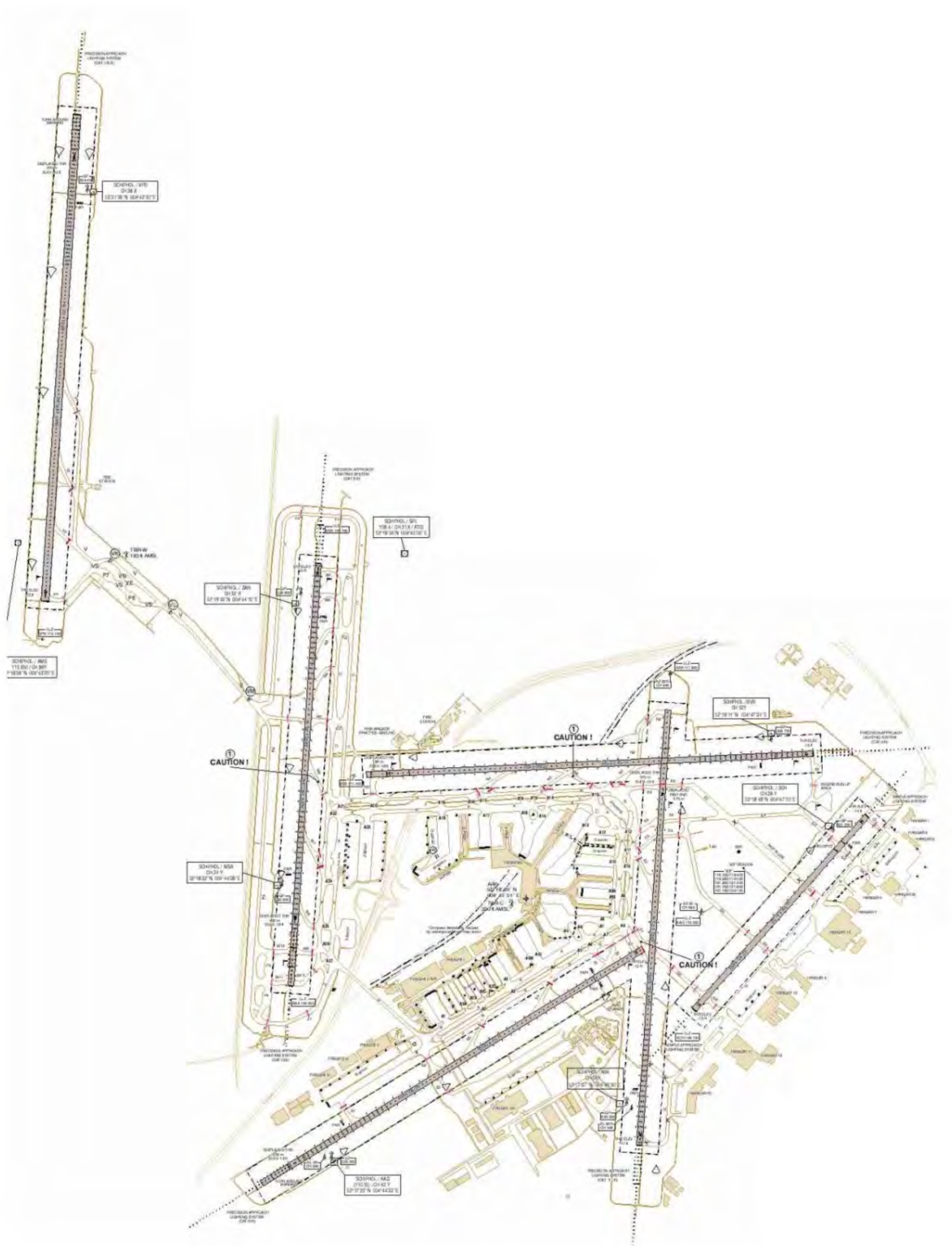
Impact of systematic factors on delays at Schiphol



R P Dwars
mBA research paper
November 2012

vrije Universiteit amsterdam

Preface

On a windy day I was checking the flight radar app on my phone that enables me to see aircraft movements around Schiphol. Many airplanes were flying in circles, waiting for their turn to land. At that moment I got inspired to write this paper.

I would like to thank Rob van der Mei for his excellent support and feedback over the past months.

Summary

Schiphol is one of the busiest airports in Europe, handling 437.082 flights in 2010 [1]. During peak hours, runway capacity is usually less than the traffic volume and delays occur. Delays can be categorized in systematic delays and non-systematic delays. Systematic delays are caused by factors that affect all flights (e.g. visibility and wind conditions) and non-systematic delays are flight specific (e.g. missing passengers and technical malfunctions).

When weather conditions are normal, a secondary runway can be used along with the primary runways to handle extra traffic. However, under certain wind conditions, only a primary runway for departures and arrivals is available. Moreover, when visibility is poor, the separation distance between aircraft has to be increased. Both weather situations cause a significant drop in capacity and this will lead to extra delays.

In this paper, only the impact of systematic factors on the delays has been investigated. This was done by analyzing three different scenarios with the use of a trace-driven simulation. The trace-driven simulation tool has a graphical user interface and can be used by air traffic control to support tactical and operational decisions. Table 1 shows the three different scenarios and each scenario represents a specific weather type.

Table 1: Scenarios for different weather conditions.

Weather type	Primary runway available?	Secondary runway available?	Increased separation distance?
Optimal weather conditions	Yes	Yes	No
Strong wind from the east of west	Yes	No	No
Reduced visibility	Yes	No	Yes

Main findings

Impact on the delays for each scenario

The results of the first scenario show that there is sufficient capacity to handle arrival and departure peaks. However, capacity is halved when no secondary runway is available. This scenario occurs when a strong wind is coming from an eastern or western direction. In this scenario, the arrival delay increases significantly during arrival peaks. In the third scenario, the separation distance for both arrivals and departure increases significantly and this causes long delays. However, the simulation model doesn’t take cancellations into account and it also assumes that visibility is reduced for the whole day. These assumptions are not realistic and therefore the results might be questionable. However, the results show that visibility can have a profound impact on delays.

Impact of separation distance on delays

The traffic pattern at Schiphol was analyzed and the analysis showed that a 30-minute buffer was separating the arrival and departure peaks. During this buffer period, fewer departures/arrivals are scheduled. When delays become longer than this period, the two or more peaks melt together and delays increase significantly. As long as the average delay is kept below 30 minutes, peaks will not merge and arriving and departing traffic will be separated. This can be reached by keeping the separation distance for arriving aircraft under 7 km and the time between departing aircraft under 1.5 minutes.

Impact of the wind direction on the delays and runway usage

Due to its location near the sea, Schiphol has runways in several directions. In general, the wind is the strongest when it comes from the North Sea, which means a western/ southwestern direction.

When a strong wind comes from this direction, only one runway can be used for takeoffs and one runway for landings. Normally, when the wind is calm, a secondary runway can be used to handle departing or arriving traffic. Having only one runway available reduces capacity significantly and this may cause longer delays, especially during the peak hours. Results show that if there would be an additional runway that faces the west or southwest, delays could be reduced significantly because this runway could be used a secondary runway.

Recommendations

The main recommendations of this research are:

1. To avoid significant delays during periods of poor visibility, the minimum separation distance has to be kept under 7 km for arriving airplanes and under 2 minutes between two departing airplanes. This way, the average delay will be below 30 minutes and the arrival and departure peak will not interfere with each other.
2. When a strong wind is coming from a western/southwestern direction (which happens relatively often due to Schiphol's location near the North Sea), there is no secondary runway available. An additional runway facing west/southwest would increase capacity during peak periods and Schiphol would then have enough capacity for the most common wind directions that occur at the airport.
3. When a strong wind (80km/h) comes from the northwest or southeast, no runways can be used because the crosswinds exceed the safety threshold. To prevent this situation, an additional runway from northeast to northwest would be recommended.

Table of contents

Chapter 1: Introduction

At this moment, Schiphol is 20th busiest airport in the world, handling 437.082 flights in 2010 [1]. Schiphol has six runways consisting of five long runways and one short runway. The short runway is mostly used to handle general aviation (e.g. Cessna's). Remarkably, London Heathrow has only two runways and handles 480,906 flights in 2010 [1]. How is it possible that Schiphol needs five runways? There are several explanations for this phenomenon. First, Heathrow is near its 100% capacity and when weather conditions are bad, delays at Heathrow are much longer than at Schiphol. Second, Heathrow is located further from the sea and faces less strong winds such that fewer runways are needed in each direction. Third, environmental regulations are restricting Heathrow to build an extra runway.

1.1 Problem and approach

Handling large amounts of traffic can be challenging for air traffic control. During normal weather conditions, there is one runway available for landings and one for takeoffs. A secondary runway is mostly used during rush hours. Because capacity is ample in this situation, there shouldn't be much delay. However, during special weather conditions (e.g. strong wind or poor visibility), only one runway can be used for takeoffs and landings. This reduces capacity significantly and it might have a dramatic effect on the length of the delays. Also, when visibility is poor, only one runway can be used and the separation distance between two aircraft has to be larger. Much research has been done on the impact of runway usage on the sound pollution, but little research has been done on the impact of the weather on the delays.

In this research paper the focus will be on the delay that was caused by systematic factors, such as wind direction, wind speed and visibility. The main research question is:

- What is the impact of systematic delays on the delays at Schiphol?

Other types of delay, such as malfunctioning airplanes and missing passengers will not be taken into account. In order to get an insight in the delay, a trace driven simulation has been built to replicate the runway system of Schiphol. Three different scenarios have been analyzed, each representing different weather conditions.

1.2 Overview

In chapter 2 the systematic factors that affect capacity of airports will be described. Chapter 3 analyses the maximum capacity of runways for several weather conditions. Chapter 4 explains why a simulation was built and which assumptions were made. Chapter 5 reports the results for the different scenarios. The paper ends with the conclusion that reports the main findings and recommendations of this research.

Chapter 2: Systematic factors affecting delay

There are two major weather factors that affect runway usage: wind and visibility. The first section describes the effect of the wind and the second section describes the effects of reduced visibility.

2.1 Wind conditions

Due to Schiphol's location near the sea, the wind can be very strong. The following figures are based on weather data from the KNMI between 1951 and 2012 [2]. Figure 2 shows the distribution of the maximum wind speed that was recorded per hour. Wind speeds can be as strong as 130 km/h, but these are often just strong wind gusts. Figure 3 shows that the most common wind direction is roughly 250 degrees, which is a western/southwestern wind as can been seen in figure 1. This direction is logical because the North Sea is located to the west of Schiphol.

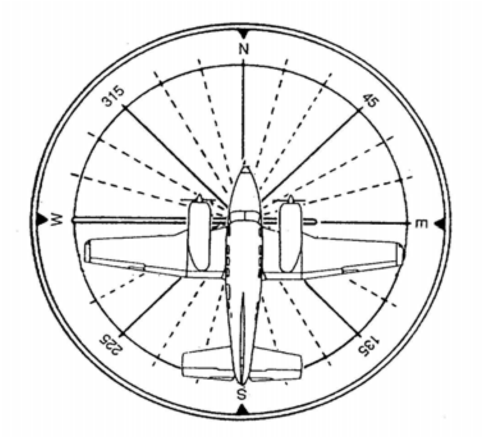


Figure 1: Compass direction.

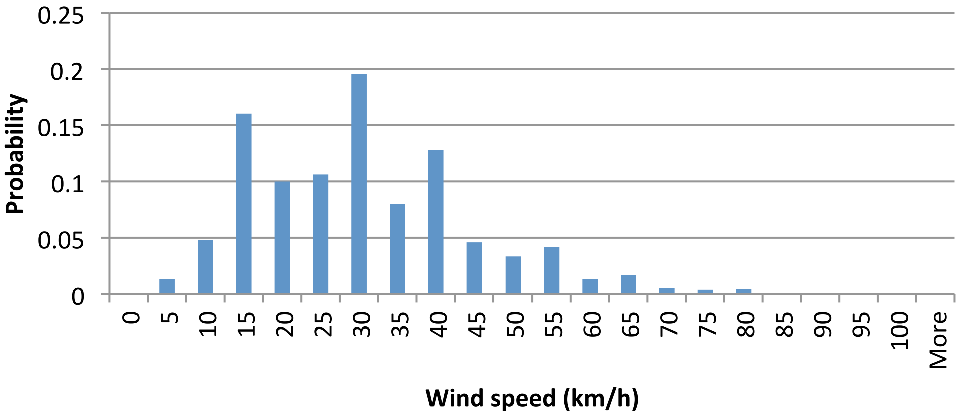


Figure 2: Distribution of windspeed at Schiphol.

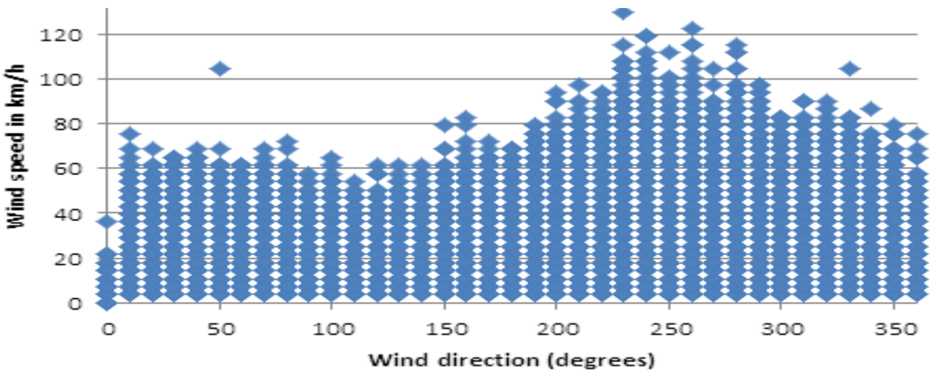


Figure 3: Relation between wind speed and wind direction.

In general, pilots prefer headwind landings, but cross wind landings can't be avoided. The maximum crosswind tolerance varies per aircraft type, but in general, landings are discontinued when crosswinds exceed 55.56 km/h [3]. Landings with tailwind are avoided as much as possible because the approach velocity becomes too high such that an aircraft might overshoot the runway.

The crosswind can be computed by using the angle and strength of the wind. This angle is shown in figure 4 and the arrow represents the wind direction. The crosswind component can be calculated by: $|\text{windspeed} * \sin(\text{angle})|$. The angle is equivalent to the difference between wind direction and flying direction.

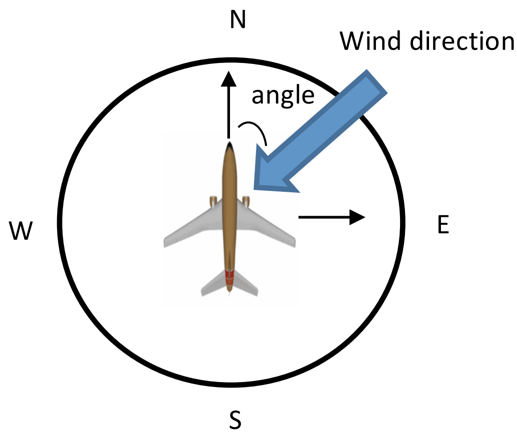


Figure 4: Calculating the crosswind component.

2.2 Visibility

Visibility has a significant impact on runway capacity. When visibility is less than 5 km, and/or the clouds are below 300 meters, airplanes cannot make a visual approach but have to rely on instruments [4]. Figure 5 shows the distribution of the horizontal visibility at Schiphol. In most cases, visibility is larger than 5200m and pilots can make a visual landing. However, the distribution of the visibility has a long left tale and when visibility is less than 550 meters, only one runway can be used for landings and one for takeoffs. There is a 1.12% probability that visibility is less than 550m, meaning that on average 4.5 days suffer from very poor visibility.

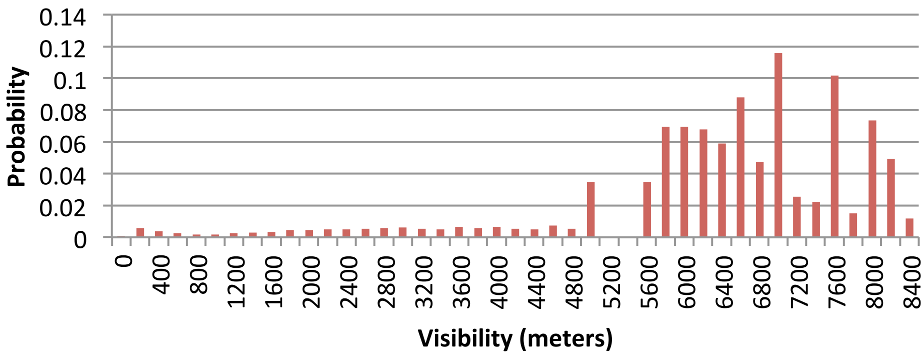


Figure 5: Distribution of the visibility at Schiphol.

Most major airports have an Instrument Landing System (ILS) that automates the landing when visibility is reduced. ILS is a sophisticated radio navigation system that guides airplanes towards the runway. Table 2 shows the different classes of ILS systems. The higher ILS categories have a higher precision such that the minimum runway visual range, i.e. the distance from which the runway can be seen, is lower than lower categories. The type of system is used is dependent on the ILS system on board of the aircraft and at the airport [5]. All runways at Schiphol are equipped with ILS III C.

Table 2: ILS categories.

Type	Minimum runway visual range	Min cloud base (height of clouds)
Category I	550m	200m
Category II	350m	100m
Category III A	200m	50m
Category III B	50m	20m
Category III C	0m	0m

Limitations of ILS

A problem of ILS is that radio signals can be disturbed when too many objects are blocking the signal. Such a situation situation is illustrated in figure 6. A distance must therefore be kept between approaching airplanes to insure a steady signal. This distance is not a fixed number, but for the sake of simplicity as distance of 9.26 km was assumed. At 9.26 km from the runway, airplanes make their first contact to the ILS system.

Departing airplanes also suffer from low-visibility because some taxiways cannot be used in order to ensure a steady ILS signal. The separation distance for takeoffs is not fixed, but a 2-minute separation is reasonable to assume.

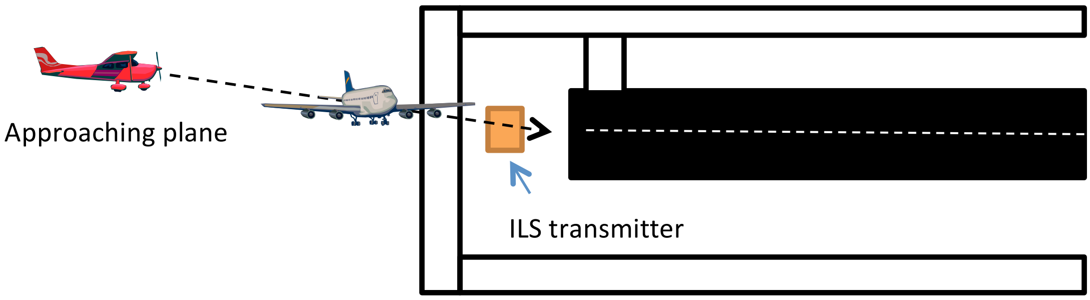


Figure 6: Blocking of ILS transmitter.

Low visibility procedures at Schiphol

Schiphol has special procedures for arriving and departing aircraft when visibility is reduced. Low visibility can lead to runway incursions and taxiway collisions on the ground and therefore special procedures were developed. Table 3 shows these procedures for arriving and departing traffic [6]. During periods of very limited visibility, only one runway is available for takeoff and one for landing and this reduces the capacity significantly during peak hours.

Table 3: Low visibility procedures at Schiphol.

Phase	Weather condition	Procedure
A	Touch down zone of a runway is not visible from 1500 m and the clouds are less than 300 feet.'	Reduced visibility has only impact on ground operations regarding departing traffic (stopbars activated, no intersection takeoffs, etc.)
B	Touch down zone of a runway is not visible from 550 m and the clouds are less than 200 feet.'	ILS CAT II separations will be provided. Runway use will be restricted.
C	Touch down zone of a runway is not visible from 350 m	ILS CAT III separations will be provided. Runway use will be restricted.
D	Touch down zone of a runway is not visible from 200 m and below	ILS CAT III separations will be provided. Only one runway with ILS CAT III will be available for landing and one runway for departure.

2.3 Traffic volume

Most airlines that fly to Schiphol are non-charter airlines, such as Air France-KLM and Delta Airlines. These airlines have fixed capacity and operate on a fixed timetable during the year (although the time table may vary a bit per season). On the other hand, charter airlines (such as Arke Fly, Corendom etc.) have more flexible capacity and do not operate on a flexible timetable.

At major airports where capacity is limited, landing and departure slots are used. One slot gives an airline the right to land at a specific time. The amount of slots available is dependent of time, demand and environmental regulations [7]. The slot system is used to spread capacity such that both capacity and demand are adjusted to each other. During peak periods, slots are in general more expensive than during quiet periods and this is the reason why most charter airlines schedule their flights during quiet periods.

In 2011, the busiest day was at 2nd of July during the holiday season. In terms of passenger volume it was the busiest day but in terms of traffic volume it was almost like a regular day. Figures 7 and 8 show the traffic volumes for different types of days. Only the peaks were a bit higher compared to a normal day and there was also a departure peak around 05:00 AM. In general, airlines put larger aircraft into service to cope with an increased demand. Scheduling extra flights into the timetable is difficult because there is a limited amount of slots.

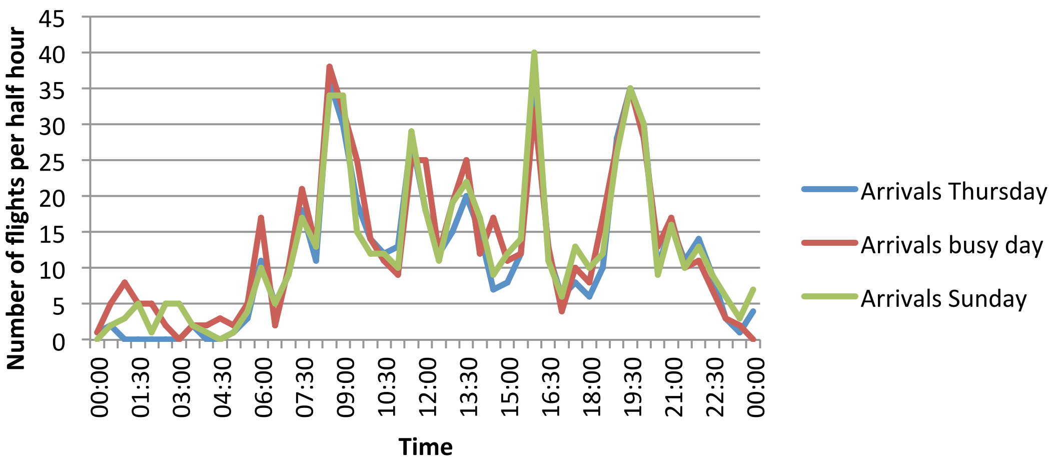


Figure 7: Arrival pattern for different types of days.

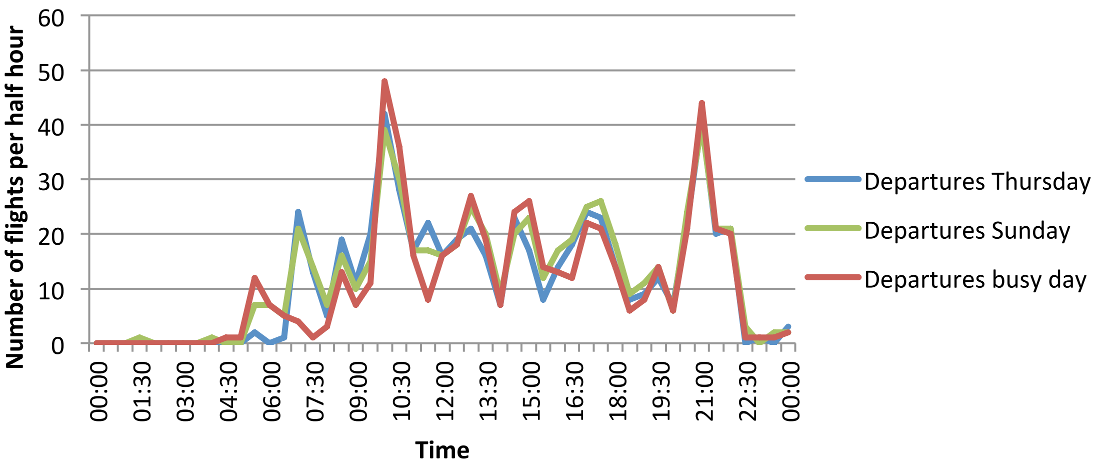


Figure 8: Departure pattern for different types of days.

Peak hours

Figure 9 shows the number of departing flights and arriving flights per 30 minutes. There are two high departure peaks that can be seen: the first is around 9:30 and the second around 21:00. There are three high arrival peaks; the first is around 8:30, the second around 16:00 and the third around 19:30. It is interesting to notice that the departure peaks occur at different times than the arrival peaks. An arrival peak and a departure peak are separated by a so-called 'fire break', which is a short buffer to separate inbound and outbound traffic [8].

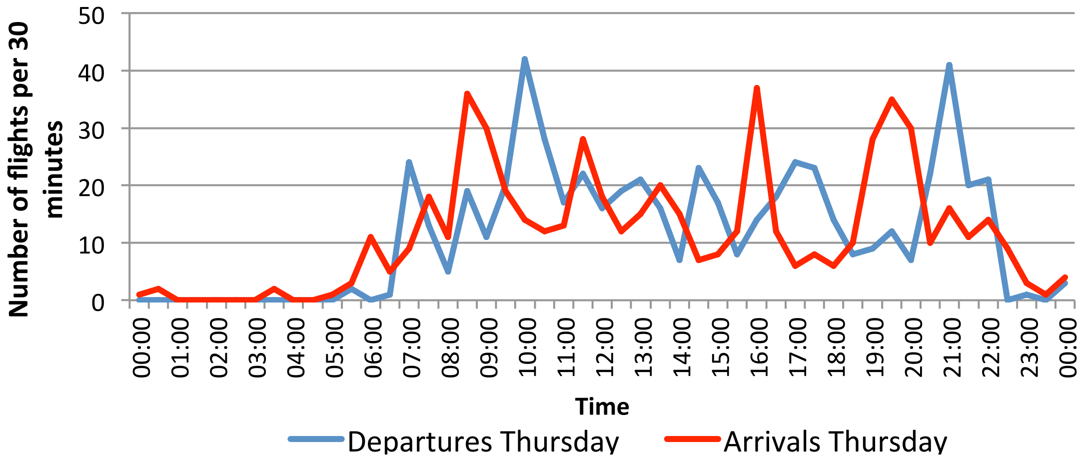


Figure 9: Arrival and departure peaks during the day.

2.4 Runway lay-out

Schiphol has six runways, which is significantly more compared to other major airports. However, there are several factors that limit the usage of runways, such as weather conditions, environmental regulations, maintenance of runways, safety regulations and noise pollution regulations.

Figure 10 shows the runway configuration and usage at Schiphol [9]. Each runway has its own ID, which indicates the compass direction it faces. For example, 18R means that the runway has a compass direction of 180 degrees (to the north) and it is the rightmost runway. The other runways that face to the north are; 18C (18 center) and 18L (18 left). The same reasoning applies to the other runways. Figure 10 shows that 36L, 9 and 18L cannot be used for landings due to sound pollution restrictions. Schiphol has one runway, the 'Oostbaan' (runway 22/04) being much shorter than all the other runways. It is mostly used by small aircraft or during special weather conditions such as a severe wind from the southwest.

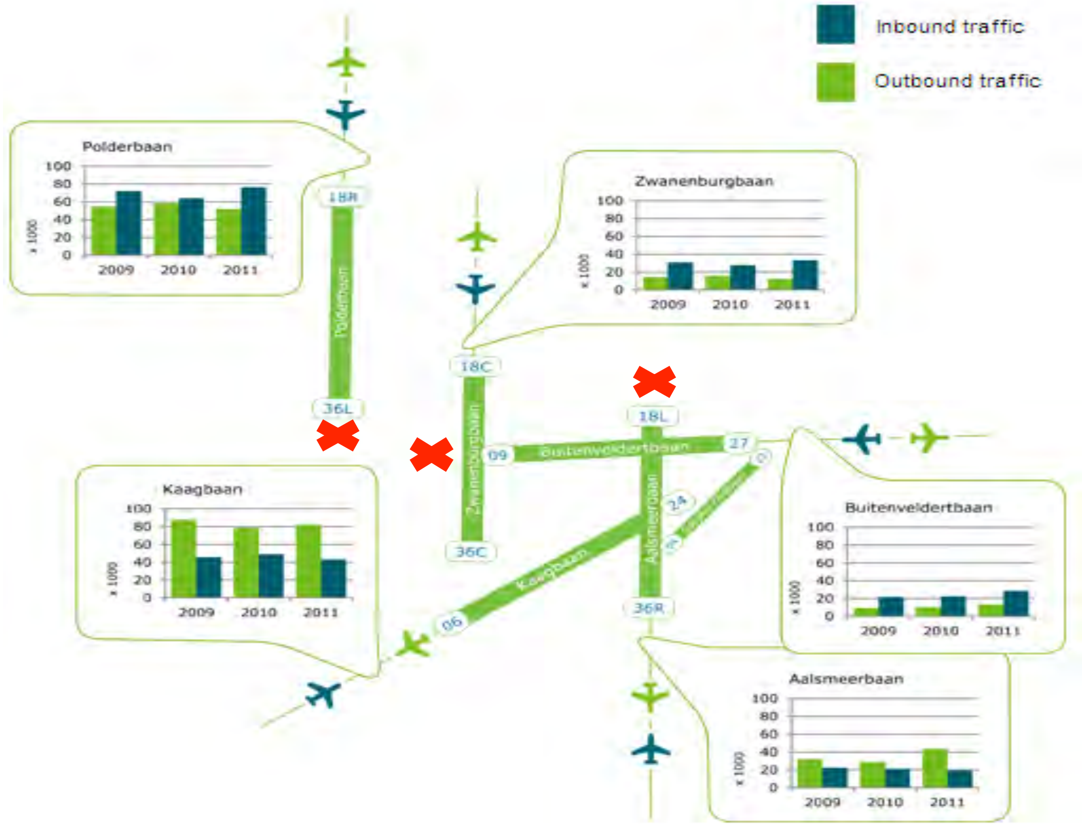
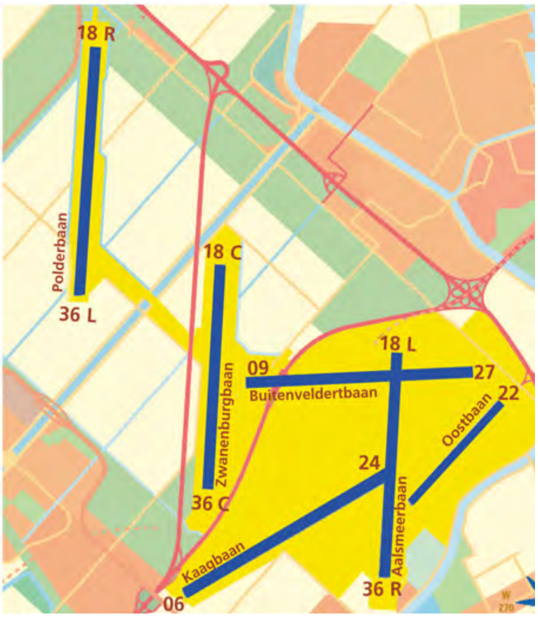
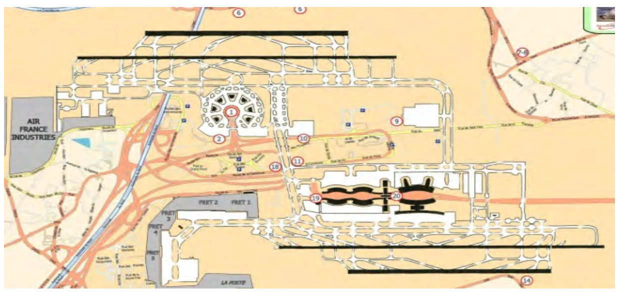


Figure 10: The runway configuration and the amount of traffic per year.

Runway dependencies

The runways of Schiphol point in various directions in order to cope with different wind directions. Other major airports in Europe such as London Heathrow and Paris Charles-de-Gaulle only have runways and face in the same direction. Figure 11 shows a comparison between Schiphol, London Heathrow and Paris Charles-de-Gaulle. The benefit of the runway configuration of Schiphol is that the airport can operate under almost all wind conditions but the downside is that the usage of the runways is dependent on each other.





Paris Charles-de-Gaulle

Amsterdam Schiphol

London Heathrow

Figure 11: Runway layout of several airports in Europe.

If we look at Schiphol, one of the reasons why the new Polderbaan (36L/18R) is located so far from the main terminal is because the Zwanenburgbaan and the Polderbaan can be used independently at the same time. The distance between both runways is 2 km, however if the distance would be less than 1300m the then runway usage would be dependent and capacity would decrease.

Between the Kaagbaan, Zwanenburgbaan and the Aalsmeerbaan there are many dependencies. For example, figure 12 shows a few situations where flight paths intercept. In the first figure an aircraft is landing on runway 18C (indicated by blue) and at the same time a aircraft takes off at runway 24 (indicated by red). In this situation, there exists a risk of collision because the aircraft that is landing at 18C might abort the landing and must make a new attempt while the airplane on runway 24 is taking of.

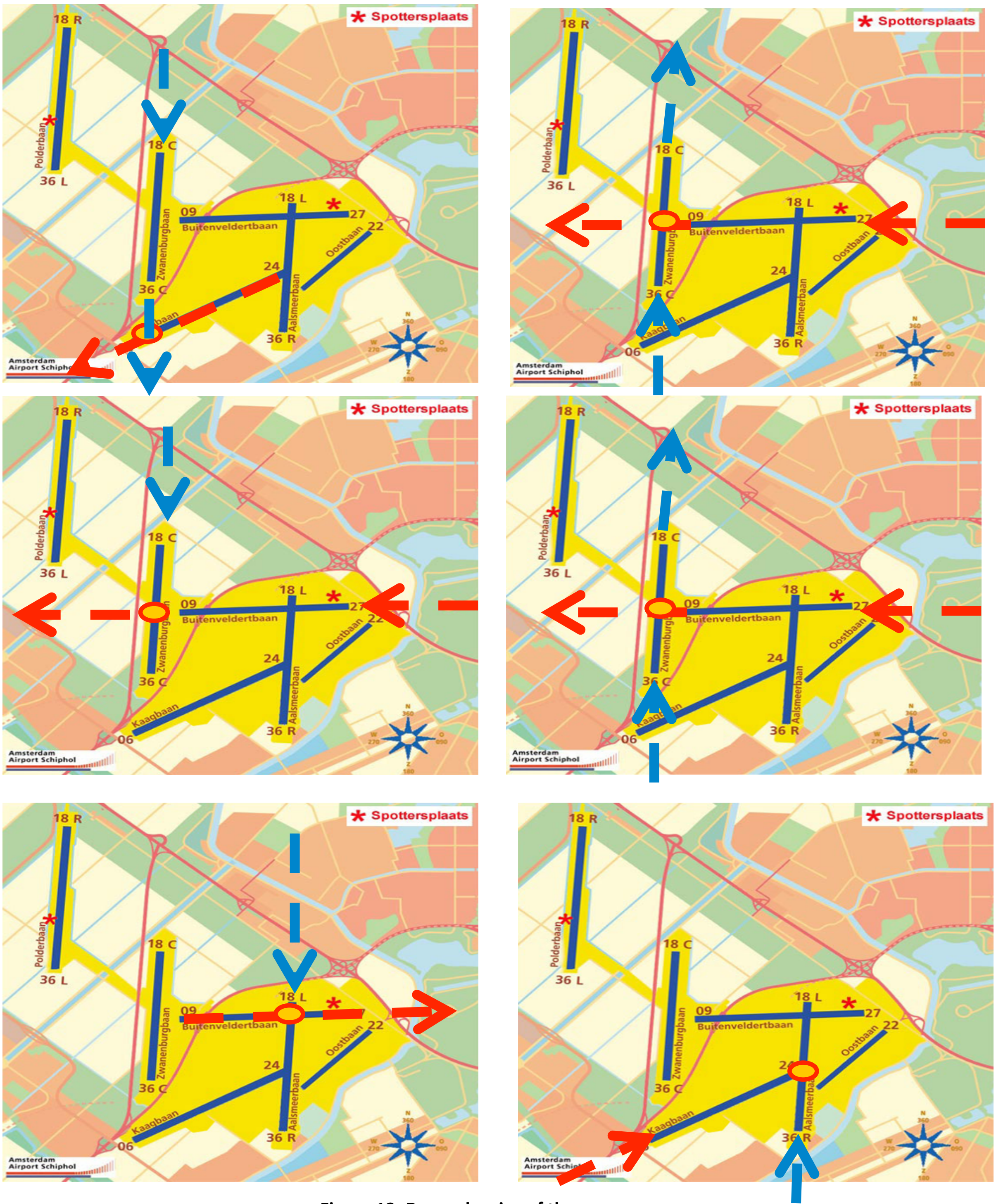


Figure 12: Dependencies of the runways.

2.5 Runway preference by air traffic control

Figure 10 showed the traffic intensity per year for each runway. The figure shows that the Polderbaan and the Kaagbaan were used most often compared to other runways. Whether a runway should be used, is dependent on the wind conditions. LVNL (Dutch air traffic control) made a preference order to determine which runways should be used under given circumstances (i.e. wind conditions, traffic volume and sound pollution regulations). Each preference is intended to be used for certain wind conditions and the order of these preferences is determined by sound pollution regulations. The preference order is showed in table 4 [10].

Table 4: Preference order for normal weather conditions.

Preference	Primary arrival runway	Secondary arrival runway	Primary departure runway	Secondary departure runway	Used under the following wind directions:
1	06	36R	36L	36C	N/NW
2	18R	18C	24	18L	S/SW
3	36R	36C	36L	36C	N/NW/NE
4	18R	18C	18L	18C	S/SW/SE
5	Other runway configurations				

During periods with a high volume of departing airplanes, two runways are assigned for departures and only one is available for arriving airplanes. The situation is reversed during periods with many arrivals. Figure 9 showed that high peaks of arriving traffic and departing traffic do not occur at the same time. In general, during normal operating hours only one runway is available for departures and one for arrivals.

It is interesting to verify whether the runway preference was followed by air traffic control. The runway usage of the period 2010-2011 was analyzed, using data from Dutch airplane spotters [11]. The results are displayed in table 5 to 9.

Table 5 shows that most of the time only a primary runway was used to handle traffic. In roughly 20% of the time, a primary and secondary runway was used. A small fraction of the time no runways were used because Schiphol was temporarily closed due to extreme weather or special circumstances (e.g. the ash cloud in 2010).

Table 5: Fraction of the time that zero, one or two runways were used.

	0 runways	1 primary runway	1 primary runway and 1 secondary runway
Landing	0.8%	77.5%	21.7%
Take-off	0.8%	79.1%	20.1%

Table 6 shows the runway preference usage for periods with a normal traffic volume. Preference 2 was used slightly more than preference 1, because the wind came more often from the south/southwest than from the north/northwest. There are two preferences for each wind directions; preferences 1 and 3 are used for a northern or northwestern wind and preferences 2 and 4 are used for a southern or southwestern wind. Preferences 3 and 4 were used significantly less compared to preferences 1 and 2.

Table 6: Fraction of time that the normal preference was used.

	Primary arrival runway	Primary departure runway	Wind direction	Fraction of time used (in 1 year)
1	06	36L	N/NW	21.03%
2	18R	24	S/SW	22.58%
3	36R	36L	N/NW/NE	1.38%
4	18R	18L	S/SW/SE	1.6%

Tables 7 and 8 show how often the runway preferences for departure peaks and arrival peaks were used.

Table 7: Occurrence of the departure peak preferences.

	Primary arrival runway	Primary departure runway	Secondary departure runway	Fraction of time used (in 1 year)
1	06	36L	36C	4.00%
2	18R	24	18L	7.25%
3	36R	36L	36C	0.70%
4	18R	18L	18C	0.22%

Table 8: Occurrence of the arrival peak preferences.

	Primary arrival runway	Primary departure runway	Secondary arrival runway	Fraction of time used (in 1 year)
1	06	36R	36L	5.91%
2	18R	18C	24	5.82%
3	36R	36C	36L	1.57%
4	18R	18C	18L	1.95%

Other runway combinations

It is interesting to notice, that there is no preference when a wind comes from the west or east. In this case, the Buitenveldertbaan (27/09) is often used in combination with the Kaagbaan (06/24). This runway is not preferred due to severe noise pollution for the Buitenveldert area.

About 75% of all takeoffs and landings can be explained using the preference order of air traffic control and the remaining 25% are non-preferred combinations. These combinations are used when there is a strong wind coming from the east or from the west. Table 9 shows some common combinations that occur when wind comes from the east or west. An example of such a combination is runway 27 for arrivals and runway 24 for departures. This is often the case when there is a strong wind from the west. These runway non-preferred combinations explain an additional 16.68% of the runway usage. So in total, about 90.1% of the time preferred or non-preferred combinations were used.

Table 9: Occurrence of non-preferred runway combinations.

Combination	Primary arrival runway	Secondary arrival runway	Primary departure runway	Secondary departure runway	Wind direction	Fraction of time used (in 1 year)
1	27	18R	24		SW	2.08%
2	27		24		SW/W	4.45%
3	27		24	36L	SW	2.688%
4	06		09	36L	NE	2.33%
5	06		09		NE/E	0.68%

Chapter 3: Capacity of runways

At large airports such as Schiphol and London Heathrow, runways are used intensively. An occupancy of more than 95% for a runway happens often, especially at London Heathrow which has only two runways and a higher traffic volume. The maximum capacity of a runway depends mainly on the minimum separation distance between aircraft. The two main factors that affect this separation distance are visibility and the wake vortex. A wake vortex occurs when an aircraft takes off or lands and can cause severe turbulence for following aircraft.

Let's simplify the situation to one runway and we assume that the fleet that uses the runway is homogeneous, i.e. all airplanes are of the same size. Moreover, the inter arrival time for both arriving and departing aircraft is estimated to be 60 seconds and the amount of traffic is ample such that there is always an inflow of traffic.

The Maximum Throughput Capacity (MTC) is defined as the maximum number of flights per hour. Considering the situation with homogeneous fleet, then the MTC would be equal to $\frac{3600 \text{ sec}}{60 \text{ sec}} = 60 \text{ flights/hour}$ (this capacity is for both departures and arrivals). This number is the maximum throughput capacity in a theoretical situation and this number almost never met in practice.

Let's extend the model to a heterogeneous fleet of airplanes. As mentioned earlier, each airplane creates a so-called wake vortex after a takeoff or landing, where air spills over the edge of the wings creating two tubes of circulating air that trail behind the aircraft. The circulating air is known as a wake vortex and has sufficient strength to cause a following aircraft to roll. The concept of wake vortex is illustrated in figure 13. Bigger aircraft tend to generate stronger and longer lasting wake vortices than smaller aircraft. Therefore, smaller aircraft have to keep a bigger distance to a large leading aircraft. There are no fixed separation distances known for take offs, but there is a rule of thumb that says that there must be 2 minutes between an aircraft of a low vortex category and an aircraft of a high vortex category. Tables 10 and 11 show the separation distances for different classes of aircraft for arrivals and departures [12].

Figure 13: Wake vortex.

Table 10: Separation distances for arriving aircraft.

	Following aircraft			
Leading aircraft		**H (Heavy)**	**L (Large)**	**S (Small)**
	H (Heavy)	7.4 km	9.3 km	11.1 km
	L (Large)	5.6 km	5.6 km	7.4 km
	S (Small)	5.6 km	5.6 km	5.6 km

Table 11: Separation time for departing aircraft.

	Following aircraft			
Leading aircraft		**H (Heavy)**	**L (Large)**	**S (Small)**
	H (Heavy)	1 min	2 min	2 min
	L (Large)	1 min	1 min	2 min
	S (Small)	1 min	1 min	1 min

Definition of aircraft sizes [13]:

- Heavy - Aircraft capable of takeoff weights of 300,000 pounds (140,000 kg) or more whether or not they are operating at this weight during a particular phase of flight.
- Large - Aircraft of more than 41,000 pounds (19,000 kg), maximum certificated takeoff weight, up to but not including 300,000 pounds (140,000 kg).
- Small – Aircraft of 41,000 pounds or less maximum certificated takeoff weight.

The separation distance between two aircraft now varies and also the composition of the arriving and departing aircraft in the sequence varies each hour. The formula below shows how the MTC can be calculated.

$$\mathrm{MTC} = \frac{3600}{3600 * \frac{\mathrm{E(D)}}{\mathrm{v}} + \mathrm{S}}\ \text{, where:}$$

$\mathrm{E(D)}$ = expected separation distance in km,
V = approach velocity of an aircraft in km/h,
S = safety separation in seconds.

To calculate the maximum throughput capacity for arrivals, we have to make an assumption about the approach velocity of an aircraft. This velocity is depends on many factors such as aircraft type, wind speed, wind direction and visibility. In general, this number varies between 241 km/h and 296 km/h [14]. As an approach velocity, we take the average of these two numbers; 277.8 km/h. To calculate the MTC for departures we have to make an assumption about the takeoff speed. In general, this number varies between 277 km/h and 296 km/h. As a takeoff speed, we take the average of these two numbers, which is 287 km/h [15].

The formula below shows how the expected separation distance can be computed.

$$E(D) = \sum_{i=1}^{3}\sum_{j=1}^{3} D_{ij} * p_i * p_j\ ,\ i,j \in \{1 = \text{Heavy}, 2 = \text{Large and } 3 = \text{Small}\}$$

In this formula, i represents the class of the leading aircraft and j the class of the following aircraft. P_i represents the probability that class i occurs and $\mathrm{D_{ij}}$ represents the separation distance between leading aircraft class i and following aircraf class j.

In order to calculate $\mathrm{E(D)}$, we need to know the probability that a aircraft class occurs. Table 12 shows the fraction of different aircraft types that visit Schiphol on a typical day.

Table 12: Fraction of different aircraft types at Schiphol.

Type	Fraction $(\mathbf{p_i})$
Heavy	0.085
Large	0.501
Small	0.414

This formula was applied to both departures and arrivals and table 13 shows the results.

Table 13: MTC for arrivals and departures.

(#flights/hour)	Expected separation time ($\frac{E(D)}{V}$)	Safety buffer	Fixed separation distance (60 sec)	MTC considering wake vortex
Arrivals	73.24 sec	30 sec	60	30 flights
Departures	77.11 sec	0 sec	47	47 flights

The arrival capacity decreases with 30 flights an hour and the departure capacity decreases with 13 flights an hour, compared to the situation with a fixed separation distance of 60 seconds. These numbers indicated that the arrival capacity is lower than the departure capacity.

Capacity during periods of reduced visibility

When visibility is reduced, arriving and departing aircraft must increase their separation distance. For arriving aircraft, this distance is 9.26 km and for departing aircraft 2 minutes. Both numbers are estimates, because separation distance is dependent on many factors. Table 14 shows the capacities for arriving and departing aircraft, assuming a homogeneous fleet. It is interesting to see that the capacity for arrivals has decreased with 30 flights. The capacity for departures has been reduced from 47 to 30.

Table 14: Runway capacity when visibility is less than 500m (assuming homogeneous fleet).

(#flights/hour)	Fixed separation distance (60 sec)	Reduced visibility
Arrivals	60	30
Departures	47	30

Conclusion

When visibility is good, the capacity of runways is only affected by the minimum separation distance requirements that concern the wake vortex. The calculations of the MTC showed that the arrival capacity is lower than the departure capacity. When visibility is poor, the minimum separation distance increases. Both the departure and arrival capacity are reduced to 30 flights per hour, which is a reduction of more that 50% for arrivals and 36% for departures.

Chapter 4: Simulation model

A simulation model was built to investigate the impact of systematic factors on the delays. The main objective was to create a flexible tool, in which different scenarios can be analyzed. It was hard to apply existing queuing theory to this problem, because the arrivals and departures are scheduled and they do not occur according to a Poisson process. Also, the 'service time', i.e. the time an aircraft occupies the runway, is dependent of the class of aircraft that arrived/departed earlier and is also difficult to model in existing queuing systems. In the paper of Bäuerle, Engelhardt-Funke and Kolonko about "On the waiting time of arriving aircraft and the capacity of airports with one or two runways", a queuing system was developed that takes dependent service times into account. The underlying assumption is that airplanes arrive according a Poisson process, because the moment of arrival is random due to external delays [16]. However, this assumption is questionable because most flights have no delays at all and arrive/depart at fixed times.

Figure 14 shows all the parameters that can be changed in the simulation tool. One of the parameters is 'queue length' and this is a threshold that indicates how many airplanes have to be in the queue of the primary runway, before a secondary runway can be used.

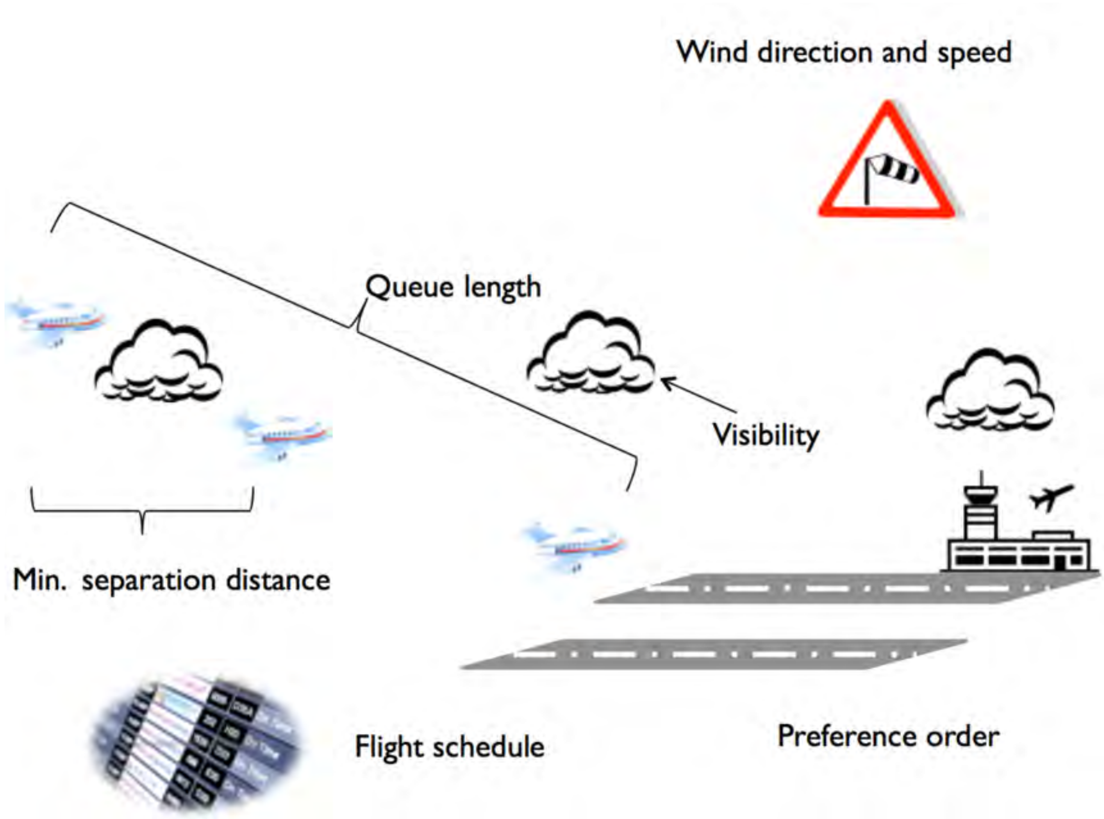


Figure 14: Parameters that can be changed in the simulation tool.

Output

Figure 15 shows the user interface of the tool. The user interface includes an animated picture of the runways of Schiphol. The simulation tool outputs the following results:

- An analysis of the delays.
- An analysis of the runway usage.
- Output the flight schedule with scheduled and actual departure/arrival times.

Assumptions

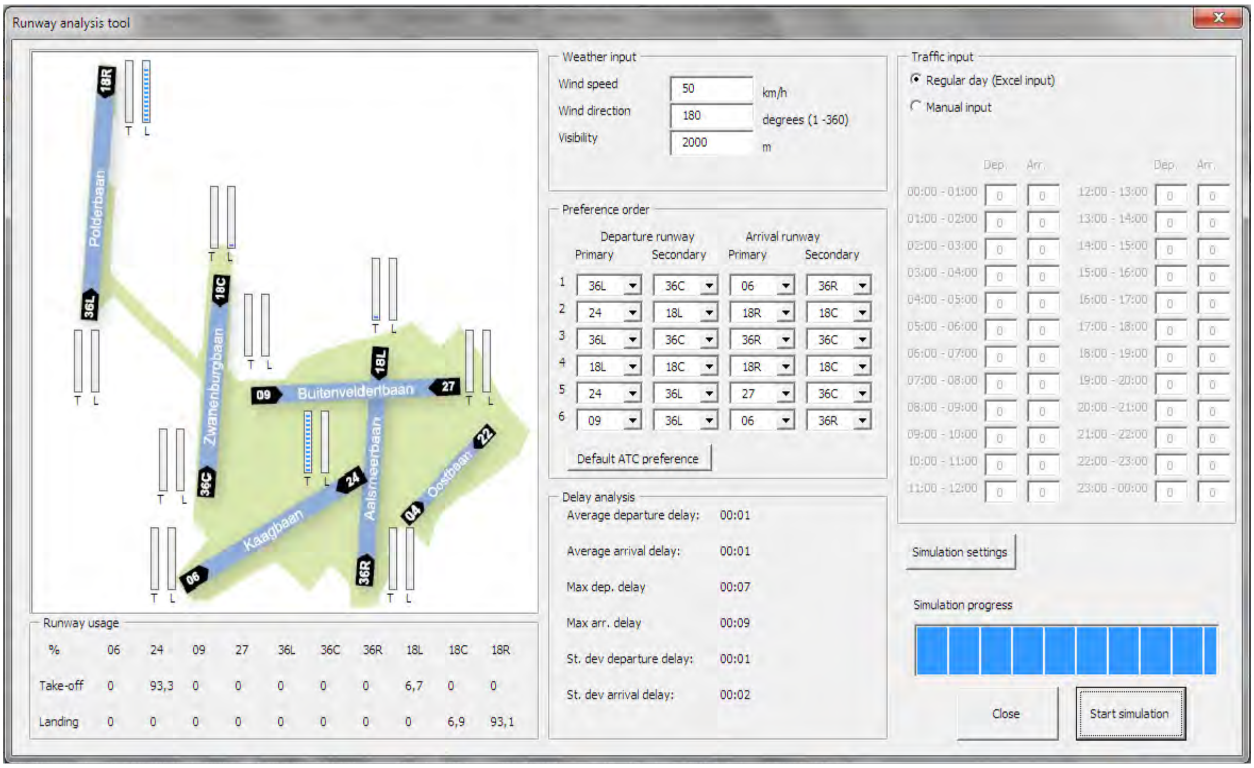


Figure 15: Simulation tool with a graphical userinterface.

The simulation tool is a simplification of the real world and the following assumptions have been made:

- The weather conditions are the same during the whole day.
- All aircraft types have the same approach and takeoff speed.
- All runways are used as independent runways.
- Delays caused by other factors (e.g. missing passengers, delay at airport of origin etc.) are not taken into account.
- All aircraft and pilots are certified for ILS cat IIIb landings, such that they can fly during periods of low visibility.
- No cancellations occur.
- The 'Oostbaan' (runway 04/22) is not modeled because most of the time this runway is only used by general aviation (small aircraft).
- Aircraft that are waiting to land or for takeoff are being served in a first in, first out (FIFO) manner.

Chapter 5: Results

In order to investigate the impact of systematic factors on the delays, three scenarios were analyzed and these are shown in table 15. Each scenario corresponds to specific weather conditions. Section 5.1 describes the distribution of the delay and also the delay as a function of time for each scenario. In 5.2 the results concerning runway capacity for each scenario are displayed and in section 5.3 the results concerning the runway usage are reported. The chapter ends with section 5.4 in which the impact of the separation distance on the delay is analyzed.

Table 15: Three different weather scenarios.

	Weather type	Primary runway available?	Secondary runway available?	Increased separation distance?
1	Optimal weather conditions	Yes	Yes	No
2	Strong wind from the east of west	Yes	No	No
3	Reduced visibility	Yes	No	Yes

5.1 Delay analysis for different scenarios

Figures 16 to 18 show the spread of the delay for different scenarios. Under normal weather conditions when a primary and secondary runway is available, the delay is under ten minutes. Figure 17 shows that the arrival delay gets a high spread compared to the departure delay, when only a primary runway is available. Roughly 11.9% of the arriving flights have a delay of 15 minutes or longer. Figure 18 shows that when visibility is less than 550m, delays of both departures and arrivals become very long.

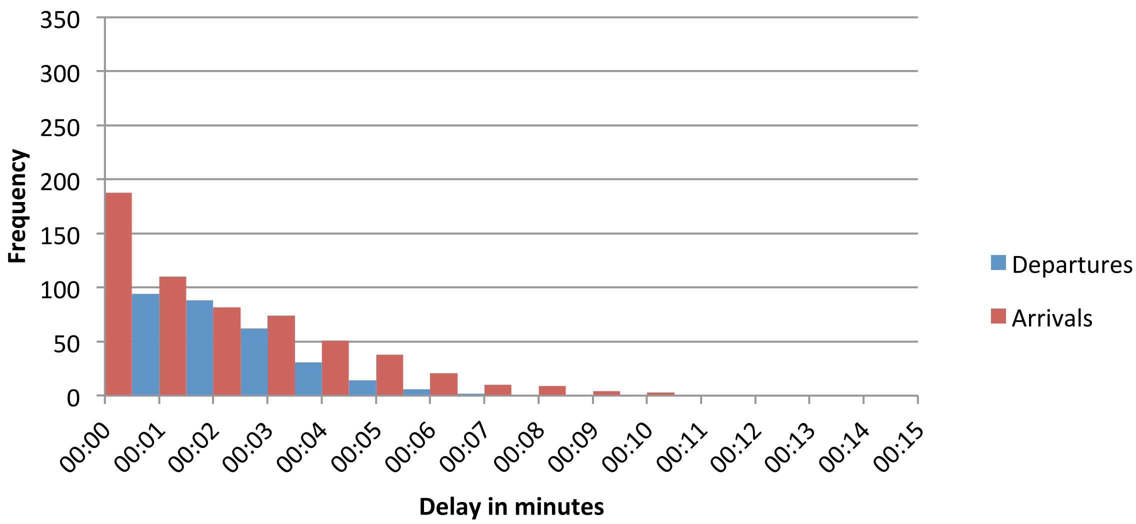


Figure 16: A histogram of the delay when there is also an secondary runway available for takeoffs/landings. (Scenario 1)

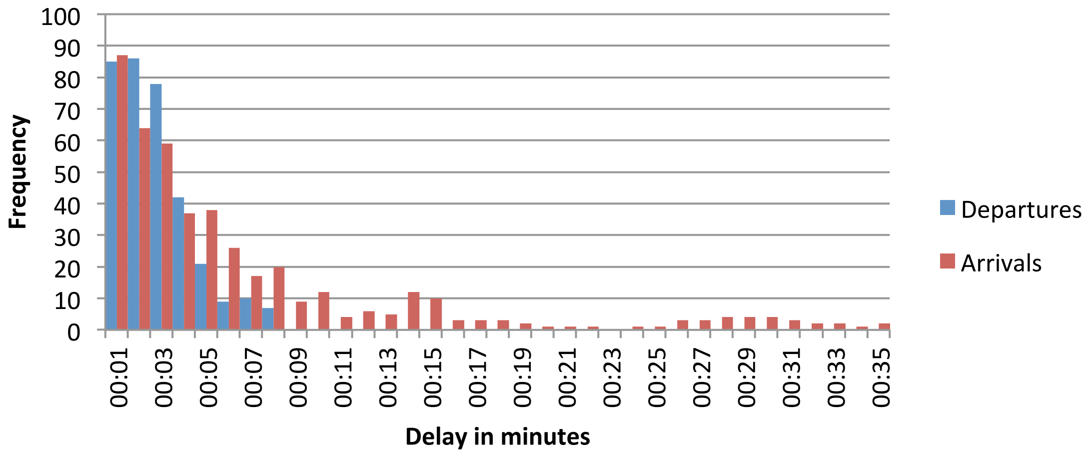


Figure 17: A histogram of the delay when there is only a primary runway available for arrivals/departures. (Scenario 2)

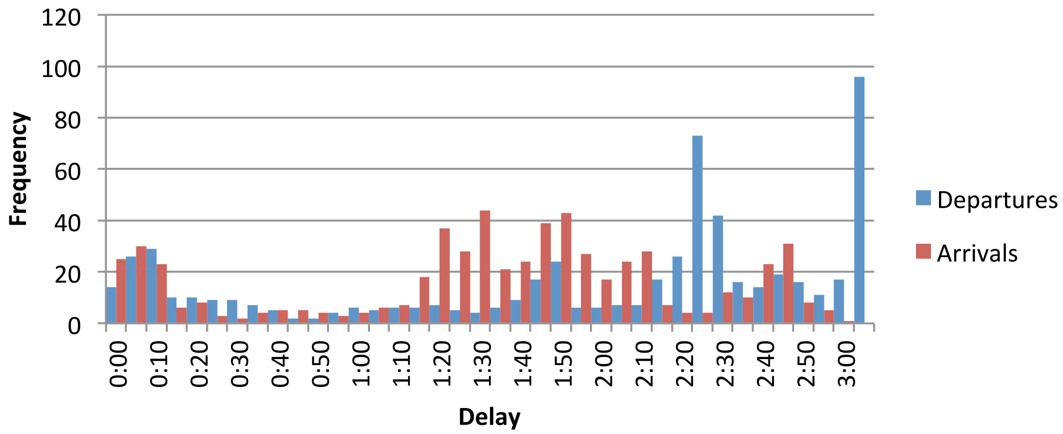


Figure 18: A histogram of the delay when there is only a primary runway available and also increased separation distance. (Scenario 3)

Figures 19 to 21 show the delay pattern during the day for the three different scenarios. Figure 19 shows that the delay is relatively short when a secondary runway is available to handle rush hour traffic. In general, arrival delays are longer than departure delays because arrival capacity is smaller. Figure 20 shows the situation when only one departure runway and one arrival runway are available. The arrival delays increase significantly, especially around the arrival peaks. However, during the departure peaks, there is no significant increase in delays. Figure 21 shows the delay pattern when visibility is less than 550 m. When the day starts, delays are relatively short, but after 9:00 delays keep increasing. The demand is larger than capacity, such that the arrival and departure queue are not stable and delays keep accumulating. However, it is very unlikely that visibility is poor for the whole day. Also, when the arrival delays becomes more than 30 minutes, most flights have to diverge to other airports. When departure delays become too long, most short haul flights are cancelled and long haul flights are given priority because their frequency is lower.

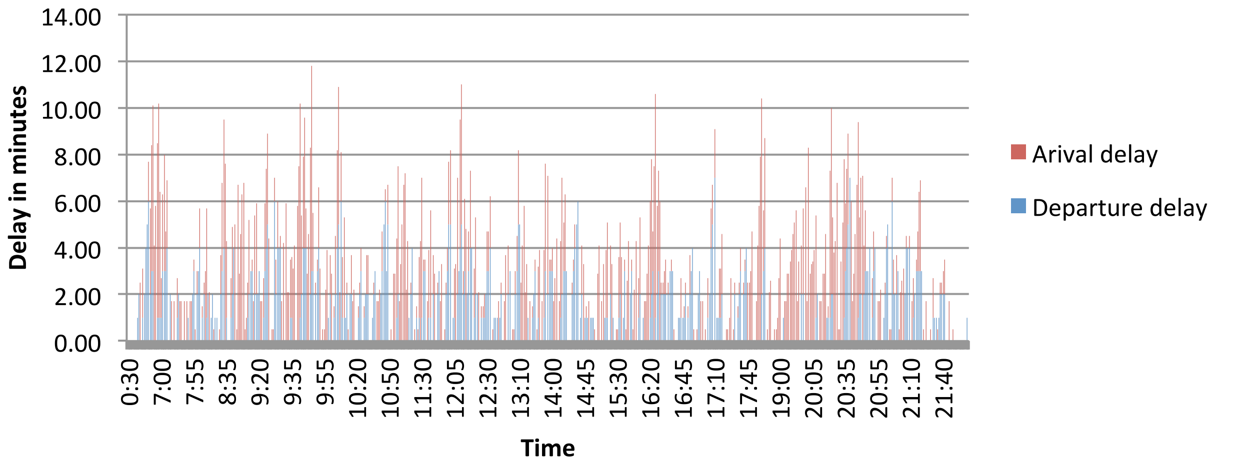


Figure 19: Duration of the delay during a day when a secondary runway is available to handle takeoffs/landings (Scenario 1).

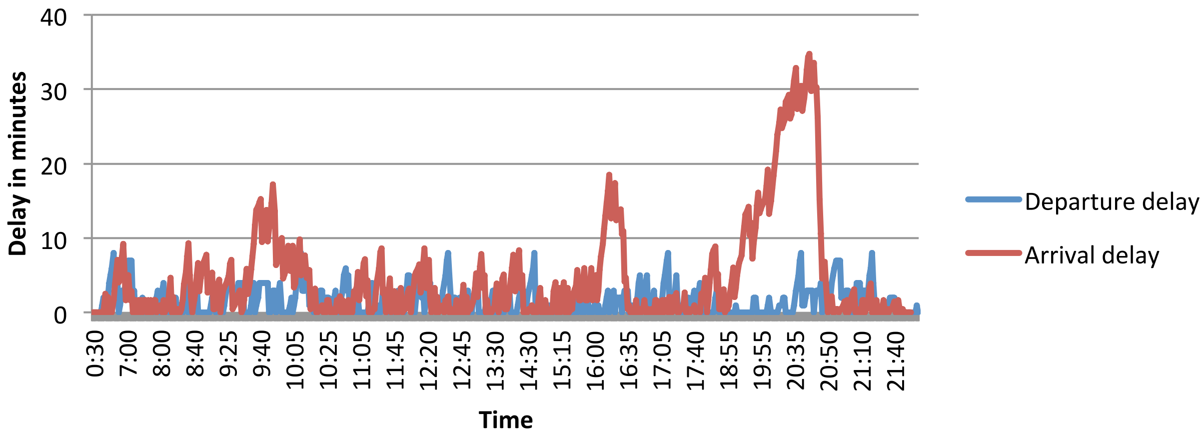


Figure 20: Duration of the delay during a day when only one runway can be used for both landing and takeoff (Scenario 2).

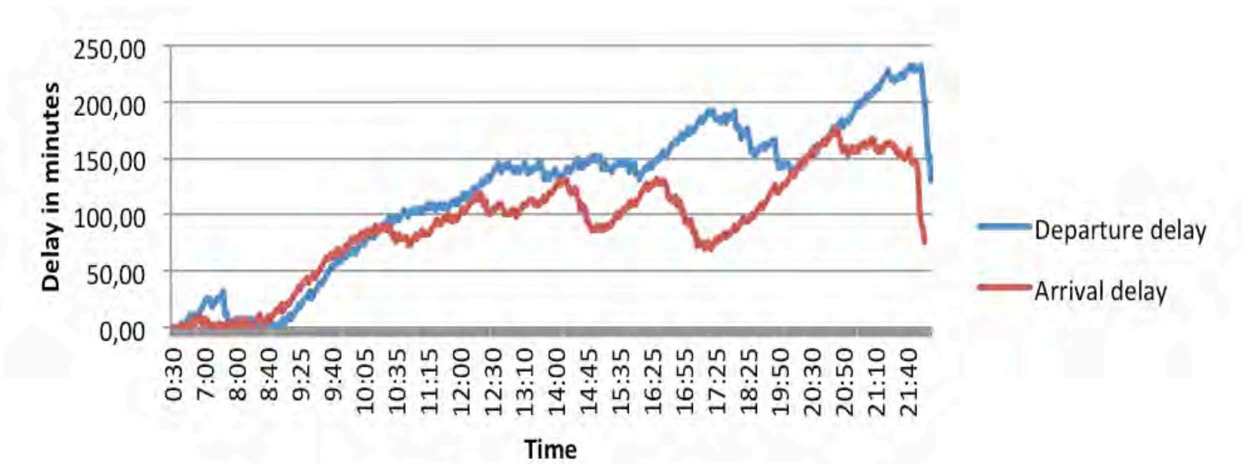


Figure 21: Duration of the delay when only one primary runway is available and separation distance has increased (Scenario 3).

5.2 Maximum traffic throughput for each scenario

Figures 22 and 23 show the average delay for different traffic volumes. If we compare the two graphs, then it can be seen that arrival capacity is smaller than departure capacity. Figure 22 shows the average departure delay for the three scenarios. The departure delay increase from certain traffic volumes, which correspond to the maximum throughput capacity calculations on pages 22 and 23 of this paper. When only one runway is available for takeoffs and one for landings, the capacity is halved compared to the situation with a secondary runway. When visibility is poor, the departure capacity decreases even more due to the increased separation distance. Figures 23 shows the arrival delay for the three different scenarios. There isn't much difference in arrival capacity when only one runway is available and the situation with poor visibility. The reason for this phenomenon is that the separation distance doesn't increase as much for arriving aircraft.

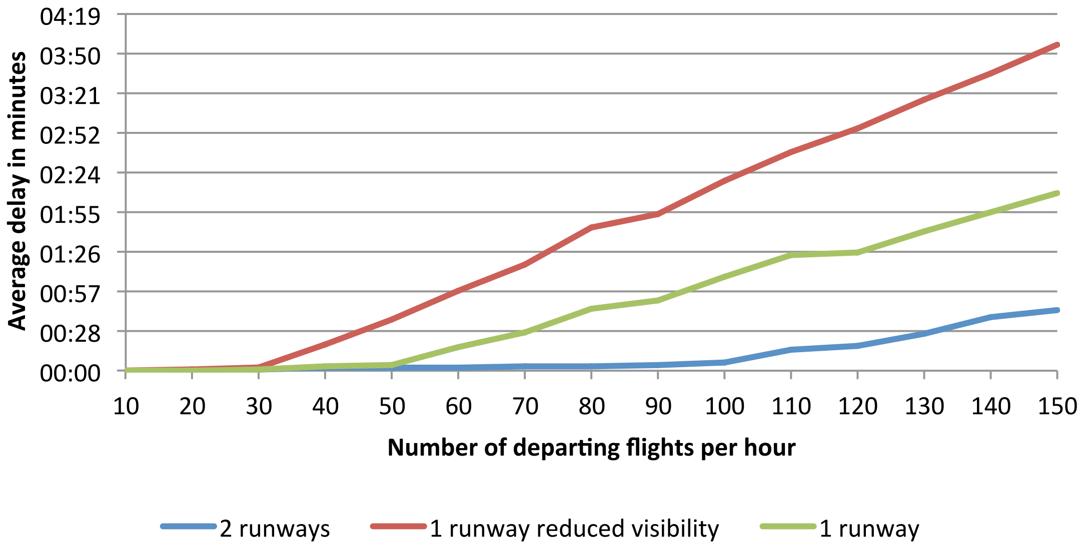


Figure 22: Average departure delay for different scenarios.

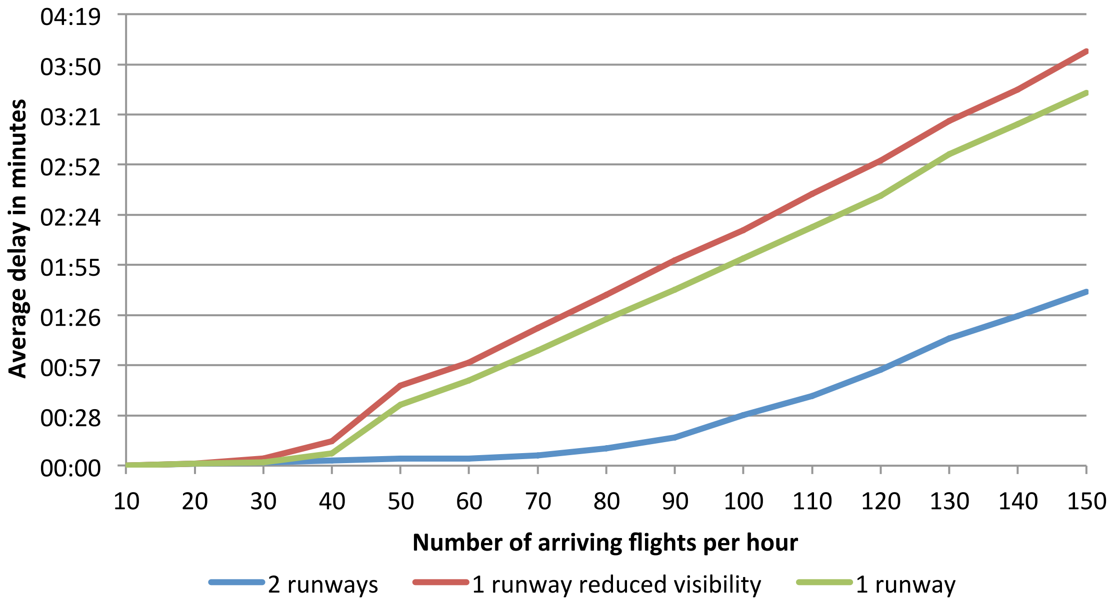


Figure 23: Average arrival delay for different scenarios.

5.3 Runway usage

Tables 16 and 17 show which runways are used for different wind conditions. When the wind is 50 km/h or less, a secondary arrival and departure runway can be used for any wind direction. In this case, airplanes might have to land with a small crosswind. However, when the wind is 80 km/h, a secondary runway can only be used when wind is coming from the north or south. Table 17 shows that when a strong wind from the west or east, no secondary runway is available. Figure 24 shows how many runways can be used when an 80 km/h wind is coming from various wind directions. It is interesting to notice that no runways can be used at all when a strong wind comes from a north western or southeastern direction.

Table 16: Runway usage for various directions when the wind speed is 50km/h.

Wind direction	Primary departure runway	Secondary departure runway	Primary arrival runway	Secondary arrival runway
N	36L	36C	06	36R
E	18L	18C	06	18C
S	24	18L	18C	18R
W	24	36C	36R	18R

Table 17: Runway usage for various directions when the wind speed is 80 km/h.

Wind direction	Primary departure runway	Secondary departure runway	Primary arrival runway	Secondary arrival runway
N	36L	36C	36R	36C
E	9		6	
S	18L	18C	18R	18C
W	24		27	

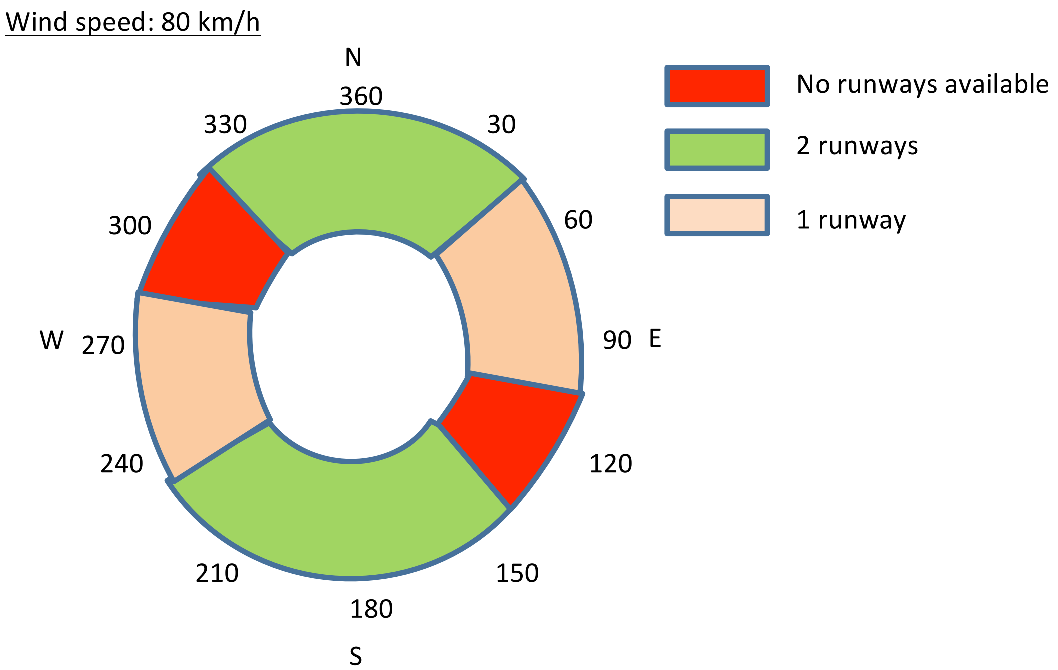


Figure 24: Number of runways that can be used in relation with the wind direction.

Effect of a secondary runway

Figure 25 shows the usage of the secondary runways for different queue thresholds. The threshold determines how many airplanes must be in the queue of the primary runway before a secondary runway can be used.

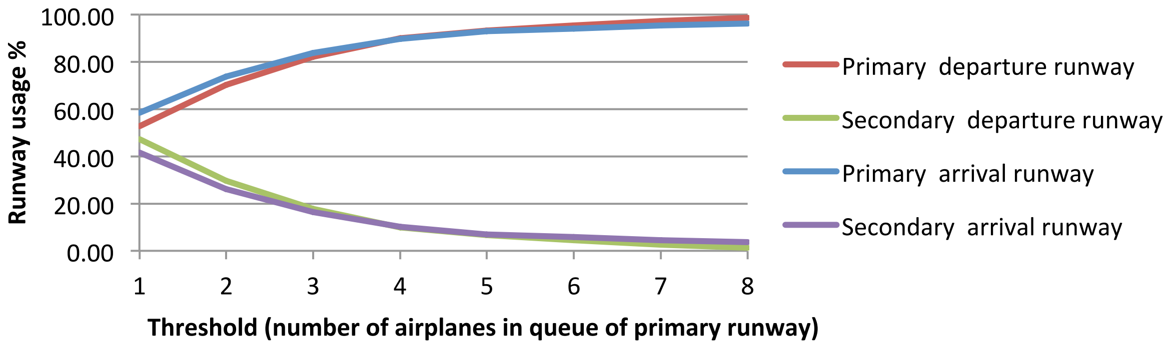


Figure 25: Usage of primary and secondary runway for different thresholds.

When the threshold becomes more than eight flights, the secondary runway is almost never used. So, the maximum number of airplanes in the queue of the primary runway is at most eight, given the current flight schedule.

5.4 Impact of separation distance on delays

The separation distance is the minimum distance that two aircraft must take. This distance is subject to two factors: the wake turbulence and minimum separation distance when flying in low visibility. Figures 26 and 27 show the average departure and arrival delay as a function of the separation distance.

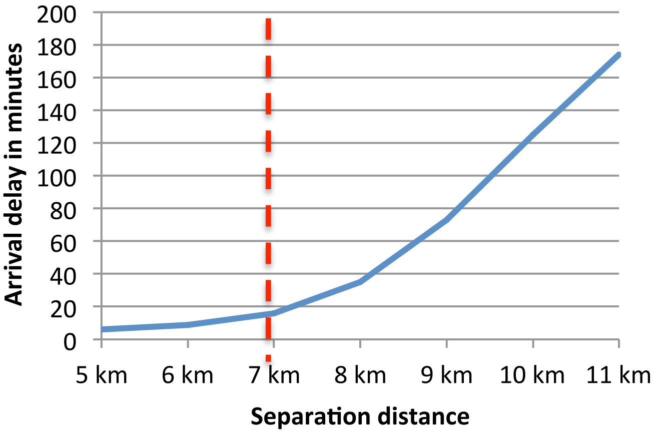


Figure 26: Impact of the separation distance on delays of arriving flights.

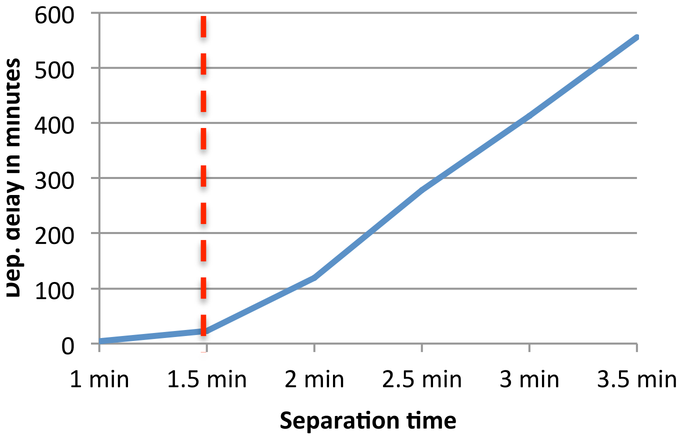


Figure 27: Impact of the separation distance on delays of departing flights.

Recall that figure 9 showed a 30 minute buffer period between an arrival peak and departure peak. When delays exceed this period, these peaks will merge together and delays increase even more. This can also be seen from figure 26, in which the average delay increases when the separation distance exceeds the 7 km. Also, departure delay increases when the separation distance becomes more than 1.5 minutes.

Chapter 6: Conclusion

This chapter contains the main findings and recommendations of this research and also a few suggestions for further research.

6.1 Main conclusions

In order support operational and tactical decisions of air traffic control, a trace-driven simulation tool was developed. This tool enables users to analyze the impact of systematic factors on delays. The tool is designed to be flexible, such that many parameters can be changed. With this simulation tool, three different scenarios where analyzed and these are displayed in table 18.

Table 18: Scenarios for different weather conditions.

	Weather type	Primary runway available?	Secondary runway available?	Increased separation distance?
1	Optimal weather conditions	Yes	Yes	No
2	Strong wind from the east of west	Yes	No	No
3	Reduced visibility	Yes	No	Yes

Delay analysis of each scenario

If we look at the first scenario, then there is sufficient capacity to handle arrival and departure peaks. However, capacity is halved when no secondary runway is available. This scenario occurs when a strong wind is coming from an eastern or western direction and the arrival delay increases significantly during arrival peaks. In the third scenario, the separation distance for both arrivals and departure increases significantly and this causes long delays. However, the simulation model doesn't take cancellations into account and it also assumes that visibility is reduced for the whole day. These assumptions are not realistic and therefore the results might be questionable. However, the results show that visibility can have a profound impact on delays.

Impact of separation distance on delays

The traffic pattern at Schiphol was analyzed and the analysis showed that a 30-minute buffer was separating the arrival and departure peaks. During this buffer period, fewer departures/arrivals are scheduled. When delays become larger than this period, the two or more peaks melt together and delays increase significantly. As long as the average delay is kept below 30 minutes, peaks will not merge and arriving and departing traffic will be separated. This can be reached by keeping the separation distance for arriving aircraft under 7 km and the time between departing aircraft under 1.5 minutes.

Impact of wind direction on delays and runway usage

Analysis showed that when a strong wind comes from the east or west, only one runway can be used for takeoffs and one for landings. This reduces capacity significantly and leads to longer arrival delays during arrival peaks. In some situations, when a strong wind comes from the northwest or southeast, no runways can be used at all, because the crosswind gets too strong. However, these weather conditions only occur a few days per year on average.

6.2 Recommendations

The main recommendations for Lucht Verkeersleiding Nederland (LVNL) and Schiphol are:

1. To avoid significant delays during periods of poor visibility, the minimum separation distance has to be kept under 7 km for arriving airplanes and under 2 minutes between two departing airplanes. This way, the average delay will be below 30 minutes and the arrival and departure peak will not interfere with each other.
2. When a strong wind is coming from a western/southwestern direction (which happens relatively often due to Schiphol's location near the North Sea), there is no secondary runway available. An additional runway facing west/southwest would increase capacity during peak periods and Schiphol would then have enough capacity for the most common wind directions that occur at the airport.
3. When a strong wind (80km/h) comes from the northwest or southeast, no runways can be used because the crosswinds exceed the safety threshold. To prevent this situation, an additional runway from northeast to northwest would be recommended.

6.3 Further research

There are many interesting extensions that can be explored. For example, inbound delays could be modeled. These delays are caused by delays at other airports or during the route of a particular flight. Another interesting extension would be to compare Schiphol with other airports such as London Heathrow and Paris Charles-de-Gaulle, because weather conditions and the runway-layout are very different at these airports. This could also be an interesting study for airlines, because they can determine which airports are the least sensitive to weather conditions. Lastly, it could be interesting to make an optimized flight schedule, such that separation distances caused by wake vortex are minimized. For example, by scheduling aircraft of the same wake vortex category after each other, the separation distance can be reduced.

Chapter 7: References

	Source name	Subject	Source
[1]	Wikipedia	World busiest airports by air traffic movements	http://en.wikipedia.org/wiki/World%27s_busiest_airports_by_traffic_movements
[2]	KNMI	Weather data at Schiphol between 1953 and 2012	http://www.knmi.nl/klimatologie/uurgegevens/
[3]	Wikipedia	Calculation of the crosswind component	http://nl.wikipedia.org/wiki/Zijwind#Luchtvaart
[4]	Wikipedia	Minimum visibility for visual approach	http://en.wikipedia.org/wiki/Visual_approach
[5]	Wikipedia	ILS categories	http://nl.wikipedia.org/wiki/Instrument_landing_system
[6]	RSTVA	Low visibility procedures at EHAM	http://www.rstva.ru/files/charts/EHAM.pdf
[7]	Slot coordination.nl	Capacity regulations at Schiphol	http://www.slotcoordination.nl/pub/capacity/ams/cap_ams_w08.pdf
[8]	Slot coordination.nl	Capacity regulations at Schiphol	http://www.slotcoordination.nl/pub/capacity/ams/cap_ams_w08.pdf
[9]	Stichting Bas	Bewoners Aanspreekpunt Schiphol	http://www.bezoekbas.nl/
[10]	Lucht Verkeersleiding Nederland	Preference order of runways	http://www.lvnl.nl/nl/omgeving/route--en-baangebruik/preferentievolgorde.html
[11]	Dutch airplane spotters	History of runway usage	http://schiphol.dutchplanespotters.nl/runways.php
[12]	Wikipedia	Separation distance for wake turbulence	http://en.wikipedia.org/wiki/Wake_turbulence
[13]	Wikipedia	Maximum Take Off Mass	http://en.wikipedia.org/wiki/Wake_turbulence
[14]	Wikipedia	Landing speed	http://en.wikipedia.org/wiki/Landing
[15]	Wikipedia	Take off speed	http://en.wikipedia.org/wiki/Takeoff
[16]	Elsevier	On the waiting time of arriving aircraft and the capacity of airports with one or two runways,	Bauerle, N Engelhardt-Funke, Engelhardt-Funke,Kolonko, M - EUROPEAN JOURNAL OF OPERATIONAL RESEARCH 2007