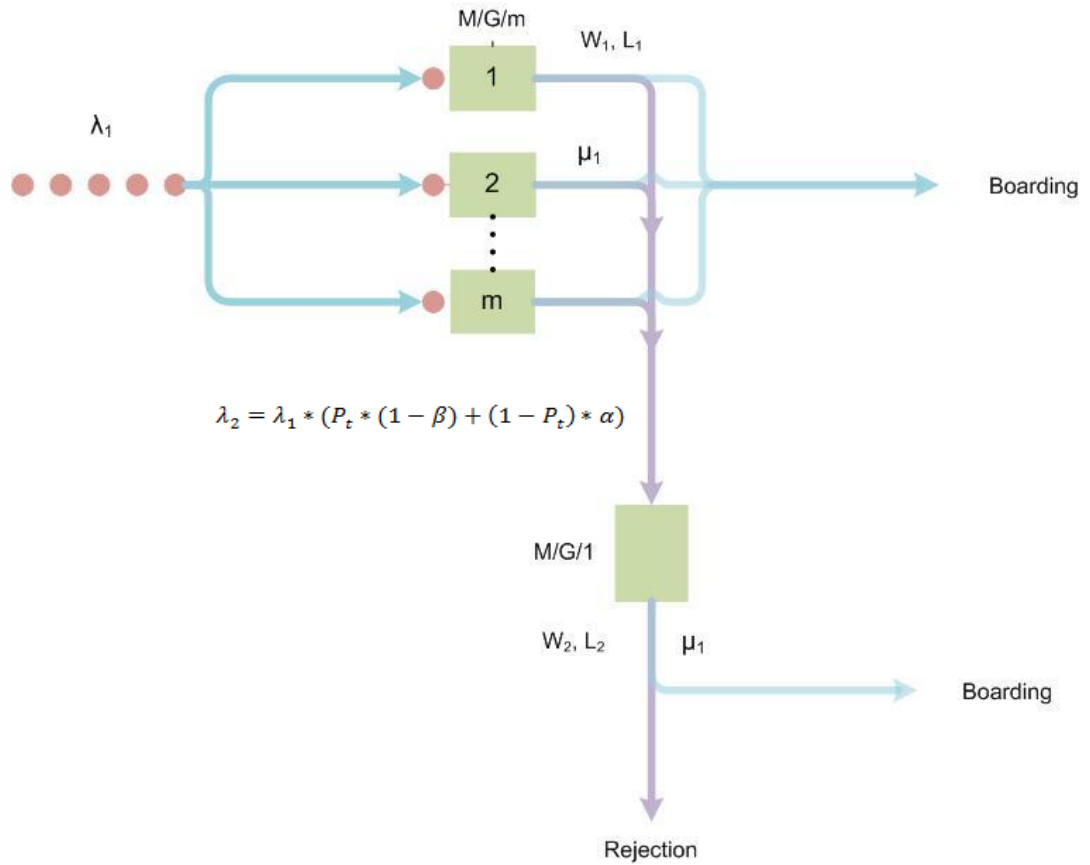


Figure 4.1 M/G/m queueing flow chart

### 4.3 Methodology Formulation

There are three input variables which have to be defined. The arrival rate  $\lambda_1$  specifies the average number of baggage arriving in one hour for primary screening. This rate depends on the number of flights and whether passenger takes none, one or two baggage to check.

The average arrival rate for the secondary screening is calculated using the probabilities of true alarm and false alarm from the previous chapter, and probability of the threat item inside the bag  $P_t$  (Feng, 2007).

$$\lambda_2 = \lambda_1 * (P_t * (1 - \beta) + (1 - P_t) * \alpha) \quad (4.1)$$

The service time, i.e., screening time is denoted by  $T$ . The average service time  $b_1 = E(T)$  is given by the screening device manufacturer. For each technology there is throughput of bags per hour from which the average service time can be easily calculated. The third variable is the standard deviation of the scanning time  $\sigma$ .

First of all after setting the input variables it is necessary to calculate  $b_2 = E(T^2)$ . The equations are as follows:

$$var(T) = E(T^2) - E(T)^2, \quad (4.2)$$

where  $E(T^2) = b_2$ , and  $E(T)^2 = b_1^2$

$$\sigma = \sqrt{var(T)} \quad (4.3)$$

$$b_2 = \sigma^2 + b_1^2 \quad (4.4)$$

The traffic intensity  $\rho_m$  depends on the number of screening devices in the system. With the value of  $\rho_m$  it is possible to compute the probability that the baggage has to wait ( $\Pi_m$ ). Using  $b_1$  and  $b_2$  the service time distribution index  $C_b^2$  is calculated.

$$\rho_m = \frac{\lambda * b_1}{m} \quad (4.5)$$

$$C_b^2 = b_2 * b_1^{-2} - 1 \quad (4.6)$$

$$\Pi_m = \frac{\rho}{1-\rho} * p_{m-1} , \quad (4.7)$$

where

$$p_0 = \left[ \sum_{k=0}^{m-1} \frac{(\alpha b_1)^k}{k!} + \frac{(\alpha b_1)^m}{(1-\rho)m!} \right]^{-1} \quad (4.8)$$

$$p_{m-1} = \frac{(\alpha b_1)^{m-1}}{(m-1)!} * p_0 \quad (4.9)$$

The average waiting time  $W_m$  and average number of baggage in the system  $L_m$  are then:

$$L_m = m\rho_m + \frac{\rho_m(C_b^2+1)\Pi_m}{2(1-\rho_m)} \quad (4.10)$$

$$W_m = \frac{b_1\Pi_m(1+C_b^2)}{2m(1-\rho_m)} \quad (4.11)$$

All the variables have to be calculated separately for primary and secondary screening. The following chapter describes two concrete examples.

#### 4.4 Example Problems

The above equations for the  $M/G/m$  queuing model were implemented in a Microsoft Excel worksheet. Figure 4.2 shows the Excel file worksheet with calculation results. The two following sections describe two examples to demonstrate how the  $M/G/m$  queuing theory works in the analysis of a two-device Level 1 CBIS.



Input variables	Primary screening	
	Insert input variables needed for the calculation	
Calculation	arrival rate ( $\alpha$ )	$\lambda_i = 350$ bags/hour
	mean service time ( $1/\mu$ )	$b_i = 10$ seconds/bag
	standard deviation of scanning	$\sigma = 3$ seconds/bag
	1st step: $b_2$	
	$\text{var}(T) = E(T^2) - E(T)^2 \text{ where } E(T^2) = b_2, \text{ and } E(T)^2 = b_1^2$ $\sigma = \sqrt{\text{var}(T)}$	
	$b_2 = 109 \text{ (time unit/bag)}^2$	
	2nd step: $\rho, C_b^2$	
	traffic intensity	$\rho_1 = 0.97$ $\rho_2 = 0.49$ $\rho_3 = 0.32$ $\rho_4 = 0.24$ $\rho_5 = 0.19$ $\rho_6 = 0.16$
	m- number of servers	
	service time distribution	$C_b^2 = 0.09$
Output Values	3rd step: $\Pi$	
	probability that a baggage has to wait	$\Pi_1 = 0.97$ $\Pi_2 = 0.32$ $\Pi_3 = 0.08$ $\Pi_4 = 0.02$ $\Pi_5 = 0.00$ $\Pi_6 = 0.00$
	$\Pi_m = \frac{\rho}{1 - \rho} * p_{m-1}$	
	$E(N)_m = L_m = m\rho_m + \frac{\rho_m(C_b^2 + 1)\Pi_m}{2(1 - \rho)}$	
	Average time spend in the system	
	$E(W)_m = W_m = \frac{b_1 \Pi_m (1 + C_b^2)}{2m(1 - \rho_m)}$	
	M/G/m	
	Number of bags in the system (bags)	Average time spend in the system (seconds)
	$L_1 = 19.52$ bags	$W_1 = 190.75$ seconds
	$L_2 = 1.14$ bags	$W_2 = 1.69$ seconds
	$L_3 = 0.99$ bags	$W_3 = 0.23$ seconds
	$L_4 = 0.98$ bags	$W_4 = 0.03$ seconds
	$L_5 = 0.97$ bags	$W_5 = 0.00$ seconds
	$L_6 = 0.97$ bags	$W_6 = 0.00$ seconds

Figure 4.2 Excel file worksheet

#### 4.4.1 M/G/1, M/G/1

This case represents a very simple scenario where there is only one device for primary and one device for secondary screening as shown in Figure 4.3. This can be applied to small airports with low passenger and bag gage throughput. The input variables are in Table 4.1.

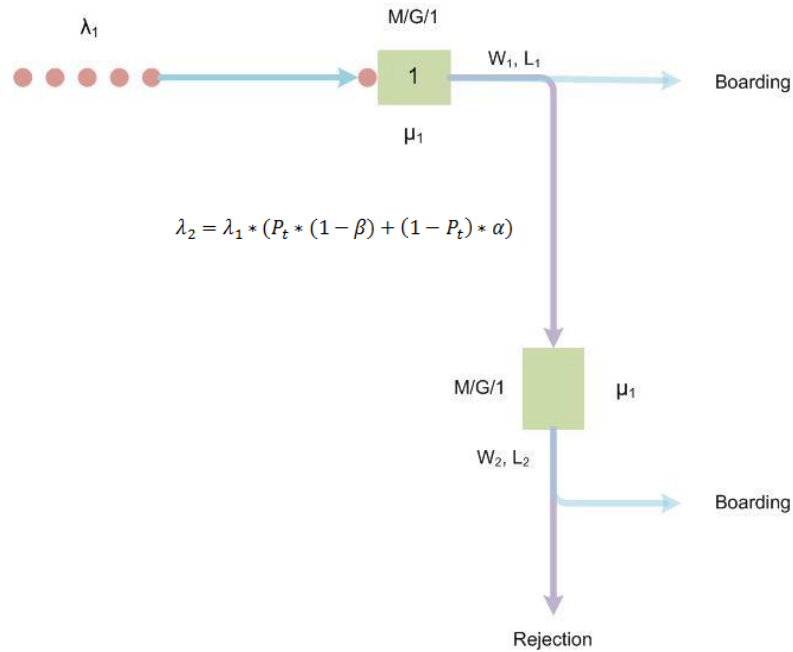


Figure 4.3 M/G/1, M/G/1 system

Table 4.1 Input variables for the first example

<b>Arrival rate</b>	$\lambda$	590	bags/hour
<b>Mean service time</b>	$b_1$	6	seconds/bag
<b>Standard deviation of the screening</b>	$\sigma$	3	seconds/bag

The mean service time can be easily obtained using the throughput rate given by the manufacturer. In this example the mean service time is equivalent to the throughput of 600 baggage/hour. The standard deviation represents the range from the mean service time in which roughly 68% of the baggage is screened.

For this case with just one screening device the arrival rate is set almost at the capacity the system can handle. If the arrival rate would be set as 600 bags/hour, which is exactly the value of the throughput of the screening device, the calculation of the waiting time and the length of the queue would fail. The arrival rate always has to be lower than the maximum number of baggage the system can screen in an hour.

#### 4.4.2 M/G/4, M/G/2

Figure 4.4 shows the setup of a Level 1 screening system with four primary screening devices and two secondary screening devices. This arrangement can be used at bigger airports.

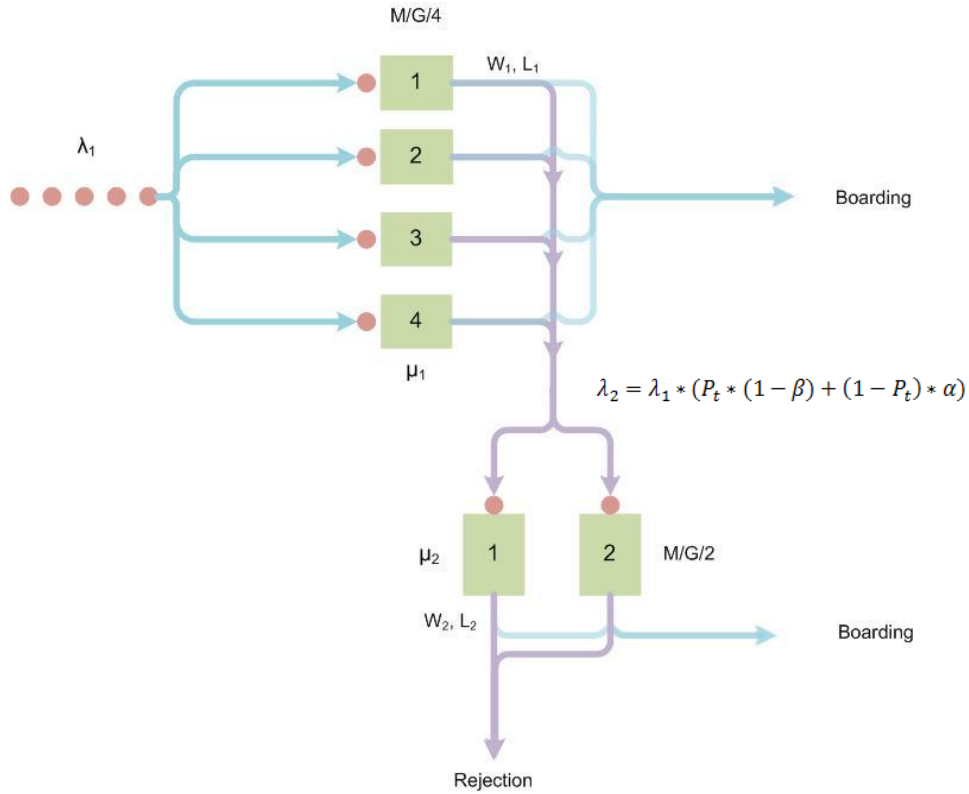


Figure 4.4 Flow chart for the  $M/G/4, M/G/2$  example

The mean service time and standard deviation of the screening time remain the same as in the previous example but the arrival rate can be significantly higher because the number of servers in primary screening has increased to four. The results were computed for both scenarios of one and two secondary screening devices. The arrival rate was set exactly four times higher than in the previous example which is close to the capacity of the system.

Table 4.2 Input variables for the second example

<b>Arrival rate</b>	$\lambda$	2360	bags/hour
<b>Mean service time</b>	$b_I$	6	seconds/bag

<b>Standard deviation of the screening</b>	$\sigma$	3	seconds/bag
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#### 4.5 Results and Discussions

In the first example the average time each baggage spent in the primary screening system (waiting time) is approximately 3.6 minutes. The number of baggage coming to the secondary screening is, according to the calculation using the probabilities from the previous chapter and the number of baggage containing a threat item  $P_t=1.0E-09$ , (Feng 2007), really low and does not create a queue at the secondary screening.

Table 4.2 shows the results for the  $M/G/1, M/G/1$  example. The average times spent at primary and secondary screenings are waiting times. They do not include the time needed to screen each bag.

Table 4.3 Results for the  $M/G/1, M/G/1$  example

<b>Average time spend at primary screening</b>	$W_1$	221.25	seconds
<b>Arrival rate for the secondary screening</b>	$\lambda_2$	135	bags/hour
<b>Average time spend at secondary screening</b>	$W_2$	1.09	seconds
<b>Total average time spend at both screening</b>	$W_T$	222.34	seconds
<b>Average number of bags in primary screening</b>	$L_1$	38	bags
<b>Average number of bags in secondary screening</b>	$L_2$	1	bags
<b>Total average number of bags in the system</b>	$L_T$	39	bags

In the second example, with four servers at the primary screening, the arrival rate is exactly four times higher but the average waiting time at the primary screening is about four

times lower. However if the arrival rate increases by 30 bags, from 2360 bags/hr to 2390 bags/hr, the average waiting time at the primary screening will increase to  $W_1 = 222.92$  seconds/bag and  $L_T = 153$  bags.

Table 4.4 Results for the  $M/G/4, M/G/2$  example

<b>Average time spend at primary screening</b>	$W_1$	54.18	seconds
<b>Arrival rate for the secondary screening</b>	$\lambda_2$	540	bags/hour
<b>Average time spend at secondary screening (2 devices)</b>	$W_2$	0.95	seconds
<b>Average time spend at secondary screening (1 device)</b>	$W_2$	33.75	seconds
<b>Total average time spend at both screening (M/G/4, M/G/2)</b>	$W_T$	55.14	seconds
<b>Total average time spend at both screening (M/G/4, M/G/1)</b>	$W_T$	87.93	seconds
<b>Total average number of bags in the system (M/G/4, M/G/2)</b>	$L_T$	42	bags
<b>Total average number of bags in the system (M/G/4, M/G/1)</b>	$L_T$	46	bags

## 4.6 Chapter Conclusion

In this chapter the  $M/G/m$  queuing theory was applied to calculate the average waiting time and the average number of baggage in the system. Two examples of the Level 1 screening system have been used to demonstrate the applications.

## **Chapter 5: VISSIM Model**

### **5.1 Chapter Introduction**

In this chapter the usage of VISSIM 5.20 software for modeling the CBIS is explored. This software was not initially developed to model this kind of system. The VISSIM software provided by the PTV Vision (PTV, 2009) was created to model traffic mobility.

The queuing theory does not allow an analyst to consider higher arrival rate than the system can handle even for a short duration. The arrival rate at the airport varies according to the number of departing flights. The number of baggage that has to be screened sometimes exceeds the capacity of the system which can create a queue. This queue may not last long but can occasionally cause significant delay. This scenario can be analyzed by simulation.

### **5.2 Model Development**

For this model the  $M/G/4$ ,  $M/G/2$  arrangement of screening devices was chosen as the example to develop and test the capability of VISSIM in modeling a CBIS. As the VISSIM software is not initially developed to simulate CBIS, some data and parameters have to be modified or created for this purpose. It is necessary to define a new Vehicle Type which will be based on the wheelchair template because of its similar geometry. How to define new Vehicle Type is described further in this section.

First of all, before the links and connections are created, Driving Behavior Parameter Sets have to be defined (see Figure 5.1). There is a need to create a new set of parameters that defines the behavior of baggage. This parameter set is called “baggage”. The

Wiedermann 74 car following model was chosen and the average standstill distance was set to 0.2 m. The other two parameters of the car following model were set to 0.0 m. To more precisely simulate real behavior of baggage, the maximum and minimum values of the look ahead distance have to be changed to a minimum of 0.5 m and a maximum of 1.2 m. A baggage does not react to the behavior of the leading baggage and it is necessary to minimize their interaction.

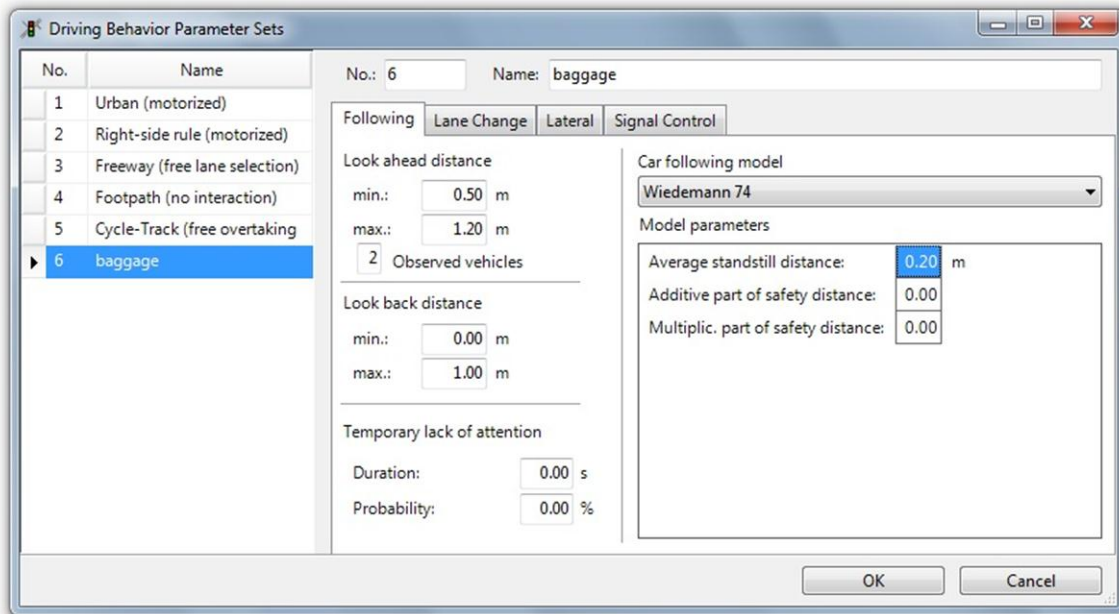


Figure 5.1 The VISSIM Model - Driving Behavior Parameter Sets

Furthermore, a new Link Behavior Type has to be defined such that each link is equivalent to the conveyor belts in CBIS when it is created. It is necessary to define a new Link Behavior Type called “baggage” and assign the previously created Driving Behavior Parameter Set named baggage to this new category. At this point the links and connectors can be created. To each link and connector the Behavior Type (baggage) and lane width (0.50 m) is assigned. Figure 5.2 shows the composition of links (in blue) and connections (in pink).



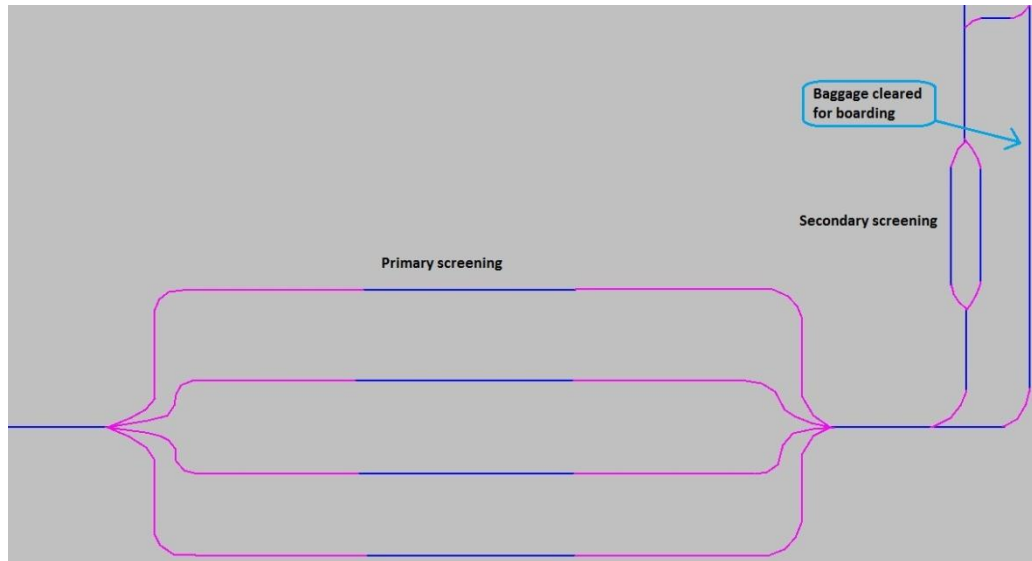


Figure 5.2 The VISSIM Model – The composition of links and connections

The next step is to set the distributions needed within the model. There are three different distributions: Desired Speed Distribution, 2D/3D Model Distribution, and Dwell Time Distribution. Using the Desired Speed Distribution (Figure 5.3), the speed of the baggage was set as 4.0 km/hour by manually specifying an empirical distribution function. All the baggage are assumed to have this same speed when travelling on conveyor belts.

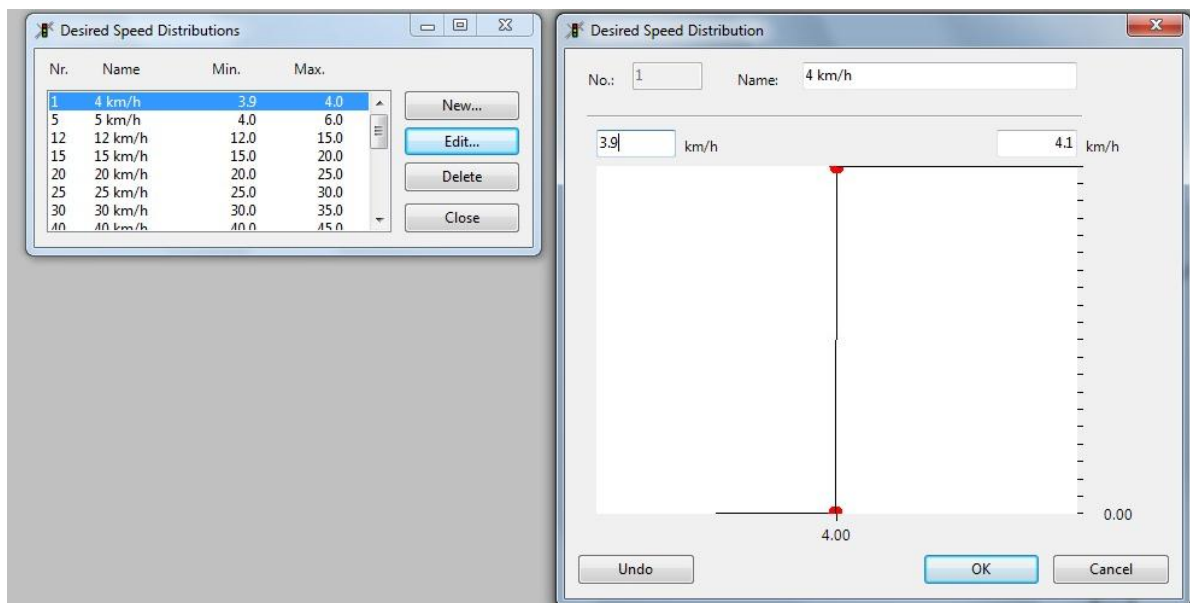


Figure 5.3 The VISSIM Model – Desired Speed Distribution

To create a visual image of the baggage, the wheelchair template in 2D/3D distribution was chosen. The length of the wheelchair was changed from 1.2 m to 0.9 m to simulate the size of the baggage more precisely (Figure 5.4). There is also a possibility to insert a 3D model created in a different software. But this tool is useful only when the user would like to make the 3D simulation look more realistic. The objective of creating the VISSIM model in this chapter is mainly focused on showing that this software is useful for the purpose of CBIS modeling. Therefore, a 3D model was not created in other software.

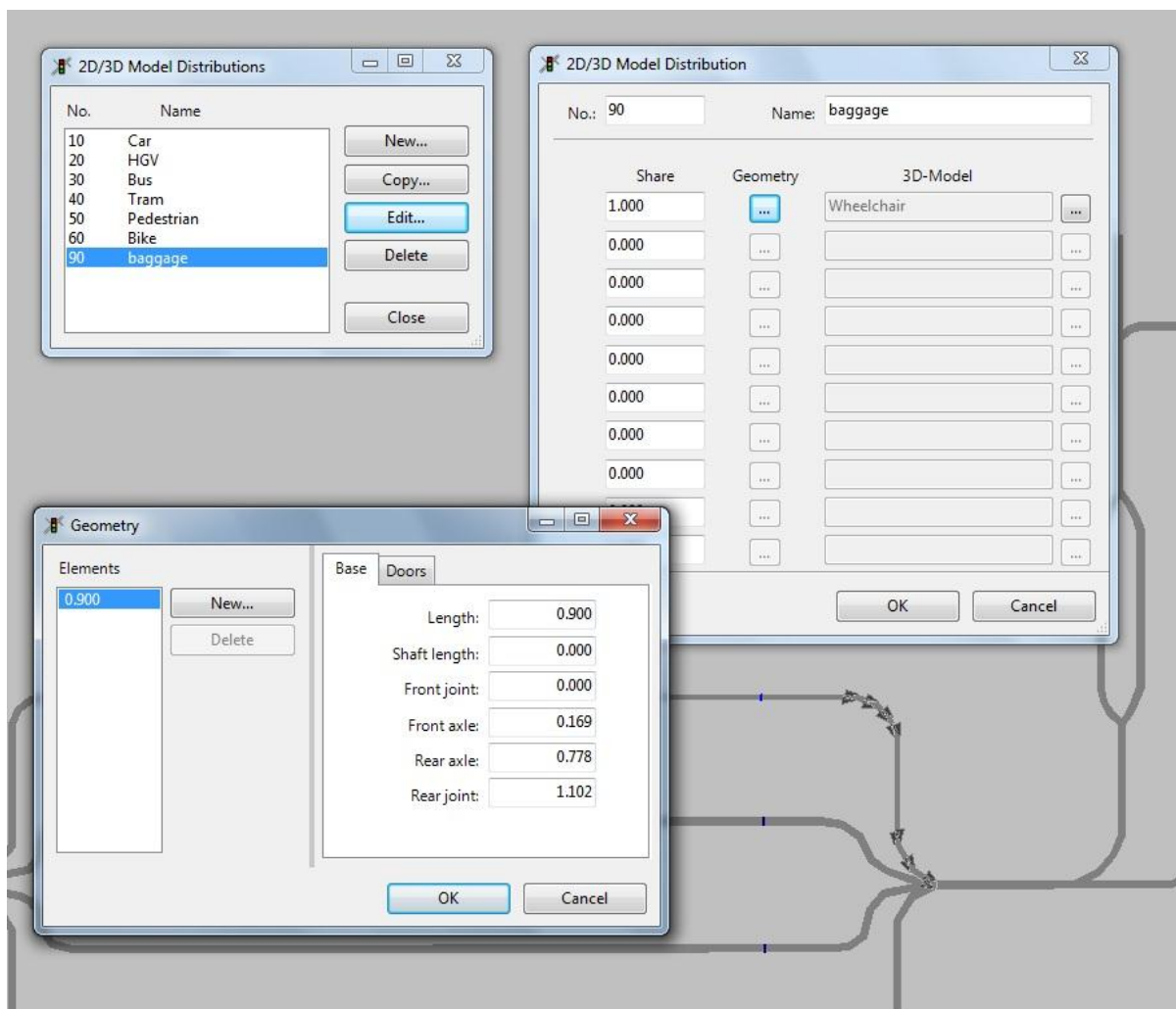


Figure 5.4 The VISSIM Model – 2D/3D Model Distribution

To simulate the screening process, a stop sign is used to substitute the screening device. To define the service time of screening, the Dwell time distribution is used. The description is mentioned further.

To be able to define Vehicle Inputs for the model there are few more parameters that have to be specified: Vehicle Types, Vehicle Classes, and Vehicle Composition. A new Vehicle Type named “baggage” was created (Figure 5.5). The next step is to create new Vehicle Class by choosing Vehicle Type baggage from the preceding step (Figure 5.6). The Vehicle Composition allows the user to specify the input ratio between and within different vehicle types and to assign them desired speed and relevant flow (Figure 5.7).

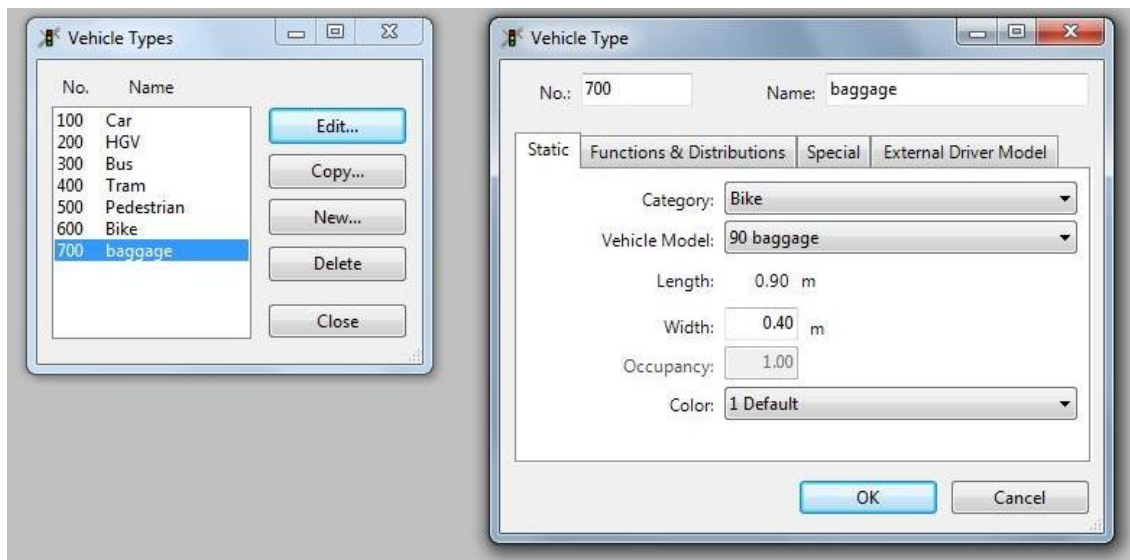


Figure 5.5 The VISSIM Model – Vehicle Types

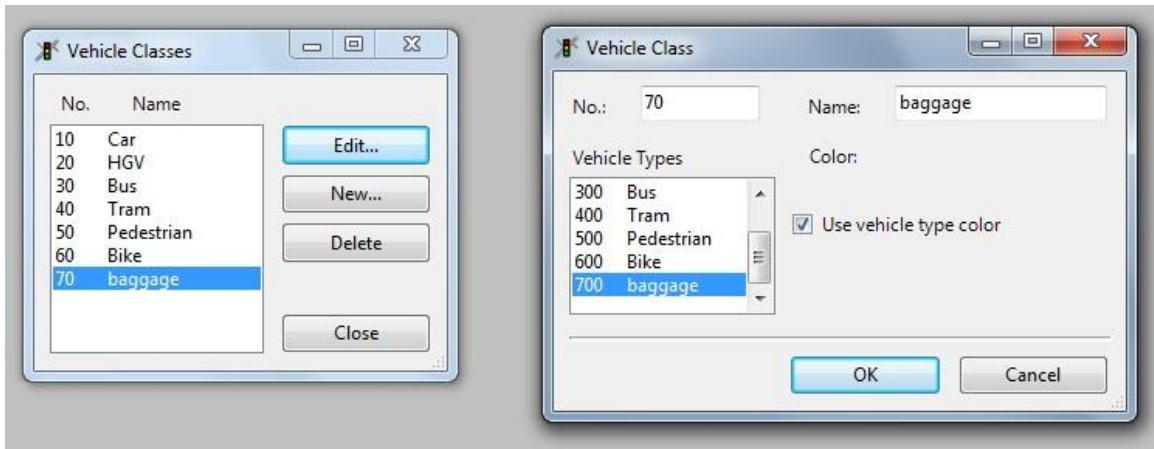


Figure 5.6 The VISSIM Model – Vehicle Classes

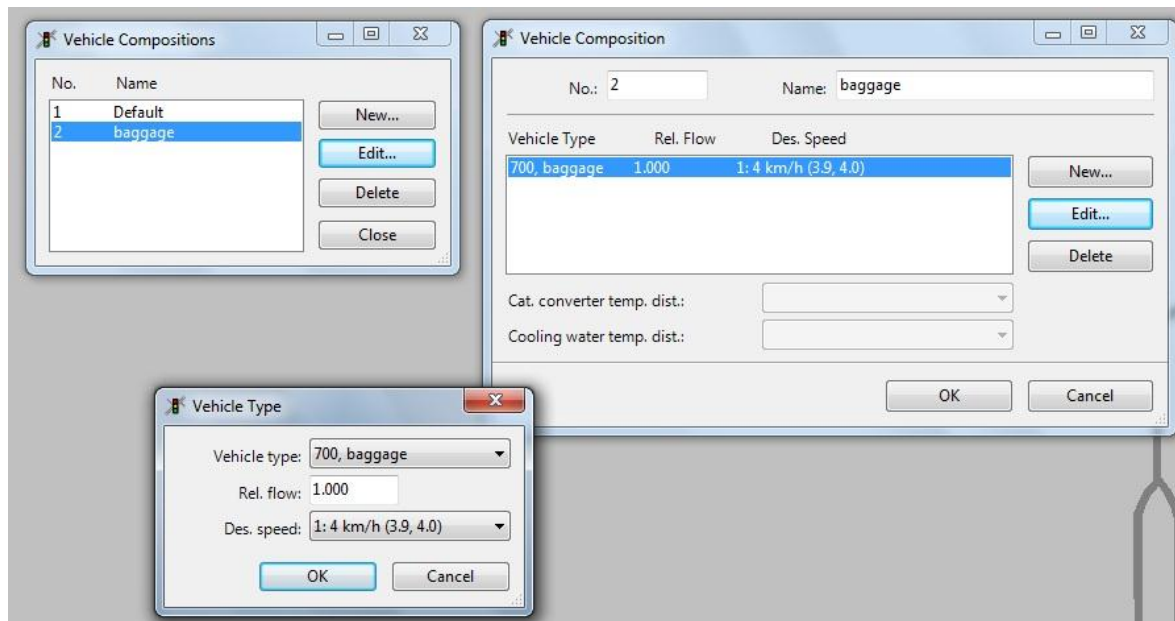


Figure 5.7 The VISSIM Model – Vehicle Compositions

There are three more steps to manage before the first run of the model: define Vehicle Inputs, set Routes, and insert Stop Signs.

There is only one shared queue constituted by one input link and the Vehicle Input for this link represents the arrival rate. The Vehicle Input is initially set to 1800 bags/hour.

At one point in the model, baggage from the only input link splits into four different links when approaching the screening devices. The VISSIM software allows the user to specify the ratio of the directions the baggage will go. The ratios for this model are 1:1:1:1 (Figure 5.8). That is, baggage are split equally (keeping stochastic approach) between the four screening devices. Unfortunately, to assign the direction of the baggage according to the length of the queue in each branch further development of the model is needed. This advanced option may be accomplished by using special module called Vehicle Actuated Programming (VAP) which is based on user defined signal control logic or Dynamic assignment.

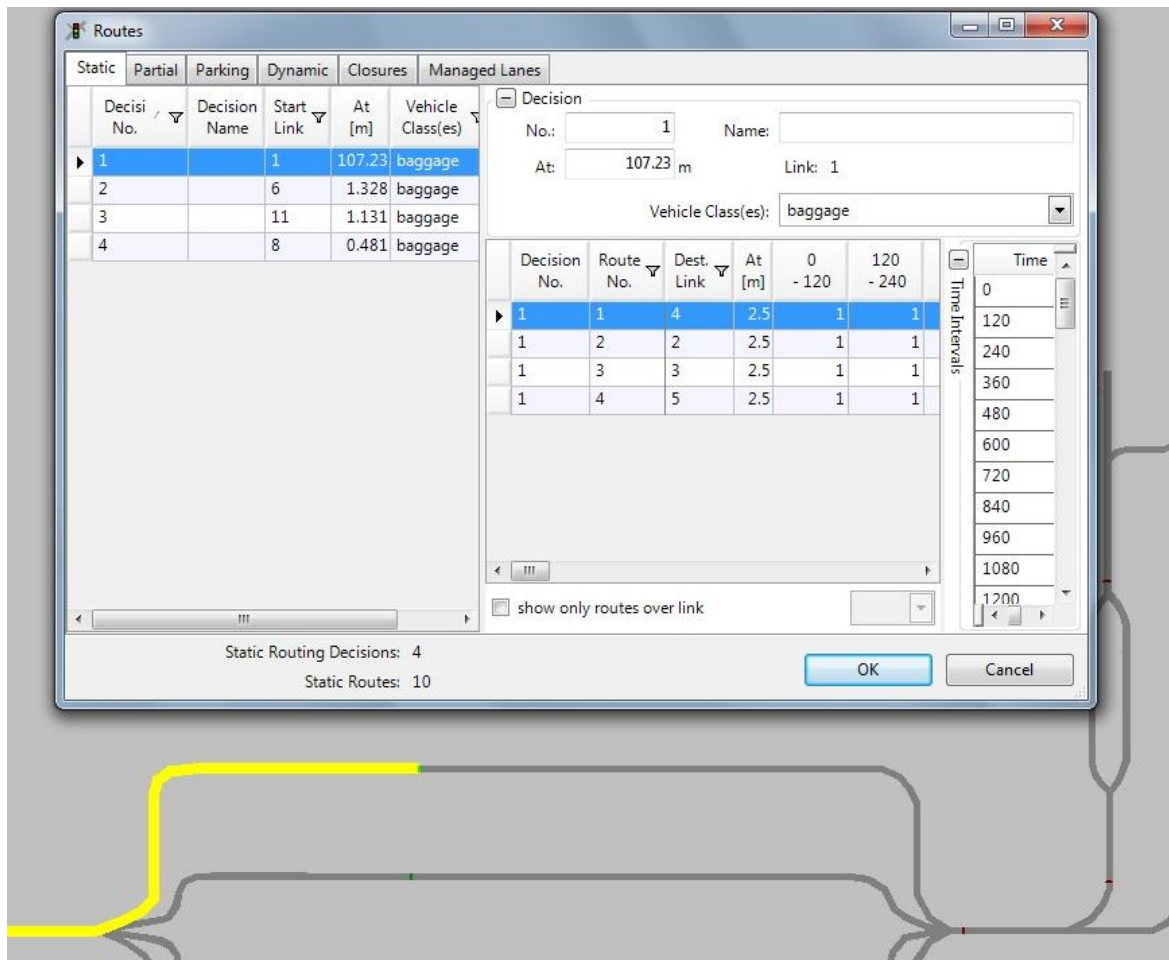


Figure 5.8 The VISSIM Model - Routes

The screening station is represented by Stop Sign with a Dwell Time Distribution (Figure 5.9). There are two ways of specifying dwell time distribution: empirical or normal distribution. For the empirical distribution the user can specify the shape of the curve, maximum and minimum values. The normal distribution is determined by the value of mean and standard deviation.

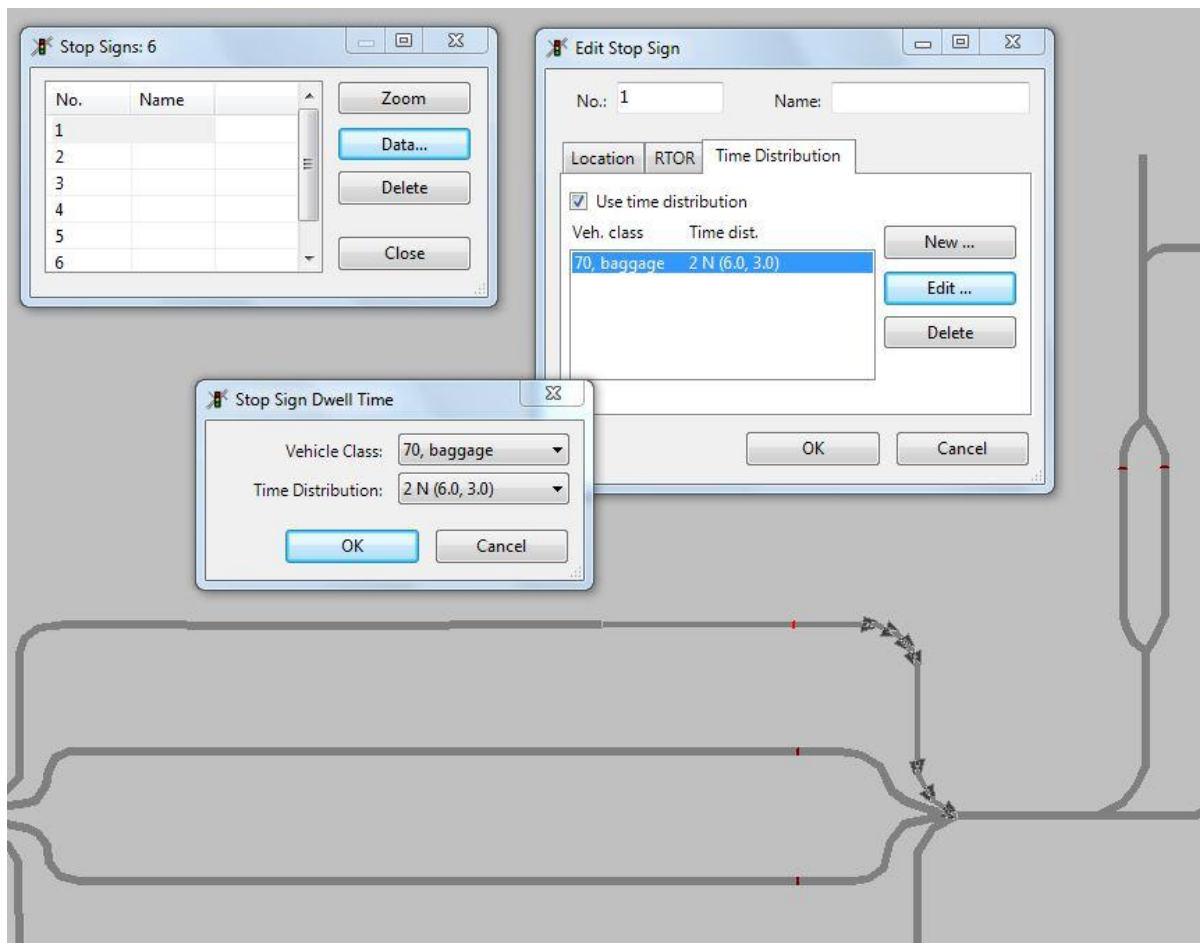


Figure 5.9 The VISSIM Model – Stop Signs

In this model, the normal distribution with the mean of 6.0 seconds and standard deviation of 3.0 seconds is used as in Chapter 4. After the baggage passed through the screening devices all the routes are merged into one and then split again to separate the baggage that are cleared by the first device and failed by the first device. The baggage that

have failed in the first device are subjected to secondary screening. According to the calculation in the previous chapter the false alarm probability is approximately 22.87%. This probability is represented by another route decision with ratio 2,287:10,000.

After finishing all the above steps the simulation model is ready to be run. To obtain statistics of the relevant data about the baggage behavior it is necessary to input special points on the network. These evaluation points are described in following section.

To record the necessary results for analysis, Data Collection Points, Travel Time Sections, and Queue Counters were inserted into the model. The Data Collection Points enable the user to record data about the total distance travelled in the network, number of vehicles, total queue delay time, and etc. In this case, only the counting of the number of vehicles (baggage) is used. Data Collection Points were placed right after the stop signs to monitor the throughput of the screening device. In addition to that, six Travel Time Sections were placed in the model (Figure 5.10). One of the travel time sections is highlighted. There are four Travel Time Sections for the primary screening and two for the secondary screening. These Travel Time Sections were used to calculate travel times and delay in each branch of the conveyor belt that leads to a screening device. The third data collecting tool are Queue Counters which were placed about 1 m before the screening point. After placing all the points, four evaluation files were configured to record the required data (Figures 5.11 and 5.12). For this model the following output files were selected: Data Collection, Travel Times, Queue Length, and Delay.

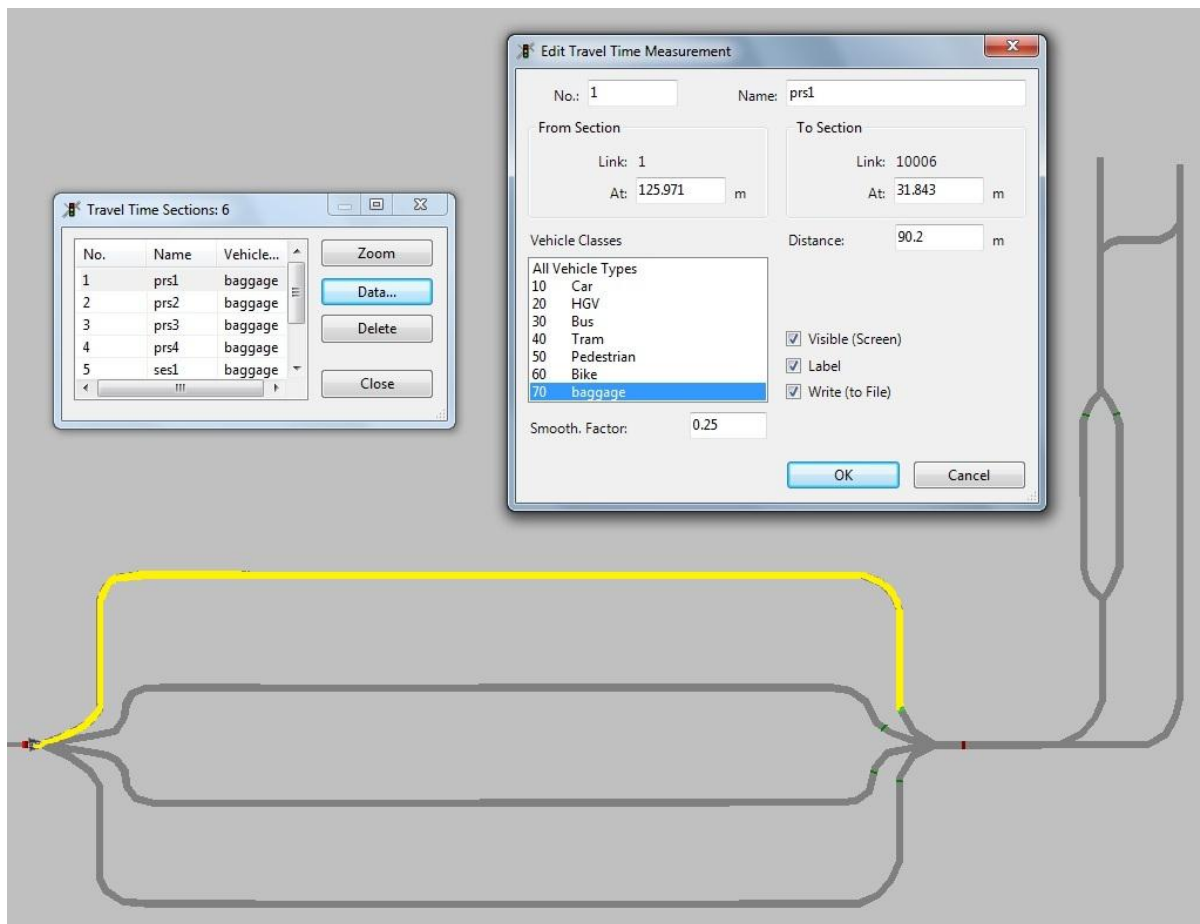


Figure 5.10 The VISSIM Model – Travel Time Sections

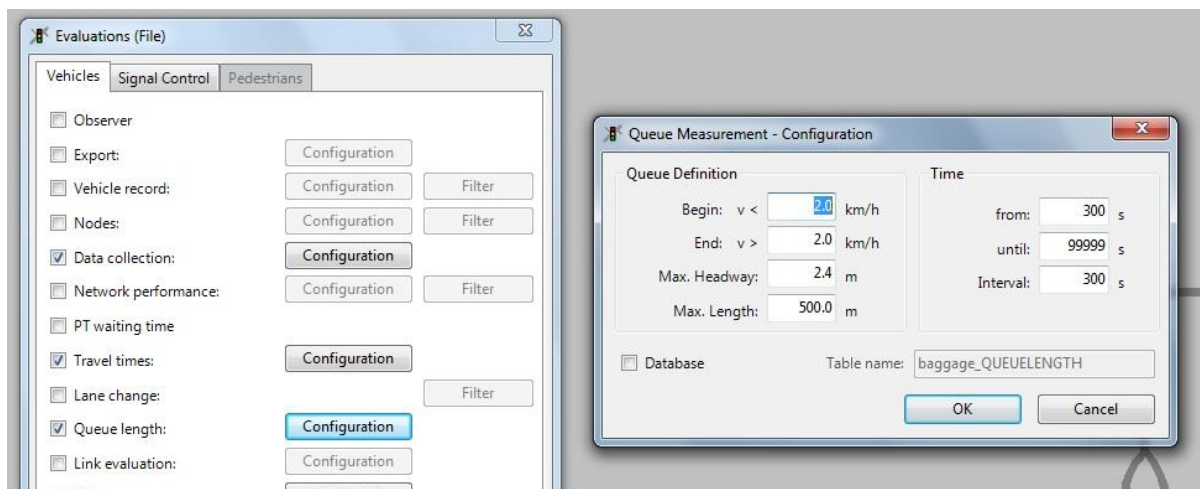


Figure 5.11 The VISSIM Model – Evaluation File: Queue Measurement



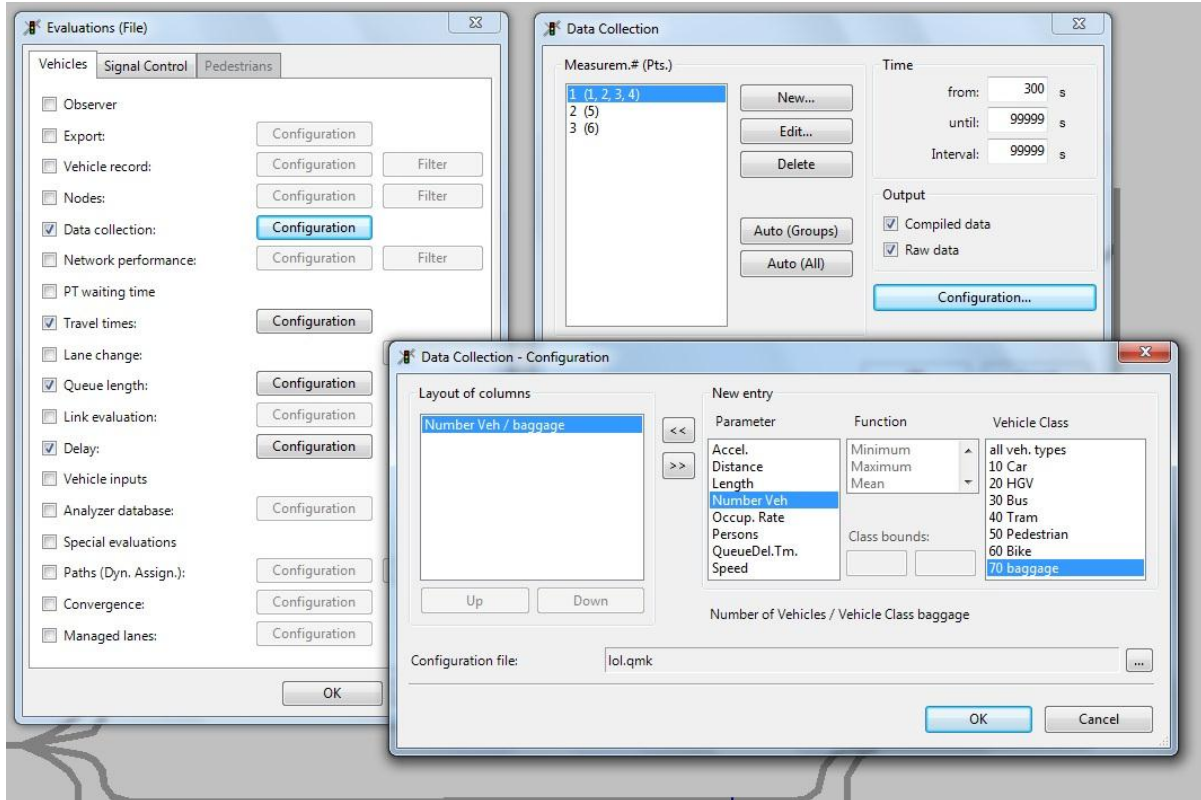


Figure 5.11 The VISSIM Model – Evaluation File: Data Collection

### 5.3 Results and Discussions

The simulation model was run 15 times with various values of random number seed. Random number seed is a parameter which initializes the random numbers in the model. Otherwise all the simulation runs would provide exactly the same results. Different random seed changes the profile of the arriving traffic, routing decision, inspection time, and etc.

The animation and results of the VISSIM model reveals a weakness in the queuing theory: the service time in the queuing model does not consider the time the baggage move from the beginning of the queue to the screening point which can take few additional seconds. This extra movement time can reduce the maximum number of bags a device can screened per hour. Even though the mean service time is  $b_1=6.0$  seconds in Chapter 4 and

mean dwell time = 6.0 seconds in the VISSIM model, there are longer queues and delays in the VISSIM model compared to results from the  $M/G/m$  queuing model. To compare the results, the input parameters for the queuing theory were changed. The mean service time was increased by 2.0 seconds and the arrival rate was set to 1,646 bags/hour (to be the same as in the VISSIM output). The arrival rate in the VISSIM model was set to 1800 bags/hour but the actual number of baggage which came within the hour observation was in average 1646 bags/hour. The real number of baggage screened was on average 1430 bags/hour (see Table 5.1). The number of baggage which passed through the screening device is lower from the number of baggage arrived because VISSIM deletes all the baggage when the simulation run ends. Even those not screened yet.

Table 5.1 The VISSIM Model – Results and comparison with queuing theory

	<b>number of bags screened</b>	<b>delay of bags [seconds]</b>	<b>queue length [bags]</b>	<b>travel times [seconds]</b>
<b>Device 1 - average</b>	579	171.33	34	251.35
<b>Device 2 - average</b>	757	226.87	56	293.16
<b>Device 3 - average</b>	758	227.43	58	298.62
<b>Device 4 - average</b>	766	218.76	56	291.70
<b>primary screening - average</b>	1430	211.94	204	284.56
<b>secondary screening - average</b>	383 (26.80 %)	9.97	negligible	40.79
<b>total</b>	1646	221.91	-	-
<b>max primary scr.</b>	-	539.70	474	622.10
<b>max secondary scr.</b>	-	47.10	-	78.80

#### Queuing theory results

<b>primary screening</b>	1646	10.89	9	-
<b>secondary screening</b>	377 (22.87 %)	0.97	1	-
<b>total</b>	-	11.86	-	-

#### Input parameters

	VISSIM	Queuing theory
<b>mean service time</b>	6 sec	8 sec
<b>standard deviation of screening</b>	3 sec	3 sec

Despite the mean service time was increased by 2.0 seconds to include the time the baggage moves from the beginning of the queue to be screened, the queuing theory provides significantly different results. According to the TSA statistics from 2006 the average waiting time was 3.79 minutes and the average waiting time in peak hour was 11.76 minutes.

## **5.4 Chapter Conclusions**

In this chapter, the VISSIM model for Level 1 CBIS is created for the purpose of testing the simulation software. The aim of this chapter was just to ascertain whether the VISSIM model is suitable to be used for the CBIS simulation. In comparison with the queuing theory, the VISSIM model seem to provide more realistic data which are closer to how the real screening process at the airport looks like. However, during the simulation runs some unexplained errors occurred, causing the simulation to abort. These errors were avoided by changing the value of the random number seed. A possibly reason of this model behavior could be due to the unusual parameter settings for the size, speed and car-following parameter baggage.

One thing that could be improved in this model is using the special module called Vehicle Actuated Programming (VAP) or Dynamic assignment to let the system decide where the baggage should go to be screened according to the queue length. This will increase the throughput of the CBIS model.

## Chapter 6: Summary

### 6.1 Conclusions

In the Chapter 3 an optimization methodology for checked baggage screening was developed to help find the detection thresholds and the sensitivity parameter of the primary and secondary screening devices. Two different approaches were considered to select the optimal solutions. In the first approach the minimum cost requirement was not taken into account and the thresholds and sensitivity parameters are selected according to the OCC. According to the OCC the EDS device for both primary and secondary screening is the most suitable solution. On the other hand, in the second approach the optimal values were chosen to have acceptable value of probability of false clear and the highest value of probability of true alarm at the same time. The results are different according to the probability of false clear. For  $\beta < 0.0001$  the best combination is BX and EDS regardless the order and for the value of false clear  $\beta < 0.001$  the optimal solution is to have two DX device.

In Chapter 4 the  $M/G/m$  queuing theory was used to estimate the optimal number of screening devices and to calculate the average waiting time and the average number of baggage in the system. The results obtained for two examples ( $M/G/1-M/G/1$  and  $M/G/4-M/G/2$ ) reveal that when the arrival rate is close to the maximum capacity of the system the values of average number of baggage in the system and average waiting time increase significantly. These results were then compared with the data given by the VISSIM model developed in Chapter 5.

In Chapter 5, the necessary changes to the settings of the VISSIM software to implement CBIS simulation has been illustrated. In comparison with the queuing theory, the data from the VISSIM model seem to be more accurate and are closer to the real screening

process at the airport. However, for some values of the random number seed the baggage stopped moving at the beginning of the input link and the simulation had to be aborted. There is no explanation for this unexpected error.

## **6.2 Future Research**

As for the future research and application of the VISSIM software in CBIS modeling the decision what screening device should the baggage go to could be improved by using special module called Vehicle-Actuated Programming (VAP) or Dynamic assignment. This will increase the realism and throughput rate of the VISSIM model of CBIS.

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## Appendix

Table A.1 The VISSIM Model – output data: number of vehicles

simulation no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
random seed	6	8	10	12	16	19	22	28	33	37	42	47	52	58	66	Average
Device 1	570	564	588	578	580	548	614	606	592	584	546	582	590	574	564	579
Device 2	764	774	790	770	716	738	780	772	756	772	740	776	694	758	752	757
Device 3	764	730	766	772	765	748	754	758	751	766	738	760	738	778	782	758
Device 4	766	786	752	762	756	770	776	763	786	774	746	763	762	755	774	766
primary screening	1432	1427	1448	1441	1409	1402	1462	1450	1443	1448	1385	1440	1392	1433	1436	1430
secondary screening	369	373	386	386	394	387	375	386	386	393	385	383	390	383	372	383
input*	1686	1611	1667	1664	1622	1611	1685	1658	1631	1668	1606	1649	1609	1665	1662	1646
percent	25.77	26.14	26.66	26.79	27.96	27.60	25.65	26.62	26.75	27.14	27.80	26.60	28.02	26.73	25.91	26.80

\* total number of incoming baggage before the simulation ended



Table A.2 The VISSIM Model – output data: delay

simulation no.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
random seed		6	8	10	12	16	19	22	28	33	37	42	47	52	58	66	
primary screening	Device 1	230.63	170.68	265.14	101.01	105.07	62.27	282.09	231.14	130.61	112.37	58.91	179.33	91.20	265.21	284.35	171.33
	Device 2	259.25	132.24	165.10	262.43	175.10	301.50	274.75	255.53	152.30	246.02	68.66	310.81	294.26	263.15	242.00	226.87
	Device 3	249.21	296.89	192.10	322.99	258.93	126.55	133.03	231.23	310.99	70.51	141.45	283.49	346.10	179.76	268.26	227.43
	Device 4	246.68	77.70	261.10	214.88	338.33	353.18	143.80	235.92	152.29	369.44	338.74	94.90	193.71	134.70	126.08	218.76
	average	246.44	171.27	221.40	225.00	221.96	212.13	208.68	238.41	187.75	200.07	153.90	216.79	233.71	210.80	230.75	211.94
secondary screening average		9.67	9.53	11.22	9.69	9.95	9.60	10.58	11.20	10.42	9.11	9.70	9.92	9.60	10.00	9.37	9.97
max																	
max primary scr.		479.50	443.80	489.20	457.40	495.70	518.00	459.40	503.10	458.30	513.40	539.70	469.90	477.30	437.40	528.20	539.70
max secondary scr.		29.20	28.90	47.10	31.20	40.00	31.60	36.70	45.50	37.90	38.40	33.50	42.30	36.90	40.30	27.70	47.10

Table A.3 The VISSIM Model – output data: travel times

simulation no.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
random seed		6	8	10	12	16	19	22	28	33	37	42	47	52	58	66	
primary screening	Device 1	311.71	250.96	347.11	179.67	183.67	140.10	364.76	312.42	209.94	191.31	136.51	259.80	169.50	346.97	365.88	251.35
	Device 2	326.12	196.65	230.31	329.52	240.63	369.09	341.68	322.42	217.34	312.73	131.74	378.45	361.37	330.36	309.03	293.16
	Device 3	315.18	364.17	340.35	390.07	325.32	190.22	197.04	296.92	378.41	133.06	205.34	349.75	413.90	244.70	334.93	298.62
	Device 4	325.20	153.50	257.02	293.44	419.45	433.89	221.00	314.66	229.68	450.65	419.18	170.93	272.14	211.69	203.04	291.70
	average	319.50	243.27	294.36	297.87	294.86	284.56	281.40	311.61	260.03	272.46	225.23	289.42	306.58	283.51	303.68	284.56
secondary screening average		40.48	40.35	42.08	40.53	40.80	40.42	41.40	42.06	41.23	39.94	40.55	40.71	40.35	40.79	40.17	40.79
max																	
max		560.00	512.20	572.20	525.60	577.40	600.40	532.50	586.40	526.40	595.70	622.10	538.70	546.10	508.00	612.50	622.10
max		60.30	60.10	78.80	62.00	71.70	62.10	68.90	77.30	70.80	69.40	64.60	74.50	68.30	72.80	59.30	78.80

## **Vita**

Nela Blejcharova was born on May 22, 1987 in Opava and raised in Hlucin, Czech Republic. She is the younger child of the family. She attended High School in Hlucin and graduated in 2006. In June 2010, Nela finished her Bachelor's degree in Technology in Transportation and Telecommunications – Air Transport major at Czech Technical University in Prague. Nela enrolled at UTEP and CTU in the fall semester of 2010 to obtain a Master's of Science in Civil Engineering Degree (MSc.) and Engineer Degree (Ing.) as a part of E.U-U.S. Atlantis dual-degree program.

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