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Analysing airport terminal performance using SLAM

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Summary

Over the past decades air traffic has experienced a tremendous growth. In recent years a lot of efficiency improvements have been made, especially in the air, enhancing, for instance, en-route capacity. Nowadays, bottlenecks are moving from the air to the airports themselves. Capacity studies are of great importance to get a better insight of airport terminal processes and the interaction between these processes. By means of capacity studies it is possible to identify airport terminal bottlenecks, which can give cause to search for improvements or optimisations.

A tool to perform similar capacity studies is SLAM (Simple Landside Aggregate Model). This report describes whether the capacity studies can be performed using SLAM. First an overview of the main processes in an airport terminal that need to be modelled is given. In addition, the basic input, modelling approach and output of SLAM is described to find out whether SLAM can be used for the analysis of an airport terminal.

A set of research questions has been formulated that are useful for the analysis of an airport terminal and which gives insight whether SLAM has the required input and output to answer these research questions. The most important results are that SLAM incorporates most of the required input and output, but has some shortcomings to answer a couple of the research questions.

In addition, the correctness and robustness of SLAM output has been verified according to a couple of tests. The most important results are that there are a couple of computational errors and shortcomings in SLAM that make the output unreliable.

Preface

This report covers my project on the analysis of airport terminal processes using SLAM, performed during my internship at the NLR (National Aerospace Laboratory). The project was done for my study "Bedrijfswiskunde & Informatica" (Business Mathematics and Computer Science) at the Vrije Universiteit Amsterdam.

I would like to thank the NLR for providing me with this internship. It has been a nice experience in which I have learned a lot about airports and how to write a report. I would like to thank my supervisors at the NLR, Dr. Michel van Eenige and Drs. Job Smeltink, for providing me with useful feedback and suggestions during the project and mainly in giving me advise how the results found could be described in this report. Finally, I would like to thank Dr. Geert-Jan Franx, my supervisor from the university.

Daan van Beusekom
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Contents

(75 pages in total)

List of abbreviations

AAS	-	Amsterdam Airport Schiphol
ADT	-	Average Dwell Time
IATA	-	International Air Transport Association
IOS	-	Index of Service
LOS	-	Level of Service
NLR	-	National Aerospace Laboratory
PK	-	Pollaczek-Khinchine
SLAM	-	Simple Landside Aggregate Model
SSCI	-	Self Service Check-In

1 Introduction

Over the past decades air traffic has experienced a tremendous growth, since more and more people use flying as a means of transportation. A lot of research has been done to improve the efficient handling of air traffic. One of the improvements was enhancing the en-route capacity. Though a lot of efficiency improvements have been made, especially in the air, bottlenecks are slowly moving from the air to the airports. Capacity studies of airports are of great importance.

Capacity of airports is determined by how aircraft and passengers / baggage are handled. In other words, the capacity depends on the processes on the airside (the apron and manoeuvring area) and the landside (passenger and baggage terminals) of airports. The current analysis on airport capacity mainly focuses on the processes on the airside and less on the processes of the landside. As a result, the insight of the processes on the landside and potential possibilities for improvements is considerably less then that of the processes on the airside. There are a lot of tools that can be used for the analysis of an airport terminal. One of these tools is SLAM. During the project insight is obtained whether SLAM can be used for analysing the performance of an airport terminal

Since an airport terminal can be seen as a complex system, first an overview of the main flows and processes in an airport terminal that need to be modelled is given. These flows and processes are described in Chapter 2. In addition, the basic features of SLAM, in which the flows and processes need to be modelled, can be found in Chapter 3. In Chapter 4 a list of research questions has been formulated. For each research question it is analysed whether SLAM possesses required input and output, to answer the research question. In Chapter 5, tests for the verification of SLAM are described followed by the results, in which three main shortcomings of SLAM are discussed. Chapter 6 winds up with the conclusions of the project. In addition, some recommendations for future research are given in Chapter 7.

2   Description of airport terminal flows and processes

In this chapter an overview is given which main flows and processes need to be modelled for the analysis of an airport terminal. An overview of flows and processes is given that is as generic as possible, such that it basically applies to any European airport. The two flows considered are the passenger flow, described in Section 2.1 and the baggage flow, which shall be discussed in Section 2.2. For each of the two flows a further differentiation into processes is made, in order to obtain a better insight about the complexity of an airport terminal.

2.1 Passenger flow

The complete passenger flow in airport terminals can be divided into three processes, based on the origin and destination of passengers. These are the departure, arrival and transfer passenger processes (see Figure 1).

- Departure: this process starts with passengers arriving at the airport terminal entrance (arrival landside) and ends when passengers have boarded an aircraft (departure airside)
- Arrival: this process starts with the passengers arriving by aircraft, entering the airport terminal, and ends when passengers leave the airport terminal using some sort of transport, i.e. by metro, bus, train or car.
- Transfer: the transfer process contains elements of the arrival and departure processes. From deboarding till walking in the piers and lounge areas, this process is identical to the arrival process. Starting at the lounge and piers, transfer passengers follow the same process as departing passengers.
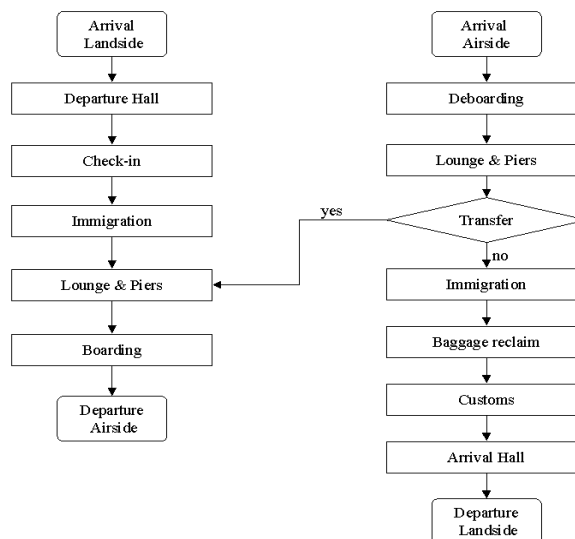

Figure 1: The passenger flow in an airport terminal

2.1.1 Departure process

From entering an airport terminal until the departure of their flight, departure passengers have to experience several processes as shown in Figure 2. Figure 2 is a further specification of Figure 1, in which a more detailed description of the departure process of passengers is given.
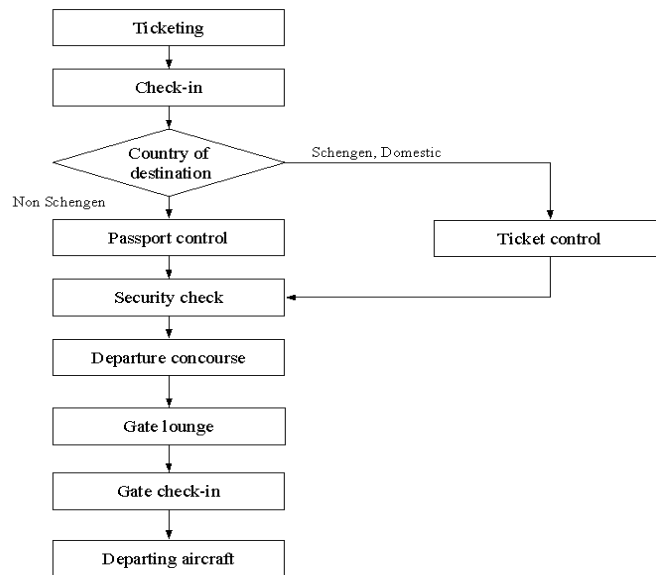
```
                    ┌──────────────┐
                    │  Ticketing   │
                    └──────────────┘
                           │
                    ┌──────────────┐
                    │   Check-in   │
                    └──────────────┘
                           │
                      ◇ Country of ◇  Schengen, Domestic
                      ◇ destination ◇ ─────────────┐
                           │                        │
                  Non Schengen                      │
                    ┌──────────────┐        ┌──────────────┐
                    │Passport control│       │ Ticket control│
                    └──────────────┘        └──────────────┘
                           │                        │
                    ┌──────────────┐                │
                    │Security check│◄───────────────┘
                    └──────────────┘
                           │
                    ┌──────────────────┐
                    │Departure concourse│
                    └──────────────────┘
                           │
                    ┌──────────────┐
                    │ Gate lounge  │
                    └──────────────┘
                           │
                    ┌──────────────┐
                    │ Gate check-in│
                    └──────────────┘
                           │
                    ┌──────────────┐
                    │Departing aircraft│
                    └──────────────┘
```

Figure 2: Departure passenger process

The departure process starts with passengers entering the passenger hall. Passengers with a ticket go to the check-in. Those passengers who still need to get their ticket first go to the ticketing facility to obtain it. Passengers who only have hand luggage can check-in at a self-service check-in (SSCI). Passengers with baggage check-in at an advised counter of the airline one is flying with. At check-in passengers get their boarding pass with information from which gate their aircraft will depart. After check-in, passengers enter the immigration process that consists of passport control and security check.

The first immigration process is normally the border between the public airport terminal area and the restricted area, which means that well wishers are not allowed to accompany departing passengers any longer and are left behind at the first immigration process. Passengers with a non-Schengen country as destination have to clear passport control. Passengers with a Schengen country as destination sometimes only have to clear ticket control, but sometimes they have to clear passport control as well. This depends on airport policy. After passport or ticket control a passenger moves on to the security screening area. Controls are conducted to ensure the safety and security of passengers. A passenger has to move through a metal detector, and an x-ray device checks hand luggage. Sometimes transfer

passengers have to pass through security screening as well, while moving to a connecting flight. After the attacks on 11-09-2001 security screening has become one of the facilities where capacity problems and service level problems are likely to form, since more security is needed, as is perceived by passengers, to guarantee the safety of passengers at airports.

After the immigration processes it is possible that some time is left before the flight of the passengers is scheduled to depart. If so, passengers can do some shopping, get something to eat or spend their remaining time at a lounge area (the departure concourse).

A certain amount of time before departure of their flight, passengers go to the gate from which their flight will depart. There, passengers wait in a gate lounge. Before boarding of the aircraft, passengers with a non-Schengen country as destination go through another passport control. Passengers with a Schengen or Domestic destination go through a boarding pass control.

2.1.2   Arrival process

Passengers who arrive at an airport, with the airport as final destination, experience processes as are shown in Figure 3. Figure 3 is a further specification of Figure 1, in which a more detailed description of the arrival process of passengers is given.
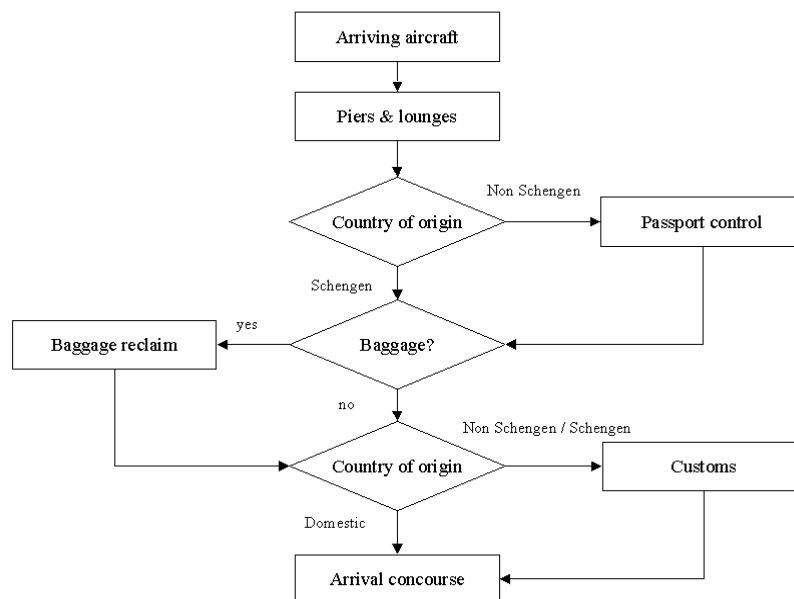

Figure 3: Arrival passenger process

The arrival passenger process starts when an aircraft has docked at a designated gate. Deboarding of the aircraft can be done indirectly by shuttling services or on foot through an aviobridge to proceed to the gate of the airport terminal. Passengers with a non-Schengen country as origin then go to passport control. Passengers with a Schengen country as origin, and who have baggage to reclaim can go directly to the baggage reclaim area. Passengers which do not have baggage to reclaim and do not have a Schengen or non-Schengen country as origin can do some shopping (arrival concourse) or leave the airport terminal using one of the possible transport possibilities such as train, car or metro.

At many European airport terminals, baggage reclaim is divided into two halls. The first hall is for non-Schengen arrivals, the second for Schengen arrivals. Baggage reclaim is considered as the interface between passenger and baggage flow. Several efforts and studies like that of IATA [7] have pointed out that the baggage reclaim process has a considerable effect on the overall performance of the airport terminal for arriving passengers. This fact is supported by the idea that passengers and their baggage do not arrive at baggage belts simultaneously. Long waiting times can be a result of a big difference between the arrival of passengers and their baggage, which negatively affect service levels. After baggage reclaim, all non-Schengen and Schengen passengers proceed to customs control. Customs control may have a deep impact on the airport operation and its level of supplied services, especially when passengers have to spend a long time at customs control. After customs control passengers can spend some time at shops (the arrival concourse) or leave the terminal using some sort of transport.

2.1.3   Transfer process

As already mentioned, the transfer passenger process is a combination of the arrival and departure processes. In Figure 4 the transfer process is shown, in which the arrival process is part of Figure 2 and the departure process is part of Figure 3.
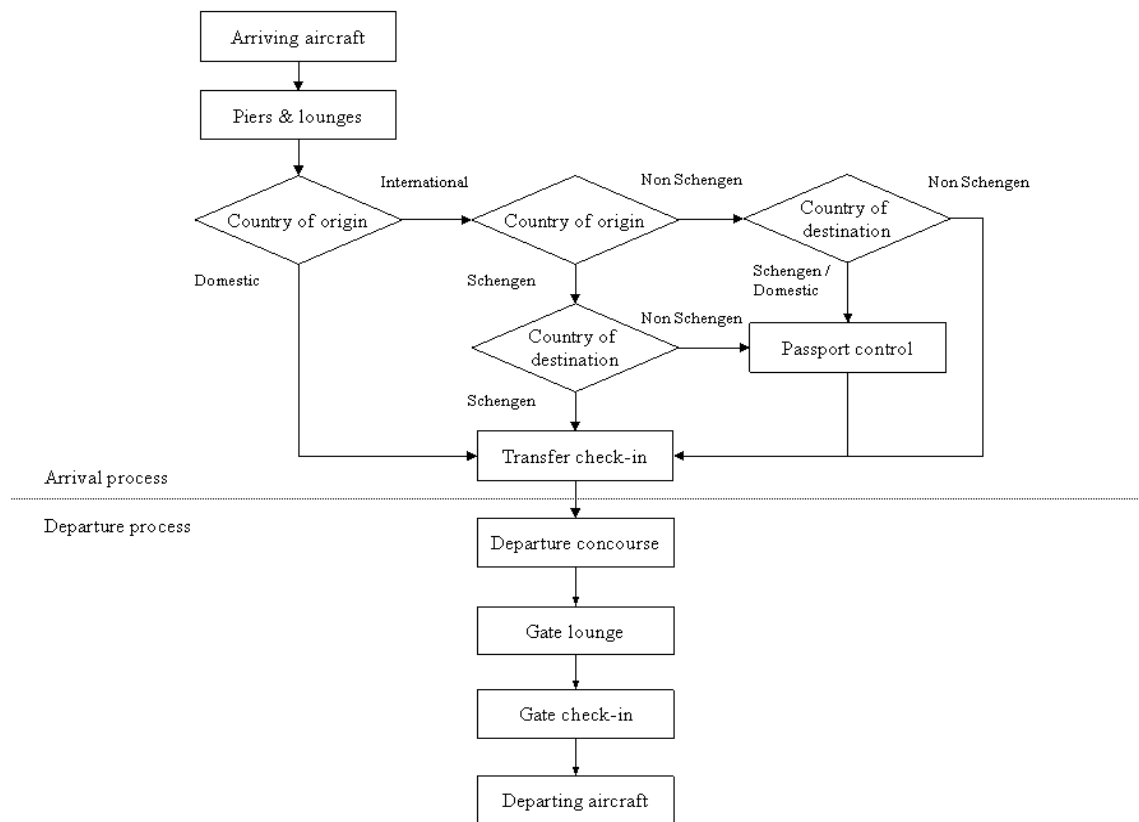
Figure 4: The transfer passenger process

The transfer passenger process starts when an aircraft has docked at a designated pier. Deboarding of the aircraft can be done indirectly by shuttling services or on foot through an aviobridge to proceed to the gate of the airport terminal.

The next facility that needs to be visited depends on the country of origin and country of destination of transfer passengers. Passengers with a Schengen country as origin and transferring to domestic or Schengen flights do not need to go to passport control. The same holds true for passengers with a non-Schengen country as origin and transferring to a non-Schengen flight. Passengers with a Schengen country as origin and transferring to a non-Schengen flight and passengers with a non-Schengen country as origin and transferring to a Schengen country go to passport control as is shown in Figure 4. After passport control transfer passengers can go to the transfer check-in if they need information about their connecting flight. When transfer passengers leave the transfer check-in area they are in the same state as departing passengers. If some time is left before a connecting flight is scheduled to depart, transfer passengers can do some shopping or move directly to the gate lounge

where they wait until another passport or ticket control is performed. After the passport or ticket control transfer passengers board the aircraft and wait until the aircraft takes of.

At many airports transfer passengers do not have to go to baggage reclaim, because their baggage is sorted on arrival and directly transported to a connecting flight. However, at some airports, transfer passengers first need to reclaim their baggage and check-in again. A more detailed and descriptive analysis of the arriving baggage process is provided in section 2.2.2.

2.2 Baggage flow

Like the passenger flow, the baggage flow of an airport terminal can be divided into three main processes: the departure, arrival and transfer baggage processes. Each of these processes shall be discussed in the following sections.

2.2.1 Departure process

Baggage of departing passengers goes through the different processes as is shown in Figure 5:

```
┌─────────────────┐                    ┌─────────────────┐
│   Baggage of    │                    │   Baggage of    │
│transfer passengers│                   │departing passengers│
└─────────────────┘                    └─────────────────┘
            ↘                          ↙
            ┌─────────────────┐
       ┌───→│  Transport to   │
       │    │  baggage hall   │
       │    └─────────────────┘
       │            ↓
       │    ┌─────────────────┐
       │    │Baggage screening│
       │    └─────────────────┘
       │            ↓
       │    ┌─────────────────┐
       └────│ Baggage sorting │
            └─────────────────┘
                    ↓
            ┌─────────────────┐
            │  Storage hall   │
            └─────────────────┘
                    ↓
            ┌─────────────────┐
            │Collection of laterals│
            └─────────────────┘
                    ↓
            ┌─────────────────┐
            │Transport to aircraft│
            └─────────────────┘
```
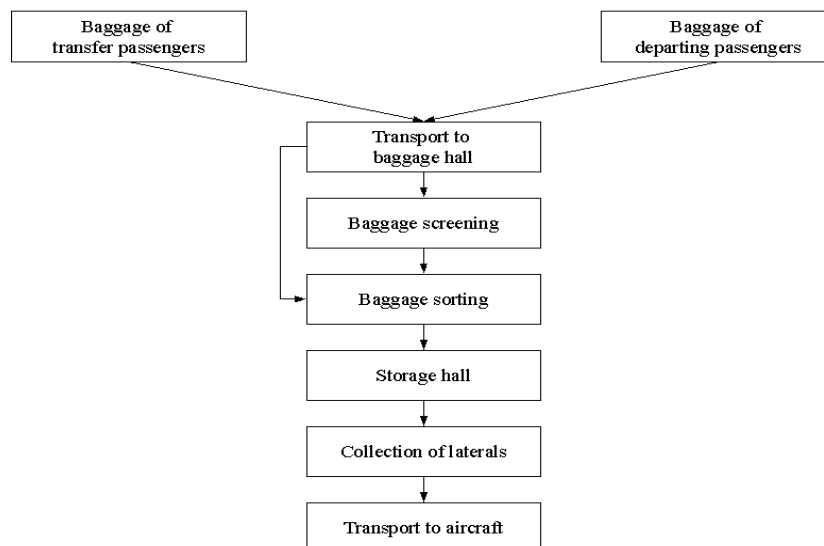
Figure 5: Baggage departure flow

When departing passengers have delivered their baggage at check-in, the baggage is transported to a baggage hall. Each airport has its own way of transporting the baggage from one location to another. In many cases, labels are applied to the baggage so they can be

scanned and the baggage is transported to a baggage hall where a specific baggage handler will process the baggage.

In the baggage hall, the baggage of departing passengers is screened for dangerous objects. After the baggage has been screened it is sorted by flight. After the sorting all baggage is temporarily stored until it can be transported to the correct aircraft.

Laterals of carousels are the destination of all baggage. From here the baggage is taken to the correct aircraft. One or more laterals are available for the collection of baggage for each flight. The laterals open a certain time before an aircraft will take off. From that moment on baggage for a flight can arrive on the lateral and will wait there until it is loaded on a car and transported to the aircraft.

2.2.2 Arrival process

The baggage of arriving aircraft goes through the processes as is shown in Figure 6:
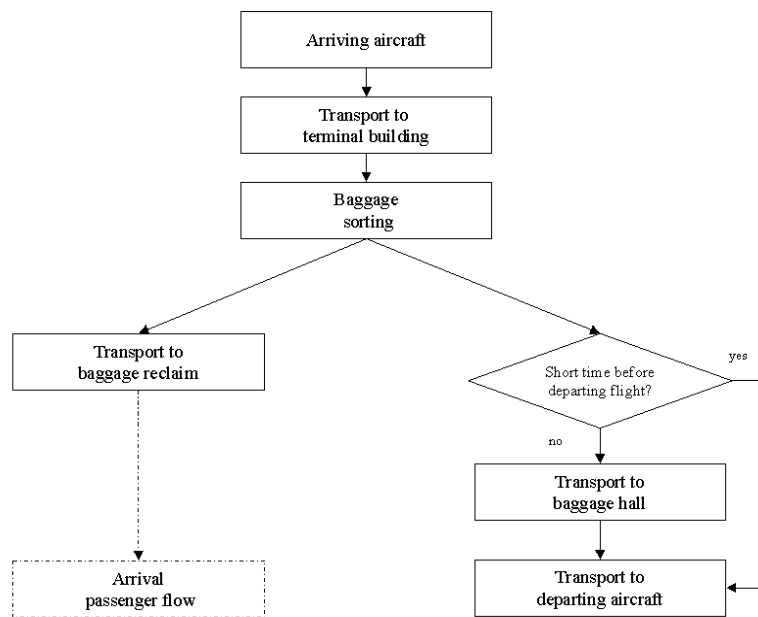

Figure 6: Baggage arrival process

An arriving aircraft may contain baggage of transfer passengers and baggage of passengers who have an airport as final destination. Baggage is transported to the airport terminal building where it has to be sorted. Baggage of passengers that have the airport as final destination is transported to the baggage reclaim area, where passengers reclaim their baggage. Baggage of transfer passengers is sorted by connecting flight. If a lot of time is left

before the connecting flight is due to depart the baggage is transported to a baggage hall, where it is stored until it can be transported to the connecting flight. Otherwise the baggage is transported directly to the connecting flight.

This process can be vital for service levels and capacity, since arriving passengers may be waiting for their baggage and connecting flights need to have all transfer baggage on board before they can depart. If the process takes to long, this can result in long waiting times at the baggage reclaim area and can cause flight delay of the connecting flight.

2.2.3 Transfer process

The transfer baggage process is a combination of the arrival and departure baggage processes as is shown in Figures 5 and 6. If an arriving aircraft has transfer baggage on board the baggage is transported to the airport terminal building and is sorted by flight. If then a short time remains before the connecting flight of transfer baggage is scheduled to depart, the baggage is directly transported to the connecting flight. Otherwise the baggage is transported to a storage hall until it can be transported and loaded onto the connecting flight. Depending on airport policy it is also possible that transfer passengers first have to reclaim their baggage or that transfer baggage is screened in a baggage hall. In many cases, transfer baggage is not screened, since this has already been done at the airport of which the transfer passengers originate.

3   SLAM

As already mentioned in the introduction, SLAM has been selected to model and analyse the airport terminal processes described in Chapter 2. In this chapter some basic features about the tool are described to give a first insight into the capabilities of SLAM[1]. In Section 3.1 the program structure of SLAM is described. After Section 3.1, the basic input requirements and possibilities of SLAM are mentioned in section 3.2. In Section 3.3 it is explained how SLAM handles all processes of an airport terminal modelled, which results in output. Finally, the output that can be obtained using SLAM is described in Section 3.4.

3.1 Program structure

SLAM is designed for estimating capacity and delays in airport passenger terminals. The general purpose of SLAM is to answer "what if" questions about alternative configurations of the various processing and holding facilities at an airport terminal. SLAM consists of a network of modules, one for each facility of the airport terminal modelled. These modules use simple mathematical formulas (see [2] and [3]) to estimate the capacity of each facility (in terms of passengers per hour) and the associated level of service (LOS).

SLAM has a graphical user interface (SLAM-Workbench (Wkb)), and an engine (SLAM-Solver). The task of the Wkb is to assist the user in providing SLAM the input data, so graphical and textual output can be created. Both input and output files are text files composed of tables, so that they can be read and manipulated using programs like MS-Excel or MS-Access (see Figure 7).
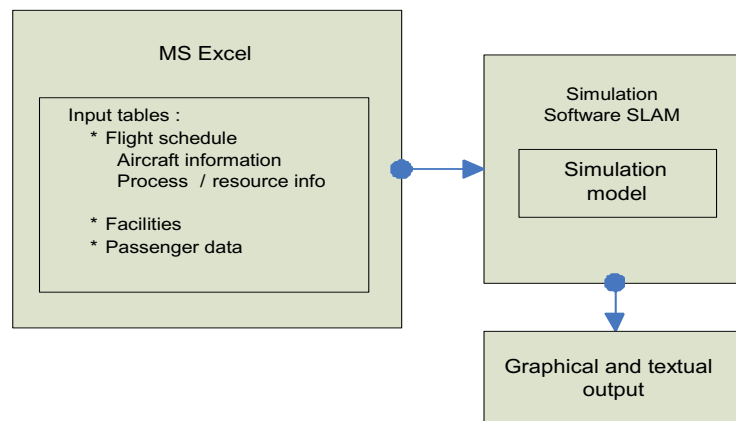

Figure 7: SLAM data flow

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[1] Note that the version of SLAM used is not the last updated version available. The user manual of SLAM and the version used do not correspond with each other.

3.2 Input

The SLAM input file is a database consisting of tables. A detailed overview of all tables used by SLAM and the input parameters for each table can be found in Appendix A. The most important input tables are described below:

Flight schedule:
There is a table for all departure flights and a table for all arriving flights. In these tables it is possible to input information about flights, like the departure or arrival time or the number of passengers on board of a flight. See Figure 8 for an example.

	Name	DepartureTime	PaxLoad	FlightClass	ExpectedDelayMinutes	Routing	Sel1	Sel2
1	D1	06:40:00	100	Departure	0	DepAirlineARouting	A	NONE
2	T3	05:50:00	100	Transfer	0	T_PierB_Routing	A	NONE

Figure 8: The flight table in SLAM

In addition, a table is present in which all references of the flight class can be made. See Figure 9 for an example. Input possibilities are:
- The arrival profile of passengers;
- The service profile at the facilities used;
- The arrival profile when passengers arrive at their gate;
- The time needed to board an aircraft (GapTimes); and
- The type of passengers that are on board (PaxClassList).

	Name	Type	ArrivalProfile	ServiceProfile	GateArrivalProfile	GateCheckinData	GapTimes	PaxClassLis
1	Departure	LONGHOUL	DepProfileGroup	DepSrvGroup	GateArrPrfGroup	GateCheckinPassPerc	StdGapTimes	PCL
2	Transfer	LONGHOUL	TProfileGroup	TSrvGroup	GateArrPrfGroup	GateCheckinPassPerc	StdGapTimes	PCL

Record 1 of 2

Figure 9: The flight class table in SLAM

Routing of passengers:
For each flight, a routing of the passengers on board can be assigned. In the routing table all different routing passengers need to follow can be stored. For each routing, information about which facilities passengers need to visit and the order in which they visit them can be inserted. See Figure 10 for an example routing.

Figure 10: The routing table in SLAM

The arrival profile of passengers:

Another possibility is to assign an arrival profile of passengers to each flight. In the profile table all different arrival profiles of passengers one wants to use can be inserted. The arrival profile represents the time at which passengers arrive at the different facilities. For example, if a flight is scheduled to depart at 10.00 AM, passengers of that flight start arriving at the airport a certain amount of time before the departure time. An example arrival profile is shown in Figure 11.

Figure 11: The profile table in SLAM

In SLAM only a single arrival profile can be assigned to each arrival flight. For the departing flights one profile can be assigned to the arrival of passengers at their gate and one arrival profile can be assigned to all other facilities passengers visit along a routing.

The service profile at facilities:

A third option is assigning a service profile to each flight. In the profile table all different service profiles used can be inserted. A service profile represents the number of counters that will be opened for a flight throughout the time passengers of that flight arrive at the airport. It is possible to change the number of counters that are opened throughout the time passengers arrive, before a flight is scheduled to depart. This implies that for each facility the number of counters is assigned per flight. See Figure 12 for an example service profile.

Figure 12: A service profile for a departing flight in SLAM

Facilities:

It is possible to insert different facilities in SLAM. The different tables that are available are listed in Table 1. For each facility it is possible to insert information like the maximum number of counters available, average service times and available space in front of each counter. An example for check-in is shown in Figure 13.

- Ticketing
- Check-in
- Passport control
- Security
- Baggage reclaim
- Customs
- Arrival concourse (shops)
- Flow facility
- Gate lounge
- Departure concourse (shops)
- Sorting facility (baggage)

Table 1: Facility tables used in SLAM

Figure 13: The check-in table in SLAM

<u>Passenger information:</u>

Next to the arrival profile of passengers, there are tables in which other passenger information can be inserted. The most important information that can be stored in these tables is:

- The average amount of baggage passengers have with them;
- How much space a passenger requires;
- The fraction of transfer passengers that are on board of a flight; and
- The fraction of passengers that has someone with them to say farewell.

Furthermore, there are some additional comments that can be made about how the different groups of data need to be inserted in the input to make SLAM work:

- For a flight, only a single routing of the passengers that are on board of that flight can be assigned. If more than one routing is assigned, only the first routing found is processed;
- For each flight only one arrival profile of passengers can be assigned;
- For each facility a reference can be made which type of passengers make use of that facility, e.g. arrival, departure or transfer passengers. Further subdivisions like Schengen or non-Schengen passengers or economy / business class passengers can also be made; and
- For each routing assigned to a departing flight a facility must be declared that passengers use first.

3.3 Model

SLAM is a simple analytical (as opposed to simulation) aggregate model to estimate the capacity, delays and possible congestion situations in an airport terminal. Capacity of a

terminal component is defined by the number of passengers or baggage that can be served by one single component per unit of time. Capacity can be estimated for a single component, like a facility, or for the entire landside. SLAM requires only simple input. Output is provided within a few seconds. Furthermore, SLAM can easily be modified to create alternative airport terminal configurations. SLAM can be run on a standard pc.

SLAM consists of a network of modules, one for each facility inserted in the input file. As can be verified in Table 1, all facilities needed to model the passenger flow, as described in Chapter 2, are present. However, for the baggage flow, the only facility that can be created in SLAM[2] is the sorting facility for departure baggage. The arrival baggage process is simply handled by using a table as is shown in Table 2.

BEGINTABLE	BagClaimTime			
BaggageTime	10	20	15	30
ENDTABLE				

Table 2: The table used for the arrival baggage process

In this table, the first two numbers respectively denote how long it takes for the first and the last passenger of a flight to arrive at baggage reclaim. The third number denotes the time needed for the first baggage of a flight to arrive at baggage reclaim. The fourth number denotes the time needed for the last baggage of the same flight to arrive at baggage reclaim. All information that was available about each module concerning the formulas and distributions used can be found in [1], [2] and [3].

The modules can be divided into three groups of facilities, of which each group needs different input data, depending on what passengers do at the facility. The three different groups of facilities are:

- Processing facilities;
- Holding facilities; and
- Flow facilities.

Since not a lot of information was available about the formulas used in SLAM, some tests have been conducted to analyse how SLAM translates input data into output. Using trial and error tests it has been tried to find out how this translation takes place. The most important findings are described below.

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[2] The user manual of SLAM does incorporate the baggage facilities. Apparently, the user manual of SLAM is made for a more recent version of SLAM. The version used during this internship does not contain the baggage facilities yet.

Processing facility

Processing facilities are the facilities that handle / serve passengers or baggage, e.g. check-in, baggage sorting, security check, passport control, baggage reclaim and customs.

Nowhere in the information available about SLAM it is explicitly stated which queuing models are used. Information provided in [2], the fact that service profiles are used at facilities and the arrival profiles used indicated that the processing facilities are modelled using the *M/G/c* queuing model. *M/G/c* is a form of the Kendall notation. The *M* indicates that the arrival of passengers is modelled as a Poisson process. The *G* stands for "general" service times distributions. The *c* is an integer, representing the number of counters available at a facility. More information about queuing models can be found, for instance, in [11], [12] or [15].

Basically, the *M/G/c* queuing model computes the expected waiting time of passengers, given the service time distribution and the arrival intensity λ, which are supposed to be constant in time. In SLAM the *average dwell time* (ADT) of passengers is approximated by the total time passengers have to wait in queue plus the time being served. According to information found in [1] the ADT is calculated by Formula 3.1.

$$ADT = \frac{1}{\mu} + \frac{\lambda\left(\sigma_a^2 + \frac{\sigma_S^2}{c}\right)}{2(1 - \frac{\lambda}{\mu c})}, \qquad (3.1)$$

where

λ = the arrival intensity of passengers

μc = the potential service rate

σ_a^2 = the variance of the inter-arrival time of passengers

σ_S^2 = the variance of service times

c = the number of servers available

This formula seems to be derived from the *Pollaczek-Khinchine* (PK) formula, which represents the *M/G/1* queue. The PK formula calculates the expected average time passengers spend waiting at a facility using the average arrival rate of passengers λ, a stochastic service time S and variance of the service time σ_S^2. The time passengers have to wait in queue (W_q), can be given as follows:

$$W_q = \frac{\lambda E[S^2]}{2(1-\frac{\lambda}{\mu})} = \frac{\lambda(\frac{1}{\mu^2} + \sigma_S^2)}{2(1-\frac{\lambda}{\mu})}, \tag{3.2}$$

where $\mu = 1/E[S]$ denotes the service rate and $E[S]$ denotes the expectation of S. There are two thinkable ways that the creators of SLAM used to transform the PK formula into Formula 3.1, but neither uses σ_a^2 to calculate the ADT. In fact, $\sigma_a^2 = 1/\lambda^2$, since the arrival process is a Poisson process. It is therefore unclear how Formula (3.1) is intended. For more details, see Appendix B.

A more fundamental problem is the fact that the PK formula is only valid for stationary queuing systems and can therefore not be used with time-varying arrival processes which are present in airport terminals.

Processing algorithm

To calculate output like the ADT, first information about all parameters of Formula 3.2 is needed.

According to research done by IATA (see [9]) the arrival distribution of passengers for a departure flight can be described by an S-shaped form (see Figure 14), which can best be described by an Erlang or Gamma distribution.
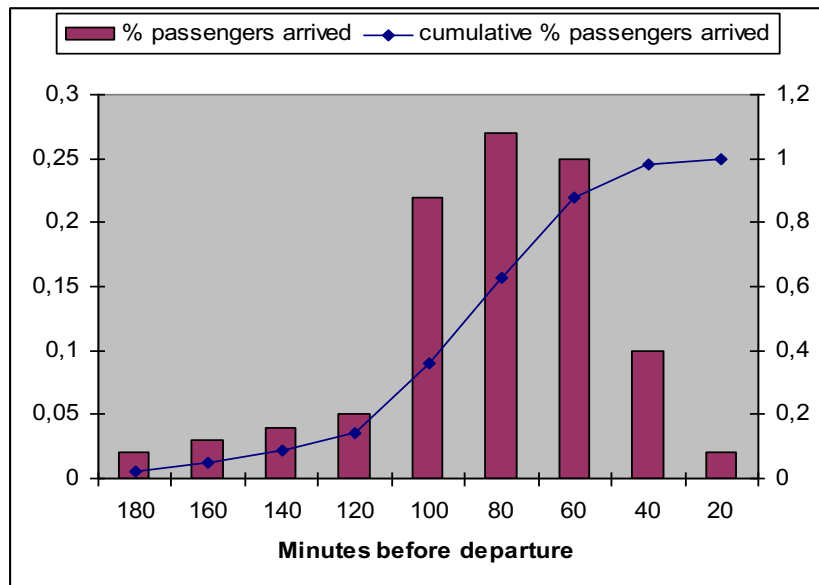

Figure 14: Graphical representation of an arrival profile

The arrival process is non-stationary, since the number of passengers that arrive during each time period is not constant. As already described in Section 3.2, the input for SLAM is a cumulative arrival profile as is shown in Table 3. The arrival profile represents the cumulative fraction of passengers that arrive a certain amount of time before a flight is scheduled to depart.

Profile	Minutes before departure of a flight	Cumulative fraction of passengers that have arrived at the airport of a single flight
Profile 1	180	0.02
Profile 1	160	0.05
Profile 1	140	0.09
Profile 1	120	0.14
Profile 1	100	0.36
Profile 1	80	0.63
Profile 1	60	0.88
Profile 1	40	0.98
Profile 1	20	1.00

Table 3: An arrival profile that can be assigned to a flight

Apparently, SLAM calculates the cumulative arrival profile $\lambda(t)$ for each facility created in the input file. This is done by running through all flights that are created in the input file. For each flight it is checked whether the facility looked at is present in the routing assigned to the flight. If so, the arrival profile assigned to the flight is assigned to the facility as well. Adding all flights gives $\lambda(t)$ of the facility throughout a day. It turns out that the same arrival profile is assigned to all facilities passengers visit along a routing, except for the arrival at the gate, which has a separate arrival profile. Secondly, SLAM uses provided information in the input file about service times (μ) and the number of available counters (c) throughout a day to approximate output like the ADT and average queue length. It is unclear how formula (3.2) can be used in SLAM, without having σ_S^2 as input for the different processing facilities. (Under these circumstances, the most reasonable thing to do would be to assume exponential service times. Then the *M/G/c* model reduces to the *M/M/c* model, which is much easier to analyse. For more details, see [11], [12] and [15]).

Holding facilities

Holding facilities are areas of the airport terminal where passengers wait for service or areas where passengers spend remaining time before they need to board their flight. An example of a waiting area is the area before check-in, where passengers have to wait for the check-in counters of their flight to open. Some other examples of waiting areas are waiting rooms at

the gates, baggage reclaim areas and waiting rooms for passengers in transit. Examples of holding areas are departure lounges, franchising and service areas. In SLAM the holding areas are used to model passengers who, e.g. wait or shop, before moving on to the next processing facility or leaving the airport terminal by boarding an aircraft or leaving the airport terminal. The time when passengers make use of the holding areas can influence the arrival time at processing facilities. For example, if someone waits a while before checking in, the arrival time at check-in and the other facilities along a routing will be different than when a passenger checks in immediately.

Flow facilities

Passengers use flow facilities to move from one processing or holding facility to the next processing or holding facility they visit along a routing. Examples of flow facilities are corridors, escalators and people movers. SLAM uses the time spent in a flow facility to approximate the total time a passenger spends in an airport terminal.

3.4 Output

As already mentioned in Section 3.1, SLAM can estimate the capacity of each facility (in terms of passengers or baggage per hour) and the associated level of service (LOS). Section 3.4.1 introduces the criteria SLAM uses to calculate the capacity and associated LOS. A general overview of all possible output in SLAM is given in Section 3.4.2.

3.4.1   Criteria

The criteria that will be discussed are *level of service* (LOS), *index of service* (IOS) and the *W80-percentile.*

Level of Service (LOS)

The s*ervice level* in a terminal is established by the passenger's perception of the service quality and conditions on one or more components. Standard measures of the level of service are: waiting time, service time, crowding, availability of restaurants, shops, etc. and a proper arrangement (in terms of space) for passengers, baggage and visitors.

In SLAM (also see [2]), LOS measures the quality of the service offered at one or more facilities. This is done by considering threshold values or minimum tolerable service levels (LOS target). The best known and most widely used factors are given by IATA [9], in which the LOS standards are defined both in terms of time (maximum acceptable waiting time) and

in terms of space (area available for each waiting passenger). A few LOS standards of IATA are listed in Table 4. The factors range from LOS = A (best) to LOS = E (worst).

	A	B	C	D	E
Check-in	1.6	1.4	1.2	1.0	0.8
Bag reclaim area	1.6	1.4	1.2	1.0	0.8
Holding area	1.4	1.2	1.0	0.8	0.6
Waiting area	2.7	2.3	1.9	1.5	1.0

Table 4: Level of service standards (square meter per occupant)

Index of Service (IOS)

Index of service (IOS) is a quantitative measure used in comparison with the numerical values of IATA tables and is defined by the available area per passenger. For processing facilities IOS is calculated as followed:

$$IOS = \text{area } (m^2) / (\text{passenger flow})*(\text{ADT in hours}). \qquad (3.3)$$

For example, consider Table 4 that reports the space standards for a check-in. Assuming that the check-in area of a given airport is $700\,m^2$, the number of passengers arriving during the peak hour is 3600 and the ADT per passenger is 0.15 hours, the IOS for that facility is 1.29 m^2 per passenger, corresponding to the C LOS.

W80-percentile of passengers

In SLAM not only output of the ADT can be given, but also the 80% percentile of the dwelling time. For example, it is possible that a service level is maintained, which states that 80% percent of the passengers have to wait less than 5 minutes at a facility. If such a service level is incorporated, SLAM gives as output the 80% percentile dwelling time of the passengers at a facility during a selected period of time.

3.4.2 Output options

SLAM provides textual and graphical output for each facility. In the textual and graphical output different output measures are provided. Furthermore, a table of the delay of departure flights is created.

Textual output

The textual output mainly contains information about the peak hour that has been chosen for a run. The output given for a facility differs, depending on the type of facility and what information is relevant. Figure 15 shows an example for passport control.
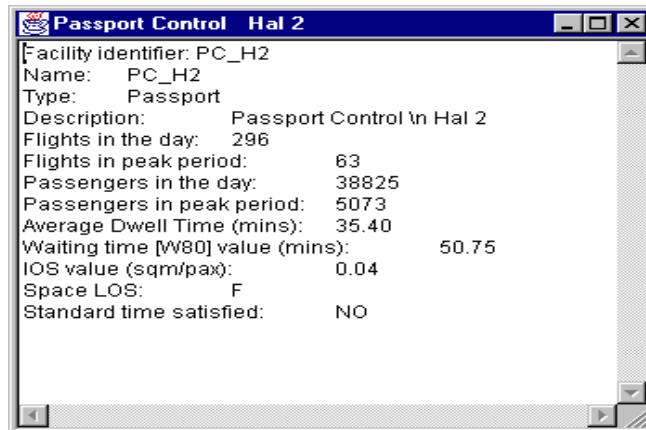

Figure 15: Textual output of SLAM

A detailed overview for each facility is provided in Appendix C. Here, only the output possibilities are summarised that can be created:

1. The number of flights that correspond to the facility;
2. The number of flights that arrived / departed during the peak hour;
3. The number of passengers that make use of the facility;
4. The number of passengers that make use of the facility during peak hour;
5. The ADT during peak hour;
6. The 80% percentile dwelling time of passengers during peak hour;
7. The LOS level during peak hour;
8. Index of service (IOS) for the peak hour; and
9. Output whether the average service time threshold is exceeded or not.

Graphical output

The graphical output is divided into two parts. First of all a window is created with the LOS levels throughout a day for each facility (see Figure 16 for an example).

Figure 16: LOS levels of facilities throughout a day

In addition, for each facility, a window can be displayed with different output throughout a day. The data that is used to create the graphical output is stored in a data file. A detailed overview of output that can be plotted for each facility can be found in Appendix B. Figure 17 shows the different output that can be plotted for passport control, a processing facility.
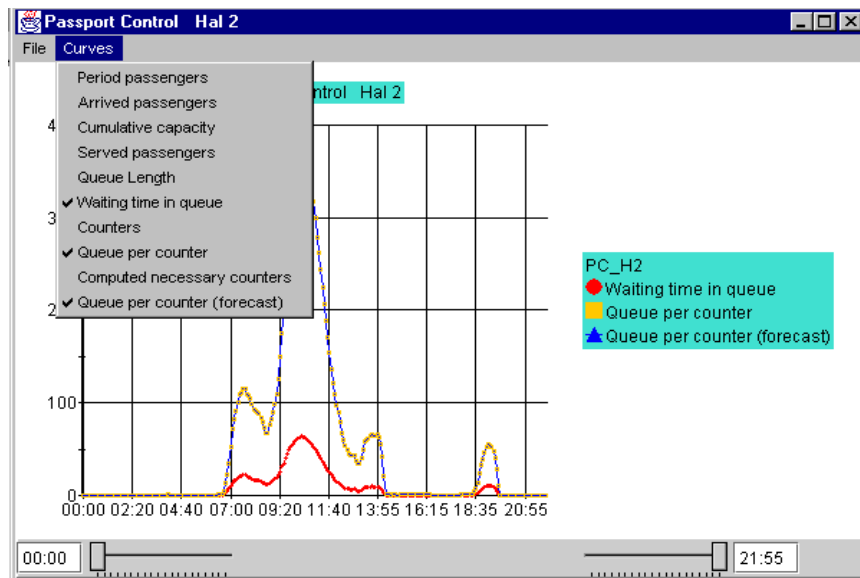
Figure 17: Graphical output of SLAM

Output of flight delays

An output table is created in which the potential delay of flights can be found. The delay is only given for all departure flights. See Figure 18 for an example.

	Departure ID	Departure Time	Total Due To Pax Delay	Total Due To Bag Delay	Additional Delay	Total Delay
1	D1	06:40:00	17.447	0	17	17
2	T3	05:50:00	7	0	7	7

Figure 18: Output of flight delay

As is shown in Figure 18, passengers or baggage can cause the possible delay. The delay is given in minutes.

4   Research questions

In this chapter a set of research questions have been formulated to obtain interesting information about the processes described in Chapter 2. For each research question it is analysed which input and output are needed to answer the research question and whether SLAM incorporates those input and output. The research questions give a better insight what possibilities a tool should have concerning input and output. In addition, the results give a first impression whether an analytical tool like SLAM can be used to analyse the performance of an airport terminal. In this chapter only the input and output are reviewed. Nothing is yet said about the modelling approach used for the calculation of the output. This is done in Chapter 5.

The research questions formulated focus on different areas of interest. The first four research questions, which are described in Sections 4.1 through 4.4, focus more on how and where problems can arise in airport terminals. The first research question discusses which bottlenecks can be present in an airport terminal and how they can be identified. The objective of the second research question is to find out how small changes in parameter values, like the average service time at a facility, affect airport terminal performance. The third research question formulated focuses on how an increase of security can affect airport terminal performance. In the fourth research question it is discussed how an increase of passengers can affect airport terminal performance. Sections 4.5 through 4.8 focus more on improvements and optimisations in an airport terminal. In these sections, the alteration of a flight schedule, a decrease of the time passengers or baggage need to spend in an airport terminal, the effect of different routing of passengers and the separation of economy and business class passenger processes are discussed respectively.

Results whether SLAM has required input and output to answer each research question is summarised in Section 4.9. These results are obtained using the information of SLAM described in Chapter 3, the user manual of SLAM (see [1]) and some simple test runs.

4.1 Bottleneck analysis

Generally speaking, passengers do not like waiting a long time at the processing facilities they need to visit. If, on average, passengers have to spend a long time at processing facilities, it is possible that passengers are delayed to such extent that they do not arrive at a gate on time which causes a flight delay. This is not in the best interest of the airlines and the airport itself,

since it can cause delays of flights that are scheduled to arrive or depart and has a negative effect on service levels.

A bottleneck analysis can point out where in an airport terminal problems lay, what the cause of the bottleneck is and how it affects airport terminal performance. For example, long average waiting times and queue lengths at facilities can have a negative effect on service level targets, but can also delay passengers to such extent that they do not arrive at their gate on time.

A way to look whether there are bottlenecks in an airport terminal is by looking at the difference between the minimum time a passenger needs to spend in the airport terminal and the actual time a passenger spends in the airport terminal. If relatively a large difference between the two is present, it is likely that a bottleneck is present in the airport terminal. For a departing passenger, the total time a passenger spends in an airport terminal can be given by the average dwell time spent at all facilities visited along a routing and the average walking time needed to get from one facility to the next.

The minimum time spent in an airport terminal can be computed by assuming that a passenger does not have to wait for service at processing facilities visited along a routing. If, relatively, a large difference between the minimum and actual approximated total time is present, one can assume that there is a bottleneck present in the airport terminal.

To find the bottleneck, information about the average waiting time, queue length and available space per passenger can be used. The bottleneck is the facility that delays passengers to such extent that the difference between the minimum time a passenger needs to spend at the facility and the actual time spent at the facility is large. In other words, the facility at which a passenger is delayed a lot longer than is actually needed can be seen as a bottleneck.

4.2 Changing input parameters

Changing input parameters can give insight how robust a model used is and how changes affect airport terminal performance.

A model can be called robust, with respect to a certain input parameter, if a small change in that parameter induces only a small change in the output. Robustness has important consequences for data analysis. If a parameter is robust, then the accuracy of its estimation is

of less importance than for a parameter that is not robust. Robustness can take many forms. Often it is considered with respect to a number, but it can also be with respect to the form of the distribution of a random variable. Knowing for which parameters the model is sensitive is one side of the coin; knowing which system parameters are likely to change is another. For an airport terminal parameters like the arrival rate of passengers, service times at counters and the number of counters that are opened during a time period can have a sensitive effect on airport terminal performance.

One important task of airport managers is to make sure that service level targets are met. A way to improve service levels is to increase the capacity at a facility. Yet, increasing the capacity may not be very cost effective, since more costs will have to be made to obtain the service levels. Thus the break-even-point has to be found between the costs that have to be made and the changes that are applied to increase service levels. In addition, it is important to analyse what effect a change at a facility has on other facilities that are visited next by passengers. For example, the time at which passengers arrive at passport control depends on the fact to what extent they are delayed at all previous visited facilities. Furthermore, it is possible that a change at check-in has a positive effect on service level targets at check-in, but has a negative effect on the service levels at a next facility that has to be visited by passengers.

To perform an analysis as described above, it must be possible to insert the processes present at the airport terminal under examination, incorporating all possible passenger routings. In addition, it must be possible to actually change the parameter values, which will be tested to evaluate the robustness of the model.

Output concerning capacity, (average) queue length, (average) waiting times and LOS levels can be useful to evaluate the effect of small changes in parameter values. For example, if the number of counters available at a processing facility is changed, it is likely that it will affect the average waiting time, queue length and available capacity of that facility. This can be confirmed by looking at the formula used in SLAM for the ADT of passengers at facilities, which is described in Section 3.3. If the number of counters available at a facility is increased, the capacity, or in other words the number of passengers that can be served during a period of time, of that facility increases as well. In addition, if the arrival rate of passengers and the service time at that facility stay the same, the average dwell time of passengers at that facility decreases.

4.3 Different security procedures

In recent years security has become an important issue at airport terminals. Especially the terrorist attacks on 11-9-2001 created the feeling that more security is needed so passengers have the perception that they fly safe. Increase of security measures could change the performance of an airport terminal by affecting, for example, the total time passengers or baggage spent in an airport terminal or the ADT of passengers at a security facility. If so, the question rises whether passengers are prepared to spend more time at security checks if it means that their journey will be a safer one. Even when passengers are prepared to spend more time a security checks, airport managers must make sure that security does not become an airport terminal bottleneck. For instance, security can become a bottleneck when passengers are delayed at the security check to such extent that they cannot arrive at their gate in time any longer. An analysis can be performed to provide information how different security procedures affect the airport terminal performance. The results of the analysis can then be used to determine which of the selected security procedures is best. Performance measures that can be used for determining the best security procedure are, for instance, effect on flight delay, the delay of passengers at security facilities and the total time a passenger has to spend in an airport terminal.

To perform this analysis it must be possible to apply different security procedures in the input. For example, the following procedures might be analysed:
- Is it best to screen baggage at check-in or in the baggage hall?
- Where along a passenger routing can security take place best?
- What effect do security checks have on airport terminal performance, when more then one security check is needed for each routing of passengers?

If the different security procedures are to be evaluated, it must be possible to incorporate the security procedures in the input file. To analyse which security procedure is best, or how different security measures affect airport terminal performance, output is needed of all facilities modelled, so not only the best security procedure can be found, but also the effect on the whole terminal performance can be evaluated. Again information about queue length and the average waiting times at facilities can be useful, since it gives a good insight into which location of security procedure results in the smallest average queue length and shortest average waiting times. In addition, information about the resources needed to obtain certain service levels is useful, since it gives insight into which security procedure requires the least resources to obtain a service level.

4.4 Increase of passengers

The number of passengers that make use of an airport terminal has grown throughout the years at many airports, since the demand of flights keeps on growing. If the same amount of resources are used while the amount of passengers increases, the inter arrival time of passengers at a facility will decrease and thus average waiting times and queue length will slowly increase. This can be verified by looking at the formula for the ADT of passengers, which has already been described in Section 3.3. If only λ (the arrival rate of passengers) increases, the ADT of passengers will increase. Thus an increase of passengers that make use of an airport terminal can result in bottlenecks over time.

To prevent the creation of bottlenecks, caused by an increase of passengers, it is useful to analyse when an increase of passengers results in bottlenecks and at which facilities this will happen first. To perform the analysis it must be possible to apply the increase of passengers in various ways. For example, bigger aircraft can be used or more flights can be scheduled throughout a day. Each of these possibilities has a different effect on airport terminal performance, since each form of increase has a different effect on the inter arrival time of passengers and thus has a different effect on waiting times and queue lengths at facilities. The output must give an answer to the question which facilities cannot handle an increase of passengers, or which facilities experience the first problems. Output parameters which are used for bottleneck analysis can be used here as well, since this research question is a form of bottleneck analysis.

4.5 Altering the flight schedule

At many airports there are a couple of peak hours during the day in which a lot of flights are scheduled to arrive or depart. This means that a large number of passengers move through an airport terminal during these peak hours. An effect of those peak hours could be that more resources are needed to obtain certain service level targets and to minimise flight delay caused by passenger and baggage processes in an airport terminal. Though it is possible that the peak hours of flights at airports do not create serious bottlenecks, it might still be interesting for airport managers to analyse how alternative flight schedules affect the airport terminal performance. For example, when departing and arriving flights are scheduled more evenly throughout a day, the inter arrival time of passengers could be more constant throughout a day as well. This means that, if one looks at the number of counters needed throughout a day, on average, the number of counters needed to obtain certain service levels is much lower than when there are peak moments at which much more counters are needed to

achieve the same service levels. This can also be seen in the formula of the ADT that is used in SLAM:

$$ADT = \frac{1}{\mu} + \frac{\lambda\left(\sigma_a^2 + (\sigma_S^2/c)\right)}{2(1-\frac{\lambda}{\mu c})}. \qquad (4.2)$$

If the arrival rate of passengers (λ) increases, the numerator becomes larger, but the denominator becomes smaller. It is assumed that λ is higher for peak periods, than in the case when flights are scheduled more evenly throughout a day. As a result, if the same service level target concerning the ADT of passengers is to be obtained, more counters (c) are needed in the situation where peaks of arriving and departing flights are present to compensate the larger λ.

Next to altering the schedule when flights arrive and depart, the number of large or small aircraft that are scheduled to arrive or depart at an airport during a period of time can affect airport terminal performance as well. Large aircraft can contain more passengers than smaller aircraft. Scheduling a lot of large aircraft during a time period has a different effect on the airport terminal performance than when a lot of smaller aircraft are scheduled, since large aircraft can contain more passengers than smaller aircraft. This can also be seen in Figure 18, in which two flights arrive every five minutes, but the dotted line contains only smaller aircraft in the first half hour and larger aircraft in the second half hour. The straight line represents a schedule in which larger and smaller aircraft arrive evenly during the hour.
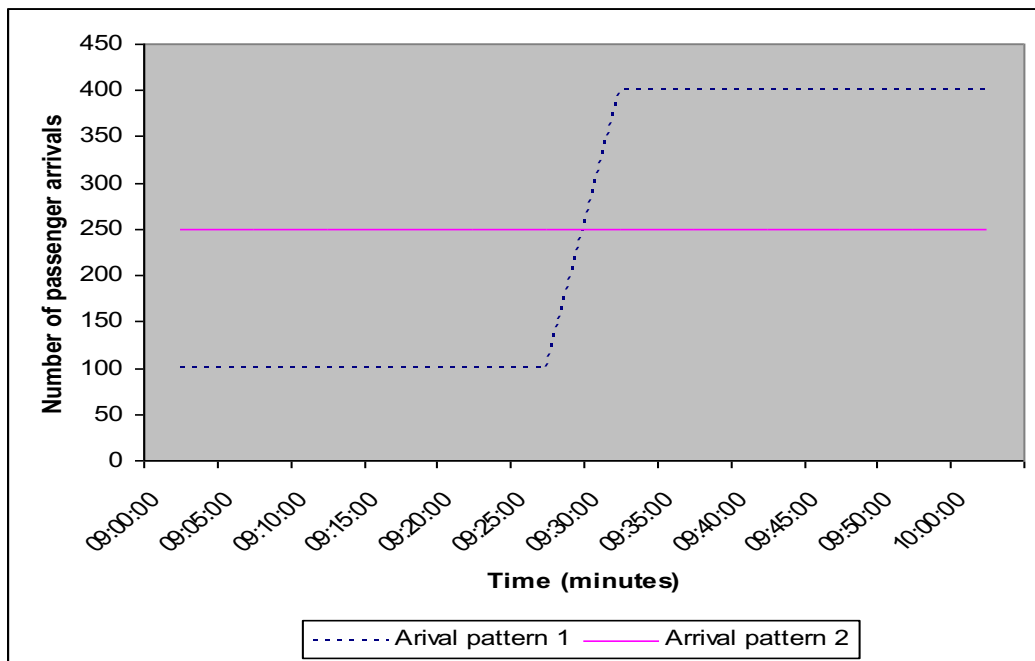
Figure 18: Passenger arrivals according to two flight schedules

As a result, Arrival pattern 1 requires fewer counters to handle all arriving passengers in the first half hour and more counters in the second half hour to obtain the same service level targets. For Arrival pattern 2 the same number of counters can be used during the whole hour. Thus scheduling larger or smaller aircraft can indeed affect airport terminal performance as well.

To be able to answer how altering the flight schedule affects airport terminal performance it must be possible to apply different flight schedules. For each flight it must be possible to change the arrival or departure time of flights and the type of aircraft used throughout a day, to incorporate different number of passengers per aircraft.

To give answer how different flight schedules affect airport terminal performance, the following output is useful:

- Performance of facilities concerning LOS levels, queue lengths, capacity and waiting times of passengers; and
- The number of flight delays or the chance of flight delay.

4.6 To decrease the time spent in an airport terminal

Service levels in a terminal are established by the passenger's perception of the service quality and conditions on one or more components. Key measures of the level of service are: waiting time, service time and walking times. Thus, when passengers do not have to wait a long time at processing facilities and do not have to spend a long time walking from facility to facility they need to visit along a routing, the better the service levels become. A way to make sure that these demands are met is decreasing the minimum total time needed for a routing. For example, decreasing the waiting time at processing facilities can be achieved by increasing the number of counters available, but this also means that more personnel and space for counters is needed, so the costs increase.

If an option to decrease the time spent in an airport terminal has been found, the effect of the decrease on airport terminal performance needs to be analysed to see whether the decrease of the time spent in an airport terminal is worth the effort. For example, increasing the number of counters might decrease the time spent at facilities and thus the total time spent in an airport terminal, but it can also negatively affect facility utilisation.

In general, a couple of ways to decrease the time spent in an airport terminal have presented themselves in the last few years. To mention a few: a first way was the introduction of so-called "people movers" which are used to move passengers to their gate faster. A second possibility has been introduced recently. Passengers with only hand luggage can print their boarding pass at home so they do not have to check-in at the airport terminal. This option decreases the total time spent in an airport terminal. A third option is to let passengers check-in at the train station.

To evaluate how a possible decrease of the time spent in an airport terminal affects the airport terminal performance, it must be possible to incorporate options found for decreasing the time spent in an airport terminal in the input file. The output must show that a decrease of the (average) time spent in an airport terminal has actually been achieved, without negatively affecting the overall airport terminal performance.

4.7 Effect of different routing

In an airport terminal, the routing of passengers or the order in which passengers need to visit facilities can have an effect on the time they need to spent at facilities or the walking time needed to walk from facility to facility. Key factors that influence the routing of passengers are the check-in location of the airline one is flying with, the location of passport control and security checks and the gate from which a passenger's flight is scheduled to depart. It is useful to analyse how different routing of passengers affects airport terminal performance. A couple of possibilities that change the routing of passengers are:

- Changing the check-in location of airlines (e.g. a different departure hall);
- Changing the gates at which flights normally depart from;
- Changing the location of passport control facilities; and
- Changing the location of security check facilities.

Each change can affect the walking time between facilities and the number of passengers that arrive at a facility during a time period.

In this case it must be possible to change the order of visiting facilities, allocation of airlines at check-in and the allocation of flights to gates. To analyse the effect of different routing, output of the total time passengers have to spend in an airport terminal can give insight which routing is best. A second possible output is flight delay. Different routing may have a positive

effect on walking times and facility performance, but it is also useful to know whether the number of flights that are delayed decreases or increases.

4.8 Type of passenger and facility assignment

One of the goals of airport managers is to make the stay of passengers in an airport terminal as pleasant as possible, while maintaining certain service levels. It is known that business class passengers on average want to spend less time in queues and shopping areas than economy class passengers. A way to fulfil the demands of both type of passengers is to use different counters for economy and business class passengers. As a result, business class passengers do not have to wait in queue with economy class passengers and the chance of long waiting times for business class passengers decreases as well, since the amount of business class passengers that move through an airport terminal a day is much lower than the amount of economy class passengers.

This solution may have a positive effect on average waiting times of business class passengers, but has a negative effect on average waiting times of economy class passengers. This lies in the fact that the number of counters needed to obtain a certain service level also depends on the number of passengers that arrive in a short time period. If many passengers arrive in a short time period and economy and business class passengers use different counters, in total, more counters may be needed to obtain the same service levels as when all passengers were handled at the same counters.

Another possibility is to use separate counters for transfer passengers. For airports where a lot of transfer passengers are handled it is important to make sure that transfer passengers are not delayed to much at processing facilities so they arrive to late at their connecting flight.

Analysis about the possibilities to fulfil the demands of different type of passengers and the effect on airport terminal performance can give insight whether an airport can benefit from separating the resources used for different type of passengers.

To evaluate the separation of economy class and business passenger processes, output is needed of the number of counters used, queue length, average waiting times and needed capacity of all facilities. This can give insight into whether it is possible to separate the processes without degrading airport terminal performance.

4.9 Analysis results

In this section an overview is given whether the input and output required to give answer to the research questions described in the previous sections are present in SLAM. First some general results that were found, reading [1] and [2] and working with SLAM are discussed. Secondly, each research question is highlighted separately, summarising whether input and output required to answer the research question are present in SLAM.

General results:
As already mentioned in Section 3.3, SLAM only incorporates the departure baggage sorting facility. This means that no output of baggage facilities like the sorting facilities of arriving flights or the transport of baggage from facility to facility is given.

It seems that SLAM gives almost all output that is required for the research questions discussed. Except for the total time passengers spend in an airport terminal for different routing, all output needed described in Sections 4.1 through 4.8 can be obtained with SLAM. This can be reviewed looking at all output possibilities of SLAM described in Section 3.4.

Analysis results for each research question:
In Table 6 an overview is given what the input and output possibilities or shortcomings of SLAM are for each research question formulated. These results were obtained using information provided in [1] and [2] and testing the tool for the required input and output described in Sections 4.1 through 4.8. Note that nothing is yet said about the calculations made to obtain the output. This is reviewed in Chapter 5.

Research question	Possibilities	Shortcomings
Bottleneck analysis	1. It is possible to perform a bottleneck analysis of the facilities listed in Table 1	1. Not all baggage facilities described in Chapter 2 can be incorporated in SLAM, so no output of these facilities is created 2. The transfer passenger process cannot be incorporated correctly in SLAM, since no connecting flights can be assigned
Changing input parameters	1. It is possible to change input parameters like service times, the number of counter,	1. Not all baggage facilities described in Chapter 2 are present, so the effect of a

	arrival profiles and service profiles used	small change in input parameters on those type of facilities cannot be evaluated
Security procedures	1. It is possible to incorporate different security procedures in SLAM, depending on which security measure is selected. Some possibilities are: • Applying a security procedure at different facilities • Placing a security procedure at different places along a routing	1. No security procedures can be analysed for the arrival baggage, since no arrival baggage facilities are incorporated in SLAM
Increase of passengers	1. It is possible to simulate an increase of passengers by increasing the number of passengers per flight or increasing the number of flights scheduled. 2. Output is given for each facility, so it can be evaluated how an increase of passengers affects airport terminal performance	1. None detected
Altering the flight schedule	1. It is possible to alter the flight schedule in SLAM. Some possibilities are: • Changing the time at which flights arrive / depart • Changing the number of passengers on board of a flight 2. Output created by SLAM can give a better insight how different flight schedules affect airport terminal performance	1. None detected
Decrease of the time spent in an airport terminal	1. It is possible to incorporate a possible decrease of the total time spent in an airport terminal in the input file and evaluate the effect on airport terminal performance	1. None detected
Different routing	1. It is possible to create different routing by, for instance changing the assignment of airlines to check-in halls or flights to gates 2. Output provided can be used to evaluate the effect of different routing	1. None detected
Type of passenger and facility assignment	1. It is possible to assign economy class, business or transfer passengers processes separately	1. It is not possible to assign more then one routing to a flight

	2. Output obtained can give insight whether it pays of to separate the two processes	

Table 6: Analysis results of the research questions

5 Verification

In this chapter tests are described which are used for the verification of SLAM. With these tests it is analysed whether SLAM output is correct and robust. To be able to test the correctness and robustness of SLAM output a lot of small, varying tests are needed to cover a considerable range of input possibilities. For each test simplified input data is used, so it was possible to manually calculate whether the obtained output was correct or not.

First an overview of the performed tests is given in Section 5.1. Accordingly, problems found with SLAM are discussed in Section 5.2. In Section 5.3 it is discussed what consequences the problems found have on the research questions in Chapter 4.

5.1 Performed tests

For the verification two standard input files have been created (see [10]), which have been adjusted for each test. The first input file (*standard.inp*) describes a very basic airport terminal in which only one departing, arriving and transfer flight is incorporated. For all possible facilities that can be incorporated in SLAM only one type of facility has been created (e.g. one check-in facility, one passport control facility, etc). In addition, only one type of passenger has been used (no separation of Schengen or non-Schengen passengers has been made). In the second input file (*standard2.inp)* a more complex airport terminal was created, which contained two arrival and departure halls, two arrival, departure and transfer flights and a separation of Schengen and non-Schengen passengers. This way it was possible to analyse whether SLAM also processed all airport terminal processes correctly when terminal complexity is increased. The flights created still contain simple input data so the calculations of output could still be done manually as well.

Below, the tests that were performed for both standard input files are described, together with their goal and what input data had to be changed. The input file of each test and the scenarios that were created can be found in [10]. For each test only the name of the input file is given so one knows which file to look at. In addition, a document *performedTests.doc* has been created in which all tests and changes are described (see [10]).

Performed tests:

I. First the standard input file has been run to verify whether the inserted flights were processed correctly. All output values of each facility were checked whether they were correct or not. (*Standard.inp* and *Standard2.inp*)

II. Changes were made in service times at facilities to see whether it had the expected effect on average waiting times, queue lengths, etc. For instance, it was checked whether the ADT of passengers slowly increased when the available capacity was not sufficient to serve all passengers immediately when they arrive at the facility. (*Service.inp* and *Service2.inp*)

III. Changes were made in the arrival profile of passengers to analyse whether passengers indeed arrived according to the arrival profile assigned. For arrival passengers a batch form profile was created, since they all arrive at the airport at the same time. For departing passengers S-shaped arrival profiles were used as described in Section 3.3. (*Profile.inp* and *Profile2.inp*)

IV. Different routing for passengers were created to analyse whether passengers indeed followed the routing. In the output it is checked whether passengers arrived at the facilities at the time they were supposed to, keeping into account how much time is needed to get from one facility to the next and how much time is needed before a passenger, or group of passengers, is served at a facility. (*Routing.inp* and *Routing2.inp*)

V. Changes were made in the number of counters available at facilities to find out how it affected the ADT and queue lengths at a facility globally and whether it affected the arrival time at the next facilities visited as supposed to the changes applied. (*Counter.inp* and *Counter2.inp*)

VI. Changes were made in the total time passengers or baggage need to spend in the passenger terminal. This was done to find out whether the delay of departing flights is indeed affected by the total time spend in an airport terminal. For instance, the walking times between facilities were increased, so passengers could not arrive at their gate on time. In addition, it is checked whether flights that are scheduled to arrive at the same gate as a delayed flight, were delayed as well. (*Times.inp* and *Times2.inp*)

VII. Changes were made in the number of passengers that have baggage with them and how much baggage, on average, each passenger has with them to analyse whether the amount of baggage that needs to be processed is calculated correctly. (*Baggage.inp* and *Baggage2.inp*)

5.2 Results

For most of the tests the output was as expected. Yet, there were a couple of results that indicated some problems in SLAM that give wrong output and make it impossible to give correct answers to all research questions described in Chapter 4. The problems found are described in the following subsections. In each subsection the problem found is described, how it is assumed that the model should work and how the modelling approach affects the output.

5.2.1 Treating facilities independently

Tests III through V gave the impression that SLAM treats each facility independently. For each departing flight one arrival profile is assigned for the time at which passengers arrive at their gate and one profile is used for all other processing facilities that need to be visited along a routing. For arrival flights only one arrival profile is used for all processing facilities visited along a routing. In Table 8 output is shown for all facilities visited along a routing for a single departing flight. For each facility created the service time chosen was too high to be able to serve all passengers within 5 minutes. This was done, so it could not be possible for all passengers to arrive at the next facility visited along a routing within 5 minutes and that the number of arrivals during the time period selected should differ for each facility. As is shown in Table 8, passengers start arriving at all facilities at the same time. In other words, it looks like passengers arrive at the different facilities at the same time. Furthermore, the number of passengers that arrive during each 5 minutes is the same for each facility as well.

Time	Check-in	Passport Control	Security
3:30	0	0	0
3:35	0	0	0
3:40	2	2	2
3:45	2	2	2
3:50	2	2	2
3:55	2	2	2
4:00	2	2	2
4:05	2	2	2
4:10	2	2	2
4:15	2	2	2
4:20	2	2	2
4:25	2	2	2
4:30	2	2	2
4:35	2	2	2
4:40	2	2	2
4:45	2	2	2
4:50	2	2	2
4:55	2	2	2
5:00	2	2	2
5:05	2	2	2
5:10	2	2	2
5:15	2	2	2
5:20	5	5	5
5:25	5	5	5
5:30	5	5	5
5:35	5	5	5
5:40	5	5	5
5:45	5	5	5
5:50	5	5	5
5:55	5	5	5
6:00	2	2	2
6:05	2	2	2
6:10	2	2	2
6:15	2	2	2
6:20	0	0	0
6:25	0	0	0
6:30	0	0	0
6:35	0	0	0

Table 8: The number of arrivals at different facilities for a single flight

The conclusion is that the arrival time and arrival rate at each facility visited next, after the first facility visited, along a routing is incorrect. This can be confirmed, since apparently the walking time needed to move from one facility to the next facility, service time and time that passengers may have to wait in queue at different facilities visited along a routing are neglected. This can give wrong queue lengths and ADT of passengers, since the number of arrivals, and thus the arrival rate of passengers (λ) given for a time period is incorrect.

For the first facility visited along a routing, i.e. for departing passengers check-in and for arriving or transfer passengers passport control or baggage reclaim, the amount of passengers arriving at that facility during a time period depends on factors like:

- The amount of flights that are scheduled to depart or arrive;
- The number of passengers that are on board of a flight;
- The routing passengers need to follow; and
- The departure hall or arrival hall passengers arrive at. For example, Schiphol Airport has three departure and arrival halls.

For all other facilities that have to be visited next along a routing, the (inter) arrival time of passengers depends on factors like:

- The rate at which they leave a previous visited facility; and
- The time needed to walk from one facility to the next.

It is tried to work around this problem by the following steps:

1) Letting SLAM run a first time so the rate at which passengers leave check-in (rate out) is given;
2) Using the rate out of the first run for the arrival profile of passengers at a second facility visited and running SLAM a second time; and
3) Repeating the second step for all processing facilities visited along a routing.

This, however, could not be done, since SLAM uses an arrival profile for each flight of which passengers visit a facility and the rate out at check-in is, for one, affected by the cumulative arrival distribution of passengers from different flights. This meant that the rate out at the check-in facility needs to be translated back into arrival profiles for each single flight for letting SLAM run a second time. This could not be done, since the rate out is a cumulative

distribution and SLAM does not keep track of each (group) of passengers that visit the facilities.

5.2.2 Number of counters available

As already mentioned in Section 3.2, it is possible to assign a service profile for each flight inserted in the input file. For example, if passenger arrive according to the arrival profile listed in Table 9, it is possible that a service profile is used as is listed in Table 10.

Arrival profile	Minutes before departure of a flight	Cumulative fraction of passengers that have arrived at the airport of a single flight
Profile 1	180	0.02
Profile 1	160	0.05
Profile 1	140	0.09
Profile 1	120	0.14
Profile 1	100	0.36
Profile 1	80	0.63
Profile 1	60	0.88
Profile 1	40	0.98
Profile 1	20	1.00

Service profile	Minutes before departure of a flight	Number of counters opened
Profile 1	181	0
Profile 1	180	1
Profile 1	121	1
Profile 1	120	3
Profile 1	61	3
Profile 1	60	1
Profile 1	11	1
Profile 1	10	0

Table 9: An arrival profile   Table 10: A service profile

In general, for check-in this is not such a bad idea, since passengers fly with different airlines and can be assigned to different counters. This is done at many airports as well. Smaller airlines often make use of the same counters. Furthermore, when passengers fly with the same airline, but have different departure times, it is possible that the service profiles are added together as is shown in Figure 19.

However, in SLAM the service profile for each flight is not only assigned to check-in, but also to all other processing facilities passengers visit. This is not very efficient, since doing so means that scale advantages are missed. A more realistic approach would be to assign a certain number of counters adaptively according to regulations used. This method is used at

many airports as well. For instance, when a lot of passengers are standing in a queue, an additional counter is opened.
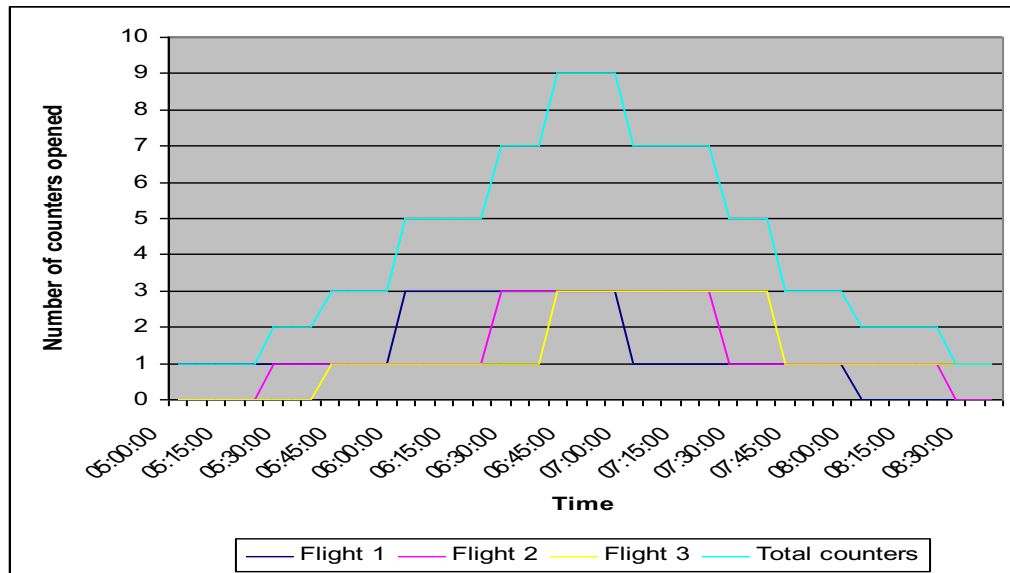
Figure 19: The number of counters opened throughout a time period

5.2.3 Incorporating transfer passengers

For airports where a lot of transfer flights arrive and depart throughout a day, one of the objectives of airport managers is to make sure that flights are not delayed too much and transfer passengers have a pleasant stay in the airport terminal.

Whether a connecting flight can depart on time depends on the following factors:
- The arrival time of arriving flights that contain transfer passengers who connect to the departing flight;
- The time that is needed for the transfer passengers to get from one aircraft to the next; and
- The time that is needed to handle the transfer baggage until it is loaded on the connecting flight.

This means that when an analysis is to be performed which incorporates the transfer processes, it must be possible to:
- Create routings that transfer passengers need to follow;

- Assign multiple arriving flights to a single departing flight or passengers of a single arriving flight to multiple departing flights; and
- Incorporate the baggage movement of transfer passengers from an arriving flight to the connecting flight.

This, however, seems not possible in SLAM. First of all it is only possible to assign one routing to each flight created, meaning that a mixed flight with passengers that follow different routing at an airport is not possible. A second problem is that connecting flights cannot be incorporated in SLAM. Accordingly, it cannot be monitored whether a departing flight is delayed as a result of transfer passengers arriving at their gate too late or the total time transfer baggage needed to spend in the airport terminal took too long.

Splitting a mixed flight into multiple flights of which each flight contains a group of passengers that need to follow a different routing can solve the creation of mixed flights. For example, if one wants to create an arriving flight which contains 50 passengers who have the airport as final destination and 50 transfer passengers, then one flight can be created with the arriving passengers and one flight with the transfer passengers. This makes it possible to incorporate the transfer process in SLAM.

The second problem, however, cannot be solved. If departing flights are created, which represent the connecting flights, it is not possible to determine how much time before the connecting flight is scheduled to depart transfer passengers arrive at the airport, since this is determined by the arrival flights. In this case no realistic arrival profile of the transfer passengers can be assigned and thus it cannot be verified whether the delay shown in the output file is correct or not.

5.2.4   Baggage handling

Baggage handling can have effect on flight delay for departing flights and the waiting time of passengers who need to get their baggage at baggage reclaim. This delay may occur if the total time needed to process the baggage takes too long and the baggage is not on board of the departing flight, before it is scheduled to depart. For arriving flights, the baggage of passengers may arrive at the baggage reclaim area a great deal of time later than the passengers do.

Key factors that influence baggage handling are the same as for passengers at processing facilities. Though output is given about the baggage sorting facility for departing passengers,

it seems that SLAM does not calculate the amount of baggage that need to be processed in a correct way. A first indication that the amount of baggage processed at a baggage sorting facility was not calculated correctly can be seen in Figure 20. The total amount of baggage processed at the sorting hall is different in the textual and graphical output, while it should be the same, e.g. the total amount of baggage according to the textual output is 134281, while that of the graphical output is more than 180000.
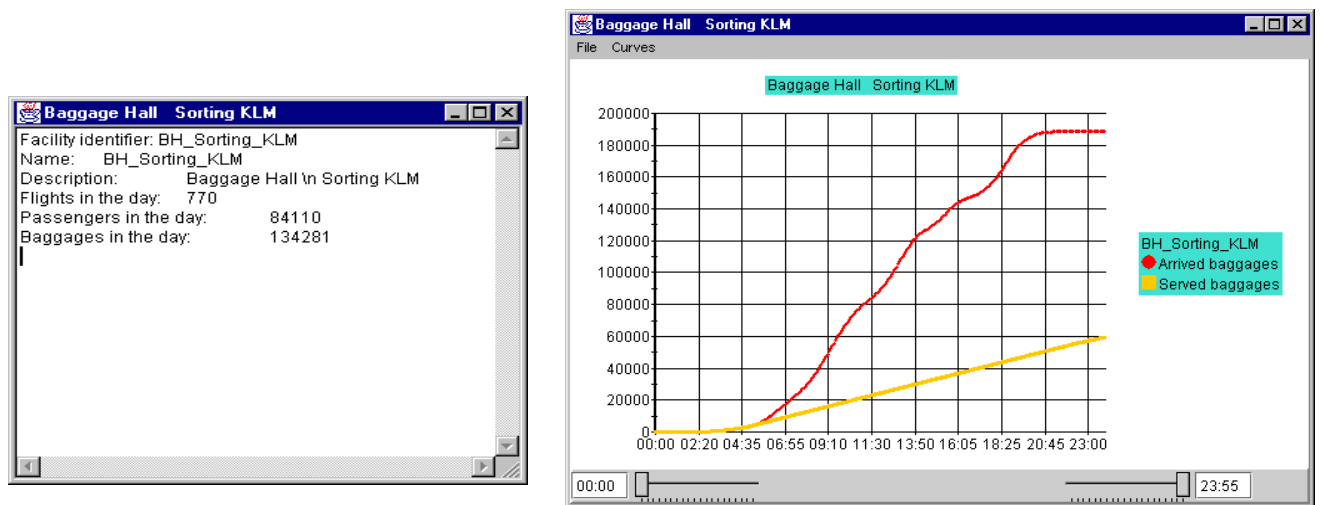
Figure 20: Textual and graphical output of baggage sorting facility

A way of calculating the amount of baggage that need to be processed at a baggage handling facility can be done by using the following parameters for each flight:

- n_j = the number of flights that are handled by baggage handler j,

    with $j = 1,...,m$
- b_i = the number of passengers that are on flight i, with $i = 1,..., n_j$
- c_i = the fraction of passengers of flight i that checks-in
- $x_{econ,i}$ = the fraction of economy class passengers of flight i that goes to check-in

    and have baggage with them
- $x_{bus,i}$ = the fraction of business class passengers of flight i that goes to check-in

    and have baggage with them
- z_{econ} = the average amount of baggage of economy class passengers
- z_{bus} = the average amount of baggage of business class passengers

Then the amount of baggage that should be processed by baggage handler j can be calculated by:

$$TotalBag_j = \sum_{i=1}^{n_j} b_i * c_i * (x_{econ,i} * z_{econ} + x_{bus,i} * z_{bus}).$$ (5.1)

SLAM input has all these parameters available, but the calculations for textual and graphical output are done in a different way. A few scenarios were created where two flights were used and a couple of parameters were changed each time to see what effect it had on textual and graphical output. The first scenario (S1) is a standard situation in which all passengers go to check-in and all passengers have baggage with them. For the second scenario (S2) the fraction of passengers that go to check-in is changed to see whether the amount of baggage that need to be processed becomes smaller according to the change applied. In the third scenario (S3) it is checked how the model reacts on a mistake, in which the fraction of passengers that goes to check-in with baggage is 100%, but the parameter describing the fraction of baggage that is processed at the sorting facility is set to 90%. This should cause an error, since 100% of the passengers go to check-in and all passengers have baggage with them and thus baggage of 100% of the passengers must be processed at the baggage sorting facility. In the fourth scenario (S4) it is checked what happens when the fraction of passengers who check-in is 100%, but only 50% of them have baggage. The different scenario input can also be seen in Table 11.

The parameters that were fixed are:

- The number of passengers on board is 100;
- The fraction of economy class passengers is 90%;
- The fraction of business class passengers is 10%;
- The average amount of baggage of economy class passengers is 1;
- The average amount of baggage of business class passengers is 1; and
- One flight was handled by baggage handler "KLM", the other by "Menzies" to see whether SLAM can incorporate two sorting facilities.

	S1	S2	S3	S4
Fraction of passengers that checks-in	100%	90%	100%	100%
Fraction of passengers of which the bagagge needs to be sorted at a baggage hall	100%	100%	90%	100%
Fraction of economy class passengers at check-in with baggage	100%	100%	100%	50%
Fraction of business class passengers at check-in with baggage	100%	100%	100%	50%

Table 11: Input differences for the scenarios created

	S1	**S2**	**S3**	**S4**
Total amount of baggages sorted by KLM (textual output)	190	190	171	95
Total amount of baggages sorted by KLM (graphical output)	380	342	342	190
Total amount of baggages sorted by Menzies (textual output)	190	190	171	95
Total amount of baggages sorted by Menzies (graphical output)	380	342	342	190

Table 12: Output of the amount of baggage processed at different baggage halls

According to formula (5.1) the amount of baggage that should be processed at each facility should be:

	S1	**S2**	**S3**	**S4**
KLM	100	90	100	50
Menzies	100	90	100	50

Table 13: The amount of baggage for each scenario for the two baggage handlers

Yet, when looking at the output results of the scenarios listed in Table 12, it seems that SLAM calculates the amount of baggage in the following way:

Textual output:

$$TotalBag_j = \sum_{i=1}^{n_j} b_i * w_i * (x_{econ,i} * z_{econ} + x_{bus,i} * y_{bus,i} * z_{bus} + x_{econ,i} * z_{econ})$$
$$\text{with } j = 1,...,m$$

where w_i is the fraction of passengers of flight i of whom the baggage is processed at the sorting facility by handler j.

Graphical output:

$$TotalBag = \sum_{j=1}^{m} \sum_{i=1}^{n_j} b_i * c_i * (x_{econ,i} * z_{econ} + x_{bus,i} * z_{bus} + x_{econ,i} * z_{econ} \quad).$$

Looking at the two formulas of the textual and graphical output it appears that the textual output has a sort of loop, where first economy and business class parameters are used, and then the economy class parameter values is added a second time. To confirm this suspicion, the values of the economy and business class passengers have been swapped in the input table. This time the output indeed added the value of the business class passengers a second time as is shown in Table 14.

	S1	S2	S3	S4
# of baggages at sorting KLM (textual output)	110	110	99	55
# of baggages at sorting KLM (graphical output)	220	198	198	110
# of baggages at sorting Menzies (tekst output)	110	110	99	55
# of baggages at sorting Menzies (graphical output)	220	198	198	110

Table 14: Output on the amount of baggage processed when the order of economy
and business class passengers is swapped

For the graphical output, the baggage handled by each baggage handler is calculated using the same loop as is used for textual output and adding up all baggage handled by all baggage handlers. Probably SLAM was not designed to work with more than one baggage handler yet.

The problem that the total amount of baggage that needs to be processed is calculated incorrectly lies in the fact that it is almost four times larger than actually should be processed. As a result, it looks like there are capacity problems at the baggage sorting facility as is shown in Figure 20. Additionally, the output of flight delay is affected as well, as is shown in Figure 21:

Figure 21: Flight delay of departure flights

As can be seen the additional delay of departure flights due to bag delay is extremely high (up to 1190 minutes), which is not very realistic. The problem of the total amount of baggage that needs to be processed, being four times larger than what one actually wants can be solved by:

- Dividing the average amount of baggage per passenger by 4; or
- Dividing the fraction of baggage that needs to be processed in the sorting facility by 4

The result of applying one of the options described above is shown in Figure 22:
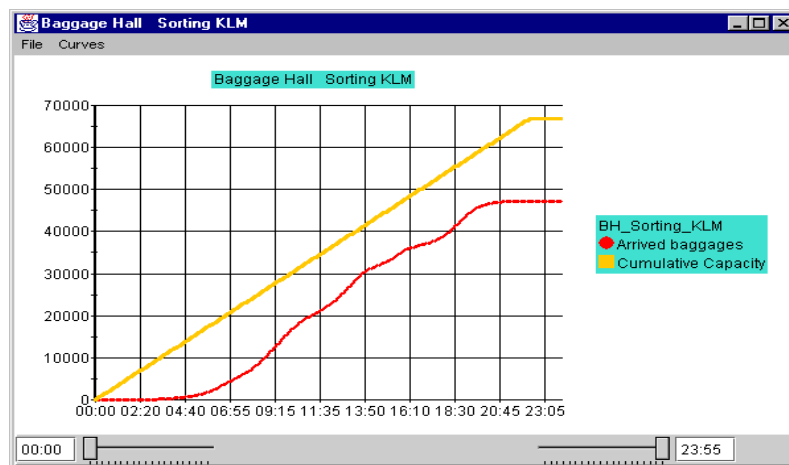
Figure 22: Cumulative capacity and amount of arrived baggage at baggage sorting

As can be seen, the total amount of baggage that arrive during a day is now approximately 45000, which is indeed a quarter of the amount of baggage shown in Figure 20.

5.3 Consequences for the research questions

The problems found have a serious effect on the fact whether the research questions, described in Chapter 4, can be answered using SLAM.

In general, no reliable output can be obtained as result of the following problems:

- Treating all facilities independently. This means that the arrival time of passengers after the first facility visited is incorrect. Furthermore, this means that the calculated ADT, queue length, etc are incorrect as well; and
- The calculation of the ADT at processing facilities is based on stationary queuing models. Since the arrival processes in airports are never stationary, the results are unreliable as well.

This means that following research questions cannot be answered using SLAM:
- Changing input parameters;
- Different security procedures;
- Altering the flight schedule;
- Decreasing the time in an airport terminal;
- Different routing; and
- Type of passenger and facility assignment.

For bottleneck analysis an indication can be made which bottlenecks are present in a terminal, but the output values themselves are not very reliable, because of the problems found in SLAM. This result also applies for the research question in which the effect of an increase of passengers is analysed.

6   Conclusions

During this study, insight is obtained whether SLAM can be used to analyse the performance of an airport terminal. An overview is given of the processes in an airport terminal that need to be modelled. For these processes it is analysed whether they are incorporated in SLAM. After the overview of the processes that need to be modelled, an overview of the basic features of SLAM is given. This gave a first insight what input and output were possible in SLAM and which modelling approach is used. This already resulted in two shortcomings of SLAM:

- It is unclear how certain calculations are done concerning average dwell times of passengers; and
- The approach used for determining the number of counters opened throughout a day at facilities is not efficient (scale advantages are missed).

Furthermore, a set of research questions has been formulated that tell something about what questions are interesting to answer about the airport terminal processes. The research questions contain the following subjects:

- Bottleneck analysis;
- Changing input parameters;
- Different security procedures;
- Increase of passengers;
- Altering the flight schedule;
- Decreasing the time in an airport terminal;
- Different routing; and
- Type of passenger and facility assignment.

For each research question it is analysed whether SLAM has the input and output required to answer the research question. The most important results are that SLAM seems to incorporate most of the required input and output, but also contains some serious shortcomings. The main shortcomings are:

- SLAM does only incorporate the sorting facility for departure baggage. All other baggage facilities cannot be incorporated and thus no (detailed) analysis about these facilities can be performed;
- It is not possible to incorporate transfer flights in SLAM, since it is not possible to assign an arriving flight to a connecting flight; and
- SLAM does not give direct output about the total time passengers spend in an airport terminal.

In addition, SLAM output has been tested according to some verification tests. The most important result of these tests was that SLAM has some technical problems that negatively affect the reliability of the output. The most important findings are:

- SLAM treats all facilities independently by assigning the same arrival profile of passengers to each facility they have to visit along a routing, except for the arrival at the gate, which uses a separate arrival profile;
- The transfer process cannot be incorporated correctly in SLAM. As a result, nothing can be said whether transfer passengers are delayed or not;
- The amount of baggage that needs to be processed at the baggage sorting facility is not calculated correctly; and
- The calculations made of the ADT (Average Dwelling Times) are based on stationary queuing models. Since the arrival processes in airports are never stationary, the results will be unreliable.

7 Recommendations for future research

In this chapter some recommendations are made for future research. The recommendations are based on research that has been performed, but that was not part of the scope of the internship or aspects that could not be performed within the time frame of the internship.

First recommendation

Do not use this version of SLAM any longer. It is considered best to search for other analytical tools like SLAM and to analyse whether these tools do not have the same shortcomings and problems. A recommendation is the tool ARENA. This tool can be used for analytical purposes as well as for simulation purposes. Furthermore, in [6], is stated that ARENA has already been used to identify the bottlenecks at Schiphol airport.

Furthermore, it might be useful to put a selected tool next to other similar tools to verify whether they give the same output. This will improve the quality of the output of the tool used. In addition, it might be interesting to put an analytical tool next to a simulation tool. In general analytical tools sacrifice level of detail for speed and flexibility.

Second recommendation

A second recommendation is to validate a selected tool using more realistic data. Finding out the possibilities of a tool is fine, but validating a tool can best be done by inserting as much realistic data as possible. In this case it might be useful to communicate with an airport like Schiphol airport to obtain the data.

During the internship, as much information about Airport Amsterdam Schiphol has been gathered as possible (see Appendix D). This information can perhaps be used to incorporate Schiphol airport in a new selected tool.

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Appendix A   Detailed overview of SLAM input

As already mentioned in Section 3.2, SLAM uses different tables as input. The four important data types are facilities, criteria, flight schedule and passenger information. The criteria tables actually contain additional information about the other three elements, like how much space a passenger uses and which service level targets are used. In this Appendix additional information about the input possibilities of SLAM is provided, containing a complete overview of all input parameters for each facility that can be modelled.

Facilities:

For each facility the following parameters are standard:

- Name: identifier of the facility;
- Description: description of the identifier;
- PaxSelector: reference to the type of passenger that makes use of the facility; and
- SpaceLOS: reference to the LOS levels that apply to the facility.

Furthermore each facility has some additional parameters, depending whether it is a processing, holding or flow facility. The options are summarised below:

Check-in / ticketing / passport control / security
- TimeTreshold: reference to the maximum waiting for passengers time allowed;
- Counters: the maximum number of counters that can be used;
- Servicetime: the average service time at a counter;
- Minqueue: the minimum queue length possible in front of each counter;
- Maxqueue: the maximum queue length possible in front of each counter; and
- Area: the available space in front of each counter.

Customs:
- PaxADT: the average time a passenger spends at a facility; and
- Area.

BagClaim:
- TimeTreshold; and
- Area.

ArrivalConcourse:

- SpaceStandard: a reference to the minimum space that has to be available for each passenger;
- GreeterAverageDwellTime: the average time a well-wisher spends at a facility;
- NumChairs: the number of available chairs; and
- Area.

Departureconcourse:

- SpaceStandard;
- PaxAverageDwellTime: the average dwell time a passengers visits shops e.g.;
- NumChairs; and
- Area.

Flow:

- Wellwisher: notification whether well-wisher are allowed in this area or not; and
- Width: the width of the flow type used.

Gate Lounge:

- SpaceStandard;
- GateCheckin: a reference to which check-in facility is used; and
- PaxAverageDwellTime.

BaggageSorting:

- Counters: the amount of baggage belts present to handle baggage; and
- ServiceTime.

<u>*Criteria:*</u>

In these tables information is provided that is used for the output calculations. For each table the parameters are given.

The following tables can be found:

- LOS: a LOS table containing all LOS levels;
- TimeTreshold: a time threshold table in which all maximum times allowed at different facilities is given;
- TimeProfile: a time profile table in which all arrival profiles and service profiles used can be inserted; and
- BagClaimTime: a bag reclaim time table in which information is given when the first / last passenger arrives at baggage reclaim and when the first / last baggage arrives;

- ArrivalStandardSpace: a table, which contains information how much space arriving passengers use. This can be done for international passengers, national passengers, standing passengers or sitting passengers;
- DepartureStandardSpace: a table with information about how much space departing passengers use. This can be done for sitting passengers, standing passengers with a trolley, standing passengers and passengers who are delayed;
- GateStandardSpace: a table with information how much space passengers at a gate use. This can be done for passengers in the check-in queue, passengers in the check-in queue with hand luggage, passengers who do not need to check-in and a delayed passenger;
- GapTimes: a table with gap times. These are the times that passengers need to board an aircraft and the time that is needed to load the baggage on board; and
- GateCheckinData: a table with information how many passengers do not check-in at the gate and which fraction of passengers has hand luggage with them.

Flight schedule:

In these tables the flight schedule of arriving and departing flights is given with information about the flight and references to passenger routing, passenger arrival profiles and service profiles used.

ArrivalFlights:
- Identifier of the flight;
- Arrival time of a flight;
- The number of passengers that are on board of a flight;
- Average baggage per passenger;
- A reference to the *ArrivalFlightClass* that applies to the flight;
- Expected delay of the flight; and
- A reference to the routing passengers have to follow.

DepartureFlights:
- Identifier of the flight;
- Departure time of the flight;
- Number of passengers on board;
- A reference to the *DepartureFlightClass;*
- Expected delay; and
- The routing that the passengers need to follow.

ArrivalFlightClass:
- Identifier;
- The type of flight;
- A reference to the arrival profile of the passengers;
- A reference to the service profile used at the facilities visited;
- A reference to the bag reclaim times; and
- A reference a reference of the type of passengers that are on board.

DepartureFlightClass:

This table is almost the same as that of the *ArrivalFlightClass*. The only two additional parameters are:
- A reference to the gate arrival profile of passengers; and
- A reference to the *GateCheckinData.*

Passenger information:

In these tables information about passengers is given concerning the type of passengers that make use of facilities, how much baggage a passenger has with him and what routing a passenger needs to follow. The different tables used are:

PaxClass:
- Identifier of the type of passenger, e.g. economy / business class passenger;
- The fraction of passengers that already has a ticket;
- The fraction of passengers that has baggage with them;
- The fraction of passengers that needs to go to customs;
- The fraction of passengers that needs to go to passport control;
- The fraction of passengers that needs to go to security;
- The fraction of passengers that is transfer passenger;
- The fraction of passengers that has a well-wisher with them; and
- The average amount of baggage a passenger has with him.

PaxClassList:
- An identifier of the passenger class;
- The name of the passenger class; and
- The fraction of passengers that belongs to the passenger class.

For example:

PaxClassList1	Economy	0.2
PaxClassList1	Business	0.8

Routing:

- Identifier of the routing;
- He average amount of time needed to walk the complete routing; and
- A reference to the *RoutingTable.*

RoutingTable:

- An identifier for the routing;
- A list of facilities that are visited for each routing; and
- For each facility is stated whether it is USEFIRST, USE or NOUSE.

Appendix B   Calculation of ADT

As already stated in Section 3.3, the average waiting time of passengers in queue (W_q), for the *M/G/1* queuing model, can be estimated using the PK formula. This formula is calculated as follows:

$$W_q = \frac{\lambda E(S^2)}{2(1-\frac{\lambda}{\mu})} = \frac{\lambda(\frac{1}{\mu^2}+\sigma_S^2)}{2(1-\frac{\lambda}{\mu})} \ . \tag{B1}$$

This, however, is only correct for a facility with a single server. There are two possible ways to change this formula to estimate the average waiting time for *c* counters. One way, is to assume that when passengers arrive, they randomly chose one of the *c* queues, when *c* counters are available. The probability that a passenger X chooses queue *n (*with *n* = 1,..,c*)* can be given by:

$$P(X = n) = \frac{1}{c} \qquad \text{for} \qquad n = 1,..,c \ . \tag{B2}$$

In this case λ of the *M/G/1* model can be replaced by λ/c (see Figure B1).
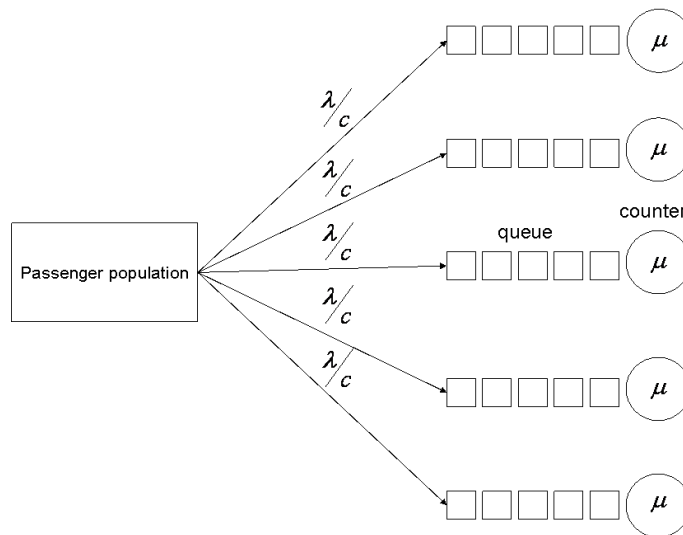
Figure B1: passengers chose a queue randomly

In this case formula B1 can be rewritten into:

$$W_q = \frac{\frac{\lambda}{c}(\frac{1}{\mu^2} + \sigma_S^2)}{2(1 - \frac{\lambda}{\mu c})} = \frac{\lambda(\frac{1}{\mu^2 c} + \frac{\sigma_S^2}{c})}{2(1 - \frac{\lambda}{\mu c})}. \qquad (B3)$$

This would lead to the following formula for the ADT:

$$ADT = \frac{1}{\mu} + \frac{\lambda(\frac{1}{\mu^2 c} + \frac{\sigma_S^2}{c})}{2(1 - \frac{\lambda}{\mu c})}. \qquad (B4)$$

This is almost exactly the formula used for the ADT in SLAM, which is given by:

$$ADT = \frac{1}{\mu} + \frac{\lambda\left(\sigma_a^2 + \frac{\sigma_S^2}{c}\right)}{2(1 - \frac{\lambda}{\mu c})}. \qquad (B5)$$

So, Formulas (B4) and (B5) differ only in the fact that σ_a^2 is replaced by $\frac{1}{\mu^2 c}$. Since σ_a^2 is an unexpected term for a model with Poisson arrivals, it cannot be excluded that Formula (B4) is the formula that was intended by the makers of SLAM.

A second option is to take the *M/G/1* queue, but letting the counter operate *c* times as fast (see Figure B2).
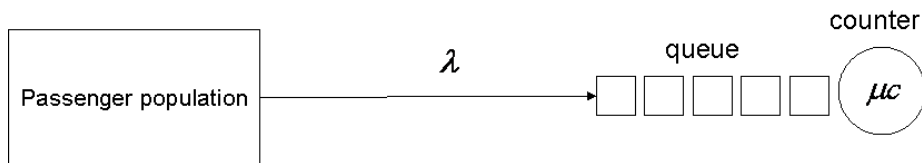
Figure B2: A M/G/1 queue of which the server operates at a rate of μc

In this case the average service rate μ needs to be replaced by μc and σ_S^2 by σ_S^2 / c^2 . This could be another way to correct for c counters being available instead of one. Formula (B1) can then be rewritten into:

$$W_q = \frac{\lambda(\dfrac{1}{\mu^2 c^2} + \dfrac{\sigma_S^2}{c^2})}{2(1 - \dfrac{\lambda}{\mu c})} . \tag{B5}$$

As can be seen, this is still not the same formula as given in SLAM for the ADT of passengers.

It is unclear why the makers of SLAM have tried to derive the ADT using formula (B4), when a good approximation for W_q of the *M/G/c* queuing model can be found in [13]. In this case W_q is approximated using the following formula:

$$W_q \approx \frac{\lambda^c E[S^2](E[S])^{c-1}}{2(c-1)!(c-\lambda E[S])^2 \left[\displaystyle\sum_{n=0}^{c-1} \frac{(\lambda E[S])^n}{n!} + \frac{(\lambda E[S])^c}{(c-1)!(c-\lambda E[S])} \right]} . \tag{B6}$$

Appendix C   Detailed overview of SLAM output

As already mentioned in Section 3.4 SLAM gives textual and graphical output for each facility created in the input file. In this Appendix and overview is given for each type of facility, what the textual output is and what curves can be drawn in the graphical output.

Textual output:
For each facility created at least the following data is provided:

- The facility identifier;
- The description of the identifier;
- The number of flights of which the passengers visit the facility;
- The number of flights during peak hour;
- The number of passengers that have visited the facility; and
- The number of passengers that have visited the facility during peak hour.

Next to that the following outline can be given:

Check-in / ticketing / passport control / security
- The average waiting time of passengers;
- The 80% average waiting time;
- De IOS value;
- The LOS value; and
- An indication whether the time threshold has been broken or not.

Customs:
- The IOS value; and
- The LOS level.

Baggage reclaim:
- The average waiting time of passengers;
- The IOS value;
- The LOS value; and
- An indication whether the time threshold has been broken or not.

ArrivalConcourse / DepartureConcourse / Gate Lounge
- Average waiting time;
- The IOS value;

- The LOS level;
- An indication whether there was enough space per passenger during peak time; and
- An indication whether the average waiting time during peak hour did not exceed the time threshold.

Graphical output:

Check-in / ticketing / Passport control / security

- Period passengers;
- Cumulative arrived passengers;
- Cumulative available capacity;
- Cumulative served passengers;
- Average queue length;
- Average waiting times;
- The number of counters available;
- Queue per counter;
- Computed necessary counters; and
- Queue per counter (forecast).

Baggage reclaim:

- Cumulative arrived passengers / baggage;
- Period passengers / baggage; and
- Queue length.

Gate Lounge:

- Arrived passengers;
- Arrived passengers at gate check-in;
- Total arrived passengers;
- Leaving passengers; and
- Passenger presence.

Baggage sorting:

- Cumulative arrived baggage;
- Cumulative capacity; and
- Cumulative served baggage.

Appendix D   Amsterdam Airport Schiphol information

For the verification whether an airport terminal could be created using SLAM, Amsterdam Airport Schiphol was chosen as example airport. Unfortunately, it was not possible to get all data required to model Schiphol Airport in SLAM. Nevertheless, the following data has been used to find out whether it was possible to create an input file that represented Schiphol Airport as much as possible and can perhaps be used for further research. Most of the data described below can also be found on the site www.schiphol.nl.

Departing from Schiphol Airport:

Getting your tickets

Passengers can get their ticket at the Schiphol Travelport that is located in departure hall 2.

Check-in

The check-in times depend on the country of destination. Schiphol assumes check-in times of two hours before a flight is scheduled to depart for destinations in Europe and three hours for destinations outside of Europe.

The check-in counters are situated in three different departure halls:
- Departure hall 1: check-in counters 1 through 8
- Departure hall 2: check-in counters 9 through 16
- Departure hall 3: check-in counters 17 through 28

If a passenger has only hand luggage with him, it is possible to check-in at the so-called Self Service Check-in counters. The SSCI are situated at different places throughout the airport terminal, depending on the airline one is flying with:
- KLM and partners: Departure hall 2, close to counter 9. The airlines that are connected to this SSCI are:
  KLM, Air Alps, Northwest Airlines, KLM City Hopper, KLM UK, KLM Exel, Braathens, Kenya Airways, CSA Czech Airlines, Cyprus Airways, Aer Lingus, Lithuanian Airlines, Maersk Air, Malev, Meridiana, Swisswings, Ukraine International.
- Lufthansa and partners: Departure hall 1, close to counter 8. The airlines that are connected to this SSCI are: *Lufthansa, Austrian Airlines, Eurowings, Air Dolomiti*
- British Airways: Departure hall 1, close to counter 2
- SAS - Departure hall 1, close to counter 8.

Overweight of baggage

Each airline handles an own maximum weight of baggage that a passenger may have with him. The maximum allowed weight is mentioned on the ticket.

If a passenger checks in and has overweight of baggage the standard weight is checked in following normal procedures. For the overweight the passenger is referred to a special counter where the passenger has to pay extra for the overweight.

Security check

For each departure hall there is one central security check behind the check-in counters. Here the controls of the following aspects take place:

- Passport or ticket control
- Metal detection on passengers
- Hand luggage is x-rayed

Passengers with a Schengen country as destination do not go through passport control. They only need to show their ticket. The Schengen countries at this moment are:

Belgium, Denmark, Germany, France, Greece, Italy, Luxembourg, The Netherlands, Austria, Portugal, Spain, Finland, Sweden, Norway and Iceland.

Airlines and the departure hall at which they are situated

The airlines and their corresponding departure hall are shown in Table D1.

Baggage handlers at Schiphol

There are a amount of baggage handlers that handle the baggage of passengers at transport them to the correct flight. Each airline corresponds to one of the baggage handlers present. The airlines and the baggage handlers that they associated with are listed in Table D2.

Airline	Code	Departure hall	Airline	Code	Departure hall
Adria Airways	JP	3	JAT Yugoslav Airlines	JU	3
Aegean airlines	A3		Jet2	LS	1
Aer Lingus	EI	2	Kenya Airways	KQ	2
Aeroflot Russian Int. Airlines	SU	3	KLM Cityhopper	KL	
Air Alps	A6	2	KLM exel	KL	2
Air Astana	4L	3	KLM Royal Dutch Airlines	KL	2
Air Baltic	BT	3	Korean Air	KE	3
Air Canada	AC	3	Kuwait Airways	KU	3
Air France	AF	1	Libyan Arab Airlines	LN	3
Air Malta	KM	1	Lithuanian Airlines	TE	2
Air Moldova	9U	3	LOT Polish Airlines	LO	2
Air One	AP		Lotus Air	TAS	3
Air Sint Maarten	E7		Lufthansa	LH	1
Air Transat	TS	3	Maersk Air Ltd	DM	2
Air Zena Georgian Airlines	A9	3	Malaysia Airlines	MH	3
Alitalia	AZ	1	Malev Hungarian Airlines	MA	2
Arkia	IZ	3	Martinair Holland	MP	3
Armavia	U8		MAT Macedonian Airlines	IN	3
Austrian Airlines	OS	1	Meridiana	IG	2
Bmi british midland	BD	1	MNG Airlines	MNB	3
British Airways	BA	1	Northwest Airlines	NW	2
Bulgaria Air	FB		Olympic Airlines	OA	1
Cathay Pacific Airways	CX	3	Onur Air	OHY	3
China Airlines	CI	3	Pegasus Airlines	PGT	3
China Southern Airlines	CZ	3	PIA Pakistan International Airlines	PK	3
Continental Airlines	CO	3	Pulkovo Aviation Enterprise	FV	3
Croatia Airlines	OU	3	Royal Air Maroc	AT	3
CSA Czech Airlines	OK	2	Royal Jordanian Airlines	RJ	3
Cyprus Airways	CY	2	SAS Scandinavian Airlines	SK	1
Delta Air Lines	DL	3	Scot Airways	CB	1
Dutch Caribbean Airlines	K8	3	Sierra National Airlines	LJ	3
DutchBird	DBR	1	Singapore Airlines	SQ	3
EasyJet	EZY	1	Sky Airlines	SHY	3
Egypt Air	MS	3	Skynet Airlines	SI	3
El Al Israel Airlines	LY	3	Spanair	JKK	1
Eritrean Airlines	B8		Sun Dor	7L	
Estonian Air	OV	3	Surinam Airways	PY	3
Ethiopian Airlines	ET	3	Swiss International Airlines	LX	1
Eurowings	EW	1	Syrian Arab Airlines	RB	3
EVA Airways	BR	3	TACV Cabo Verde Airlines	VR	3
Finnair	AY	1	TAP Air Portugal	TP	1
Fly Air	FLM		THY Turkish Airlines	TK	3
Futura International Airways	FUA	1	Transavia airlines	HV	1
Garuda Indonesia	GA	3	Tunis Air	TU	3
Holland Exel	HXL	3	Ukraine International Airlines	PS	2
Iberia	IB	1	United Airlines	UA	3
Icelandair	FI	1	US Airways	US	3
Inter Express Airlines	INX	3	VARIG Brasilian Airlines	RG	3
Iran Air	IR	3	Virgin Express	TV	1
Israir	ISR	3			
Japan Airlines	JL	3			

Table D1: Airlines and their departure hall at Schiphol Airport

Airline	Code	Baggage handler	Airline	Code	Baggge handler
Adria Airways	JP	GlobeGround	Japan Airlines	JL	KLM Ground Services
Aer Lingus	EI	KLM Ground Services	JAT Yugoslav Airlines	JU	GlobeGround
Aeroflot Russian Int. Airlines	SU	KLM Ground Services	Jet2	LS	Aviapartner
Air Aegean	A3	GlobeGround	Kenya Airways	KQ	KLM Ground Services
Air Alps	A6	KLM Ground Services	KLM exel	KL	KLM Ground Services
Air Anatolia	NTL	GlobeGround	KLM Royal Dutch Airlines	KL	KLM Ground Services
Air Bosna	JA	GlobeGround	KLM uk	UK	KLM Ground Services
Air Canada	AC	Menzies	Korean Air	KE	GlobeGround
Air Dolomiti	EN	GlobeGround	Kuwait Airways	KU	KLM Ground Services
Air France	AF	Aviapartner	Libyan Arab Airlines	LN	
Air Holland	HLN	Air Holland	Lithuanian Airlines	TE	KLM Ground Services
Air Jet	V6	Aviapartner	LOT Polish Airlines	LO	KLM Ground Services
Air Malta	KM	KLM Ground Services	Lotus Air	TAS	Menzies
Air Moldova	9U	GlobeGround	Lufthansa	LH	GlobeGround
Air One	AP		Maersk Air Ltd	DM	KLM Ground Services
Air Sint Maarten	E7	Menzies	Malaysia Airlines	MH	KLM Ground Services
Air Transat	TS	GlobeGround	Malev Hungarian Airlines	MA	KLM Ground Services
Air Zena Georgian Airlines	A9	Menzies	Martinair Holland	MP	Martinair
Alitalia	AZ	Menzies	MAT Macedonian Airlines	IN	Dutchport
Arkia	IZ	GlobeGround	Meridiana	IG	KLM Ground Services
Armavia	U8	KLM Ground Services	MNG Airlines	MNB	Menzies
Armenian Airlines	R3	GlobeGround	MyTravelLite	VZ	Aviapartner
Austrian Airlines	OS	GlobeGround	Northwest Airlines	NW	KLM Ground Services
bmi british midland	BD	GlobeGround	Olympic Airways	OA	GlobeGround
British Airways	BA	Aviapartner	Onur Air	OHY	Menzies
Bulgaria Air	FB	GlobeGround	PIA Pakistan International Airlines	PK	Menzies
Cathay Pacific Airways	CX	Aviapartner	Pulkovo Aviation Enterprise	FV	KLM Ground Services
China Airlines	CI	KLM Ground Services	Royal Air Maroc	AT	Menzies
China Southern Airlines	CZ	KLM Ground Services	Royal Jordanian Airlines	RJ	GlobeGround
Continental Airlines	CO	Aviapartner	SAS Scandinavian Airlines	SK	GlobeGround
Croatia Airlines	OU	Menzies	Scot Airways	CB	Menzies
CSA Czech Airlines	OK	KLM Ground Services	Singapore Airlines	SQ	GlobeGround
Cyprus Airways	CY	KLM Ground Services	Skynet Airlines	SI	KLM Ground Services
Delta Air Lines	DL	Menzies	Spanair	JKK	Menzies
Dutch Caribbean Airlines	K8	Aviapartner	Sun Dor	7L	Menzies
DutchBird	DBR	Menzies	Surinam Airways	PY	KLM Ground Services
easyJet	U2	Menzies	Swiss International Airlines	LX	Aviapartner
Egypt Air	MS	GlobeGround	Syrian Arab Airlines	RB	Menzies
El Al Israel Airlines	LY	Menzies	TACV Cabo Verde Airlines	VR	Menzies
Eritrean Airlines	B8	Menzies	TAP Air Portugal	TP	Aviapartner
Ethiopian Airlines	ET	GlobeGround	THY Turkish Airlines	TK	GlobeGround
Eurowings	EW	GlobeGround	Transavia airlines	HV	KLM Ground Services
EVA Airways	BR	Menzies	Tunis Air	TU	Menzies
Finnair	AY	Aviapartner	Tyrolean Airways	VO	Dutchport
Fly Air	FLM	GlobeGround	Ukraine International Airlines	PS	KLM Ground Services
Futura International Airways	FUA	Menzies	United Airlines	UA	Menzies
Garuda Indonesia	GA	GlobeGround	US Airways	US	GlobeGround
Iberia	IB	Aviapartner	VARIG Brasilian Airlines	RG	GlobeGround
Icelandair	FI	KLM Ground Services	Virgin Express	TV	Menzies
Inter Express Airlines	INX	GlobeGround			
Iran Air	IR	KLM Ground Services			
Israir	ISR	Menzies			

Table D2. Airlines and their baggage handler at Schiphol Airport

Arriving and transferring at Schiphol

Passport control on arrival

When passengers arrive at Schiphol signs with "arrival" and "exit" lead the passengers to passport control. After passport control passengers can go to the baggage reclaim area to get their baggage.

When a passenger has a Schengen country as origin no passport control is required.

Check-in for transfer passengers

Transfer passengers can get additional information about their connecting flight at transfer check-in counters. The transfer counters are situated at the pier shown in Table D3.

Located at	Transfer counter group
C-pier	T2
D-pier (second floor)	T3
D-pier (at gate D11)	T4
D-pier	T5
E-pier	T6
F-pier	T8
G-pier	T9

Table D3: Transfer counters at the location in the airport terminal