Waiting times in Copenhagen Airport

An economic evaluation of delays in the central security check

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Content

Summary

This report evaluates the cost to travellers of waiting time in the central security check in Copenhagen Airport. It predicts the reduction in passenger cost that follows from increasing the capacity in the central security check and compares this reduction to the cost to the airport of increasing the capacity. The general conclusion is that considerable reductions in waiting time costs are feasible and that the savings for passengers outweigh the additional cost to the airport over a large range of reductions. Requiring the airport to reduce waiting times in the central security check will therefore yield a net benefit to society.

The physical capacity in the central security check is 18 lines. The number of lines that are manned and open varies over the day. The present analysis considers only the opening of more of the 18 lines, while the physical capacity is retained as it is now.

We have used data that describe the actual waiting times, the number of open lanes, and the number of passengers passing security. We have observations every 15 minutes over a period of about 8 months, which means that the present analysis is based on a substantial database: altogether we have 16,195 observations.

Based on these data, we have developed a statistical model that predicts the waiting time cost to travellers as it depends on the number of open lanes. We find that the statistical model gives a satisfactory description of the historical data. We have ensured that our estimates of the cost reductions that follow a capacity increase are conservative: they will tend to be on the low side of the actual cost reductions that may be achieved. The model is strongest in the range where we have most data. In the presentation of results we omit the times outside the interval from 6am to 8pm every day where the number of passengers and the number of open lanes are low and the model predictions therefore are less reliable. This increases our confidence in the predictions that we present.

The passenger waiting time cost depends on the mean waiting time and on the random variability of waiting time. This takes into account that it is not only the waiting time that matters to passengers but also the uncertainty they face regarding how long the waiting time will be when they arrive at the airport.

We have simulated four scenarios describing an average week in 15 minute intervals during the period from 6am to 8pm every day. A base scenario replicates the average week with the historical average number of open lanes every 15 minutes.

Three policy scenarios predict the consequences of opening 1, 2, and 3 additional lanes, respectively, at all times through each day, while staying within the physical capacity of 18 lanes. The distribution of waiting times is shown in Figure 1 for the base scenario and for the scenario with 3 additional lanes. Figure 2 shows for an average Wednesday how waiting times are affected across the day by adding 3 lanes .

We compare the cost savings to passengers from opening more lanes to the cost to the airport as estimated by the Danish Transport and Construction Agency. Both the modelling and the cost estimate are conditional on the existing physical lane capacity. We find that adding 1 or 2 lanes yields a net benefit at all times during the week. Adding three lanes yields a substantial net benefit in general, but there are a few 15 minute intervals during the week where the net benefit of the third lane becomes negative.

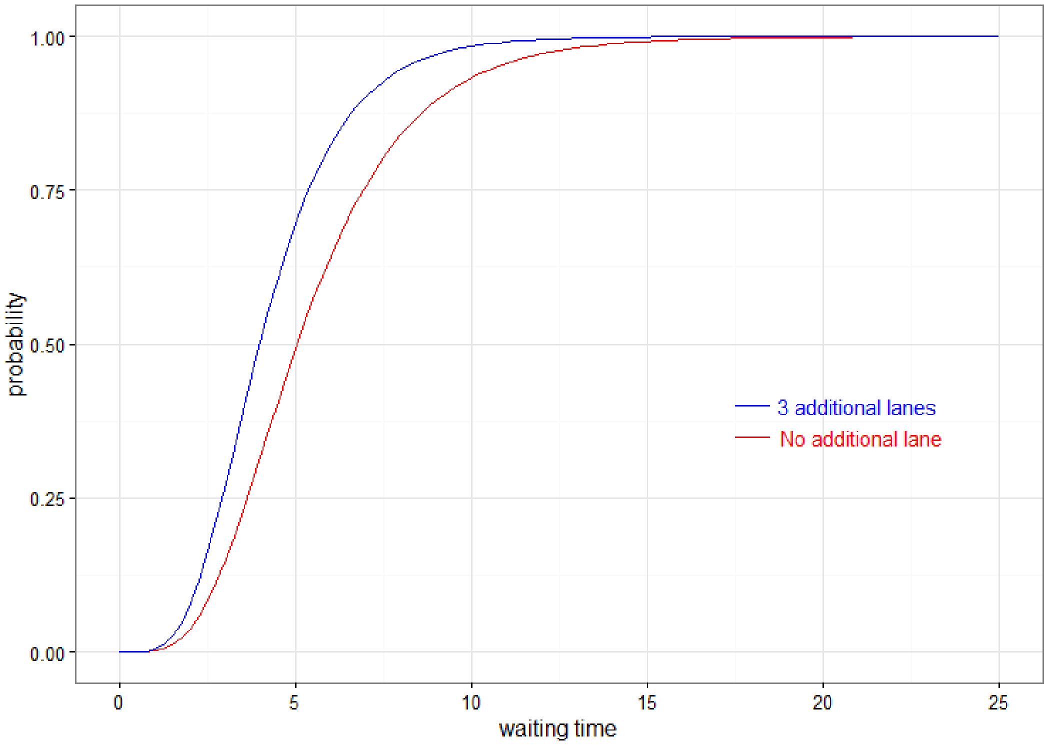

Figure 1. The distribution of waiting times in base scenario and with 3 additional lanes

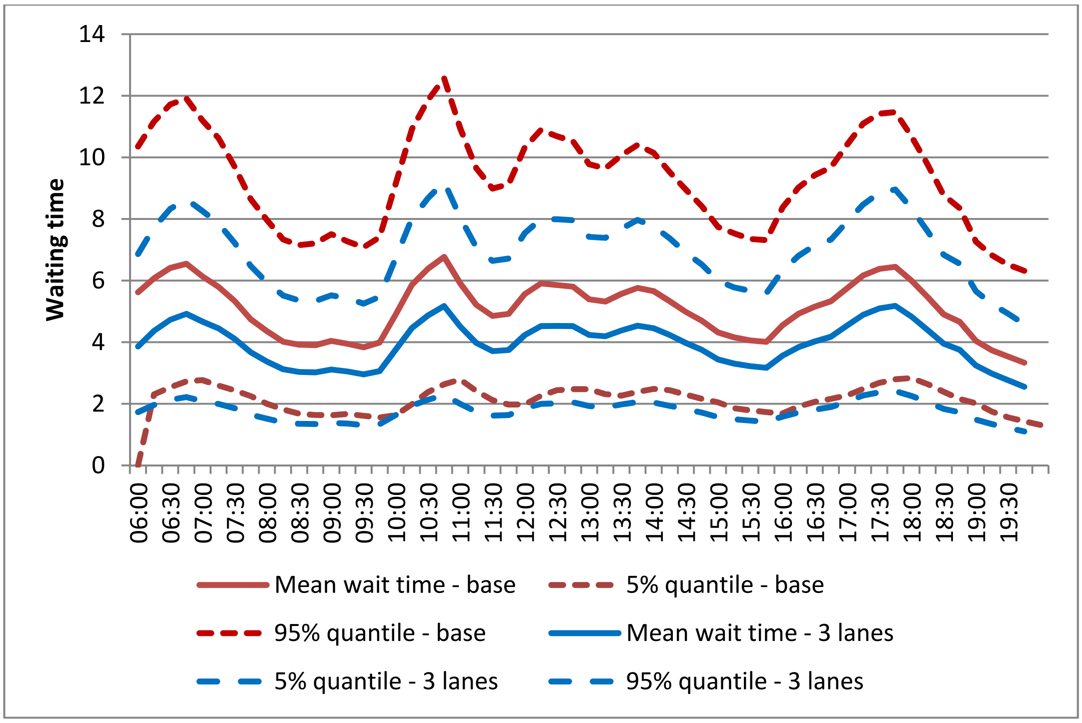

Figure 2 Waiting time statistics on an average Wedneday.

Opening one additional line yields an average benefit to passengers of 3358 DKK per hour with a corresponding cost to the airport of 1452 DKK per hour. Opening a second additional line yields an additional average benefit to passengers of 2801 DKK per hour, which is still larger than 1452 DKK per hour. Opening a third additional line yields an additional average benefit to passengers of 2310 DKK per hour, which is also larger than the cost to the airport of 1452 DKK per hour.

The conclusion is thus that there is a clear net benefit from increasing capacity in the central security check. The cost savings to passengers clearly outweigh the corresponding cost to the airport.

The uncertainty inherent in the model predictions increases as we add lanes and move away from the range we observe in the data. We therefore do not investigate further capacity increases as we would then be less confident about the model predictions. The implication is that the net benefits are so large that we are not confidently able to identify the break-even point where additional capacity no longer yields a net benefit.

The capacity in the baseline scenario is the average number of lanes that was open during the period observed in the data. The airport varies the number of open lanes day by day and during the day according to their expectations regarding the number of passengers. The number of open lanes is also influenced by the short term availability of staff. The baseline is thus a moving target and it does not make sense to impose requirements on the airport in terms of the number of open lanes.

The table below presents the mean waiting time, the standard deviation of waiting and the 95% quantile of waiting time. The standard deviation is a measure of the width of the range of waiting times that travellers are likely to meet. Roughly 95% of waiting times are with a range of two standard deviations around the mean waiting time. 95% of waiting times are smaller than the 95% quantile. The first line in the table presents the observed data, while the next four present the baseline scenario 0 and the three scenarios where additional lines are opened. The numbers concern the period 6am to 8pm for an average week.

The baseline scenario does not reproduce the observed data exactly. The statistical reasons for this are explained in the report. We therefore provide recommendations in terms of the changes that are achievable according to the model predictions.

Table 1 Summary statistics, average week, 6am to 8pm

Scenario	Mean waiting time	Standard deviation of waiting time	95% quantile of waiting time
Observed	6.0	3.2	11.7
0	5.6	2.5	10.1
1	5.1	2.2	9.1
2	4.7	2.0	8.3
3	4.3	1.8	7.6

The analysis predicts that adding two or three lanes at all times will reduce the mean waiting time for passengers between 0.9 and 1.2 minutes. The standard deviation is reduced between 0.5 and 0.7 minutes, which means that the typical range of waiting times faced by travellers is reduced by around two minutes. The 95% quantile is reduced between 1.8 and 2.5 minutes. This would mean that travellers can expect to wait no longer than 9.9 minutes instead of 11.7 minutes in at least 95% of their departures. The corresponding reductions in waiting time costs for passengers clearly outweigh the cost to the airport of opening more lanes.

The airport is able to allocate capacity more efficiently than the present simulations indicate, by adapting capacity to the variation in demand that they observe from day to day and during each day.

Requiring that the airport reduces the mean waiting time and some convenient measure of the size and frequency of large waiting times seems very operational.

Using round numbers, a requirement that the airport reduces the mean waiting time by one minute and the 95% quantile by two minutes would clearly lead to a net societal gain, accounting for the benefit to passengers as well as for the cost to the airport.

The main points relevant for assessing the robustness of this conclusion are the following. First, the values of time and reliability used are on the low side of the available evidence, which indicates that the actual benefit of reduced waiting times is likely to be larger than the calculated benefit. Second, the cost per lane hour could be 50% larger without changing the conclusion that a welfare gain is available. We therefore find that the conclusion is quite robust.

1. Background and purpose

This project evaluates the costs to travellers of waiting times in the central security check in Copenhagen Airport. It compares the reduction in these costs that would follow from a capacity increase in the central security check to the cost of this capacity increase. These comparisons are used to provide recommendations regarding the potential for achieving a welfare gain by reducing waiting times through increased capacity.

Waiting times in the central security check force travellers to arrive at the airport earlier than they would have in the absence of waiting time, as they have to allow sufficient time to make sure they reach their departure in time. While the mean waiting time is 5.43 minutes, waiting times are variable and unpredictable from the point of view of travellers, ranging between 0.02 and 30.07 minutes (these numbers are based on data from March 2nd to October 31st 2015). Travellers need to allow both for the average waiting time as well as for the variability of waiting times, which means both should be taken into account.

The purpose of this project is to

- Undertake an economic evaluation of waiting times in the central security check at Copenhagen Airport.
- Compare the cost of additional capacity in the central security check to the economic benefit to passengers of reduced and less variable waiting times.
- Define the optimal capacity in the central security check.

The project is carried out by Mogens Fosgerau, Abhishek Ranjan and Stefan L. Mabit for the Ministry of Transport and Building.

1.1 IATA recommendations

As described by the Danish Transport and Construction Agency [1], the IATA airport development reference manual suggests a maximum waiting time for security checkpoints between 5-10 minutes. The average waiting time in the central security check at Copenhagen Airport is within the interval.

But actual waiting times vary considerably. As shown in section 2.2, at most times of day, there are at least 10% of days where the waiting time exceeds 10 minutes. The airport does then presently not conform to the IATA recommendations.

2. Data and descriptives

2.1 Data

We have received the following data from the Danish Transport and Construction Agency.

- Waiting times, 15 minute bins, from March 2ndto 29th of November, 2015.
- Number of lanes open, 15 minute bins, from March 2nd to 29th of November, 2015.

- Number of passengers departing by each airplane from March 1 to October 31, 2015.

The latter file provides us with the number of passengers that depart from Copenhagen Airport. We use the time stamp in the file to aggregate them into 15 minute bins. The time stamp is in UTC. We have converted to Danish time, taking daylight time saving into account.

We correct for the fact that travellers do not arrive at the security at the exact time stamp by including forward lags of demand in the modelling.

We do have information about the number of travellers that actually used the central security check (CSC) on a given day. We find this share to be 0.756 as described in section 2.2. This is used to scale down the number of passengers that departed to the number of passengers that used CSC, i.e. excluding transit, fast track, etc.

The datafile with departures contains ICAO codes for the destination. We have split departures by destinations in Europe and abroad, this allows us to account for differences in the time passengers pass through security.

2.2 Descriptives

The following figures use all available data where both demand, number of open lanes, waiting times are available, i.e. the period March 2nd – October 31rst, 2015. Figure 3 shows the average number of open lanes across the average day in 1 hour intervals (blue curve) and the average number of passengers embarking planes (red curve). The time used for demand is the actual take-off time, which should occur some time after passengers pass through security.

The number of passengers per hour fluctuates between approximately 1500 and 2500 persons from 6 am to 9 pm. Not all of these pass through the central security since there are fast track and other additional lanes. Based on the total daily number of passengers passing through security and the total daily number of passengers departing from the airport, we have calculated that an average share of 0.756 of the departing passengers pass through the CSC.

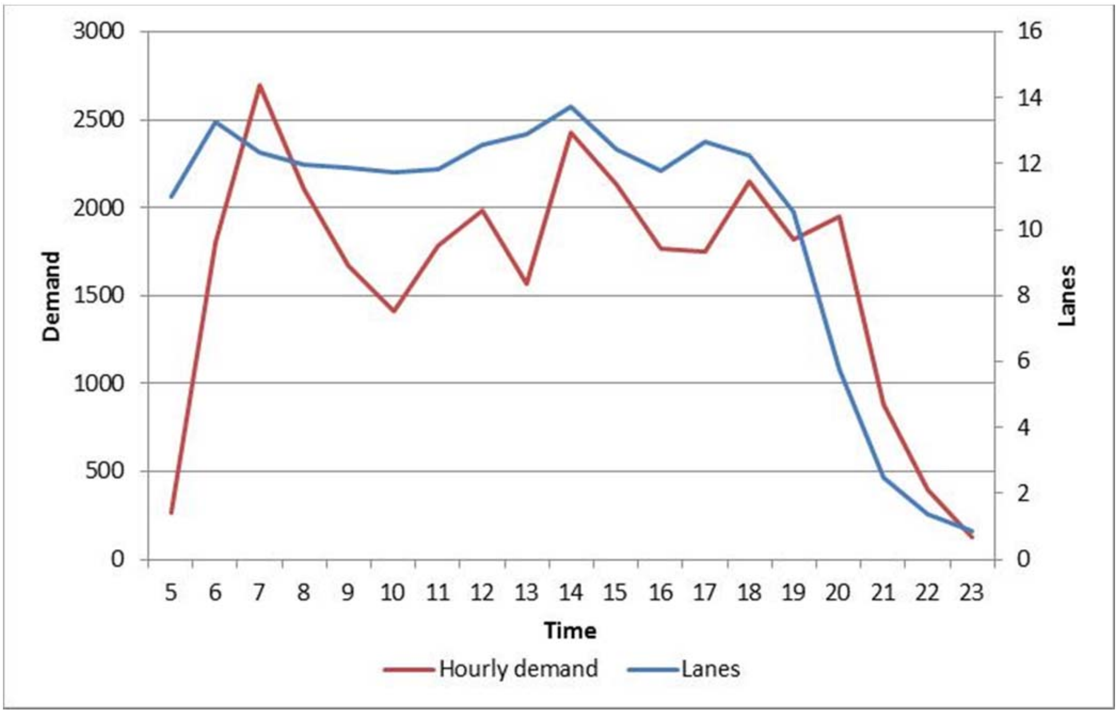

Figure 3 Average hourly demand and open lanes

Figure 4 shows the average waiting time in CSC (blue curve) and the average number of open lanes (red curve) for every 15 minute intervals. The waiting time graph shows an expected morning peak as well as an late afternoon peak. But is also shows some variation in the middle of the day not related to the peak hours.

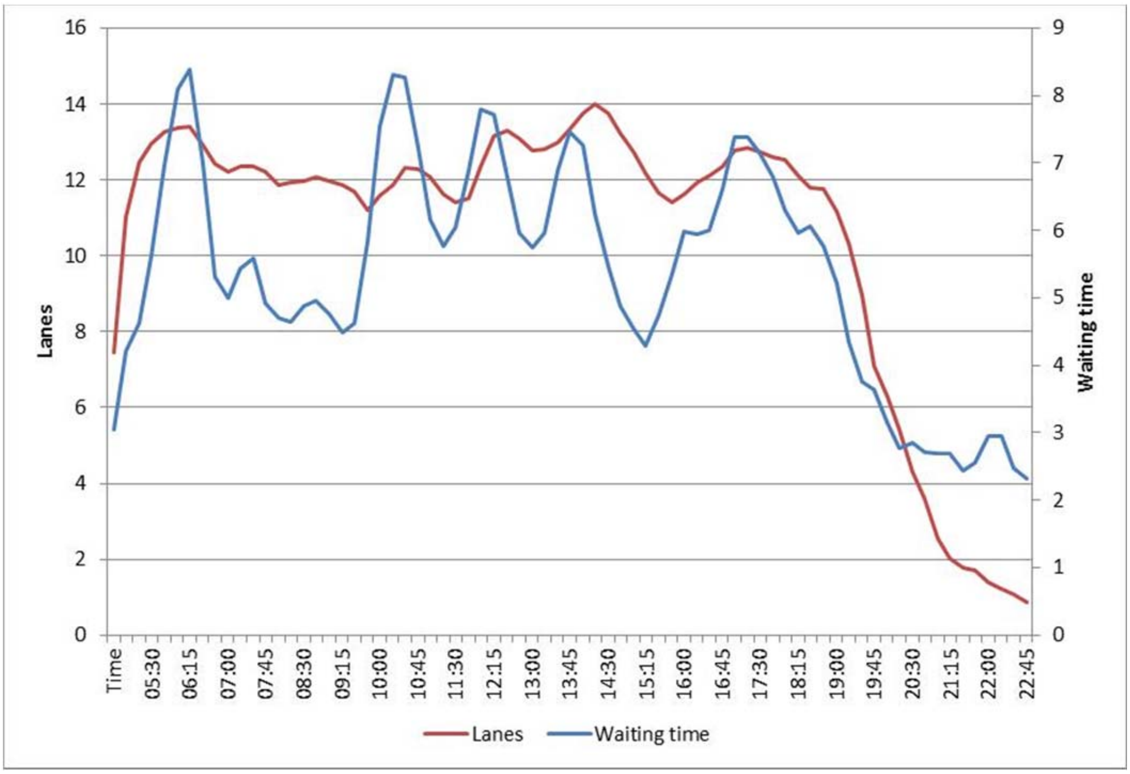

Figure 4 Empirical distribution of average waiting time and average open lanes

Figure 5 shows the average waiting time as well as the 5% and 95% quantiles over the average day. 5% of waiting times are shorter than the 5% quantile, while 5% of waiting times are longer than the 95% quantile. It is seen that the variation is higher for 15 minute intervals where the average waiting time is high. The 95% quantile is mostly 2 and sometimes 3 times larger than the average waiting time. The 95% quantile is also larger than the 10 minutes maximum waiting time recommended by IATA during much of the day, which means that the waiting time exceeds 10 minutes more than 5% of days at these times.

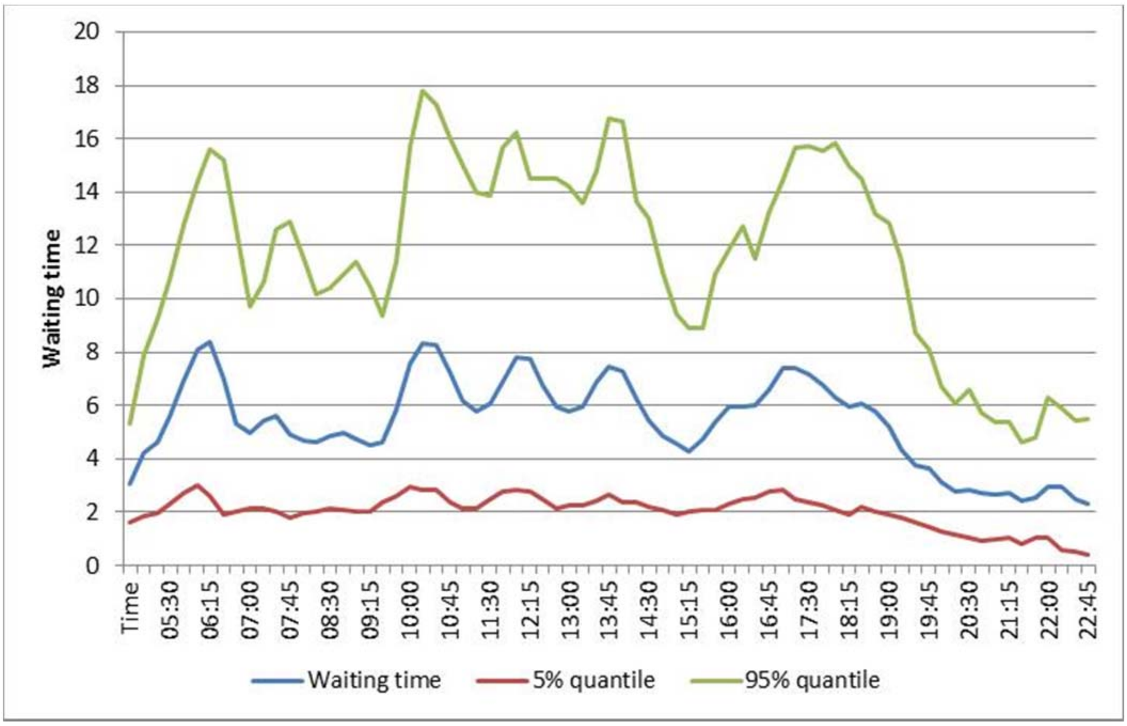

Figure 5 Average quarterly waiting time together with the 5% percentile and the 95% percentile across the day

Figure 6 shows the empirical cumulative distribution function of waiting time. The median waiting time is 4.25 minutes. 25% of waiting times are larger than 6.88 minutes, 10% of waiting times are larger than 10.27 minutes, while 5% of waiting times are larger than 12.82 minutes.

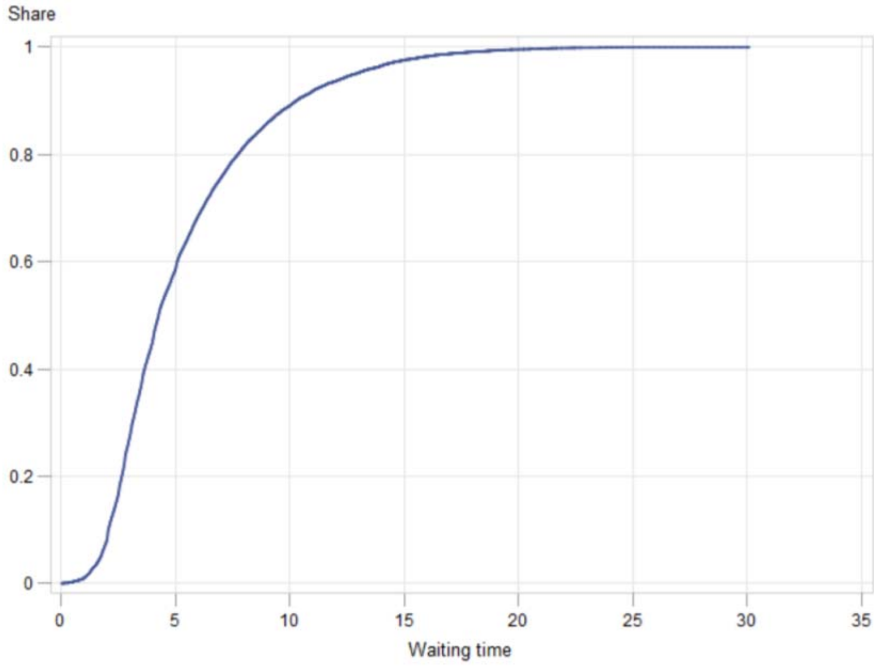

Figure 6 Empirical cumulative distribution of quarterly waiting times

3. Modelling

3.1 Waiting time cost

The cost of random waiting time is computed according to the model in a paper by Fosgerau and Karlstrom [2]. The model is described in more popular terms in a paper delivered to an OECD/ITF Roundtable [3]. The model describes the cost of random waiting time to a traveller who knows the distribution of waiting time and who chooses optimally when to arrive at the airport.

In our calculations, we assume that travellers know exactly the distribution of waiting times. This is a simplification but avoids speculation about how well informed travellers are about the actual distribution of waiting times at every time. The effect of this assumption, that travellers anticipate variation in the distribution of waiting time, is a reduction in the variability of waiting time from the passenger point of view. It thus means that our calculations of the waiting time cost will be conservative.

Let α, β, γ be the parameters of the step scheduling model (see e.g. Fosgerau and Karlstrom [2]), where α is the value of time, β is the cost of earliness, and γ is the cost of lateness. We find suitable values of the time and scheduling preference parameters from a brief literature search, reported in section 5.1.

Denote random waiting time by W, let μ be the mean waiting time, let σ be the standard deviation of waiting time, and let F be the cumulative distribution of standardised waiting time. Then the cost of random waiting time for one passenger is

$$WTC = \alpha\mu + (\beta + \gamma) \int_{\frac{\gamma}{\beta+\gamma}}^{1} F^{-1}(s) ds \cdot \sigma. \tag{1}$$

The integral is referred to as the mean standardised lateness.

For convenience, and as documentation of our computations, we rewrite (1) in terms of the distriution G of raw waiting times.

$$\begin{aligned} WTC &= \alpha\mu + (\beta + \gamma) \int_{\frac{\gamma}{\beta+\gamma}}^{1} F^{-1}(s) ds \cdot \sigma \\ &= \alpha\mu + (\beta + \gamma) \int_{\frac{\gamma}{\beta+\gamma}}^{1} (G^{-1}(s) - \mu)\, ds \\ &= (\alpha - \beta)\mu + (\beta + \gamma) \int_{\frac{\gamma}{\beta+\gamma}}^{1} G^{-1}(s) ds. \end{aligned} \tag{2}$$

To apply this expression we then need to know the mean and the standard deviation of waiting time as well as the standardised waiting time distribution. Both are available from data. We also need values for the value of time and the scheduling parameters. As mentioned, we will specify these values based on a literature review, see section 5.1.

To assess the effect on the waiting time cost of increasing capacity in the CSC, we need to estimate how the waiting time distribution depends on capacity.

The analysis is performed using the steps described in section 3.2.

3.2 Waiting time modelling

We use the following model for the waiting times, which has been found after experimenting with various functional forms.

$$\log W_t = f(x_t) + \epsilon_t, \epsilon_t = \eta_t e^{\frac{g(x_t)}{2}}, \tag{3}$$

where x_t is a vector of explanatory variables including the number of open lanes, η_t are iid with mean zero and $Elog(\eta^2) = 0$. The zero mean condition is standard in regression. The second condition on the squared residuals is important in this context, since we will use the model to predict variability and therefore need to control the variance of waiting times.

The model is formulated with waiting times in logs rather than levels. This ensures that negative waiting times are impossible. This makes the model more robust in that the non-negativity constraint is built into the model.

The model predicts the log of the waiting time, which means it should match the observed log of the waiting time. This implies that the model estimate of the mean waiting time is downward biased, since $EW_t = E\exp(\log W_t) > \exp(E\log W_t)$. We thus expect the model to underpredict the mean waiting time. This does not affect the conclusions of the report as the purpose is to capture the relative effect of an increase in the number of open lanes.

We assume the joint distribution of dependent and independent variables is weakly dependent and jointly stationary. This allows us to obtain consistent estimates using OLS.

3.2.1 Mean regression

We regress the waiting times on the number of lanes L, the demand D, and lagged waiting times. We include forward lags of the demand to allow for the fact that people from the same flight pass through security at different times. We estimate a regression of the following form.

$$\log W_t = f(W_{t-1}, L_t, L_{t-1}, L_{t-2}, D_t, D_{t+1}, \dots, D_{t+12}) + \epsilon_t \tag{4}$$

By assumption, the residuals in (4) have mean zero and so we can obtain consistent estimates of (4) using OLS.

It is crucial to have demand in this equation, since otherwise there will be a strong bias if the number of open lanes is determined in response to demand, which is correlated with the waiting time.

The dynamic specification of the regression (with lags) means that we can take into account the dynamics of queueing, whereby the waiting time in one period affects the waiting time in the next period.

The presence of forward lags in the specification makes it possible to allow for that fact that passengers pass through security at various intervals prior to departure.

We seek a dynamic specification that removes serial correlation of the residuals. The sign of the coefficient for the number of lanes must be negative, but will be positive if we fail to remove the endogeneity bias by controlling for demand.

To further control for demand, we include dummies for each day of the week and each hour of the day.

3.2.2 Variance regression

Having estimated f we construct

$$Y_t = \log\left(\left(\log W_t - f(x_t)\right)^2\right) = g(x_t) + \log(\eta^2). \tag{5}$$

By the assumptions made, this can also be estimated using OLS.

3.2.3 Standardized waiting time distribution

With the results of these two regressions, we compute residuals from the standardized waiting time distribution by

$$\hat{\eta}_t = \frac{\log W_t - f(x_t)}{\exp\left(\frac{g(x_t)}{2}\right)}. \tag{6}$$

These will be used to simulate from the estimated models and to generate counterfactual scenarios.

3.2.4 Simulation of waiting time cost and counterfactuals

We construct a profile for the number of open lanes for a typical week by averaging data. We similarly construct separate demand profiles for the passengers flying within Europe and to outside Europe.

We then simulate the typical week a large number of times, using the above model. It is necessary to use simulation, since the lagged waiting time occurs in the regression equation for the current waiting time. The lagged waiting time in the first periods is fixed at the stationary value given demand at 6am and the number of open lanes at 6am; this avoids large jumps in the predicted waiting time early in the morning. The forward lags of demand in the evening are set to 0, whenever the data is not available. This will be the case when there are no later flights.

The typical week is simulated recursively, where the simulation of one time period depends on the realization for the previous time period. At every step, residuals are drawn at random from the residuals of the variance regression. The simulated waiting time is calculated using the specification of the two regressions.

Having simulated the typical week a large number of times, we compute the mean waiting time, the standard deviation, some percentiles of waiting time and the waiting time cost according to the scheduling model for every 15 minute time interval during the week.

The demand profile at the security gate for European and non-European destinations is calculated using the simulation demands and the regression coefficients. These coeffecients are normalized to 1, separately for travellers to European and non-European destinations, which achieves that each passenger is counted just once.

Using the demand profile, we calculate the total waiting time cost. First the demand is multiplied by 0.756 to take into account that not all passengers go through the central security check. This number was found as described in Section 2.2. Then we use this scaled demand to weight the quarterly waiting time cost, which allows us to calculate the average hourly weighted waiting time cost.

We repeat the calculation for alternative scenarios where the number of open lanes is increased. Then we compare the reduction in the waiting time cost for the scenarios to the estimated cost (provided by the Danish Transport and Construction Agency [10]) of opening more lanes. The cost estimate is conditional on existing lane capacity. We look at three scenarios where capacity is increased by 1, 2 and 3 lanes respectively through the day. In each scenario, the number of open lanes is capped at 18, which is the number of lanes available in the CSC. We also limit the evaluation to the period from 6 am to 8 pm.

3.3 Estimation results

3.3.1 Mean regression

A number of regression models have been tested based on the specification in (4).

- The model was extended with lags until the point where the Durbin-Watson statistic as well as other tests did not reject the hypothesis of zero autocorrelation of the residuals. This is a requirement for the model to yield statistically valid conclusions.

The estimated regression parameters are shown in the following table. The dependent variable is log waiting time.

Table 2 Estimation results, mean regression

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.91620	0.06256	14.6	< 2e-16	***
log(Open.lanes)	0.02288	0.02067	1.1	0.26840	
log(laglane)	-0.50660	0.02395	-21.2	< 2e-16	***
log(laglane2)	0.17990	0.02057	8.7	< 2e-16	***
OLoad25	0.00007	0.00002	4.6	4.89E-06	***
OLoad69	0.00011	0.00002	6.5	7.40E-11	***
OLoad_Sum10	0.00027	0.00003	8.6	< 2e-16	***
OLoad_Sum11	0.00027	0.00003	8.7	< 2e-16	***
OLoad_Sum12	0.00013	0.00003	4.3	1.45E-05	***
ELoad_Sum4	0.00004	0.00001	2.9	0.00386	**
ELoad_Sum5	0.00016	0.00001	11.1	< 2e-16	***
ELoad_Sum6	0.00019	0.00001	12.7	< 2e-16	***
ELoad_Sum7	0.00014	0.00002	9.1	< 2e-16	***
ELoad_Sum8	0.00009	0.00002	5.5	3.49E-08	***
ELoad_Sum9	0.00005	0.00002	3.0	0.00256	**
log(lagwait)	0.71140	0.00570	124.9	< 2e-16	***
day2	-0.00735	0.01090	-0.7	0.50060	
day3	-0.02521	0.01085	-2.3	0.02018	*
day4	-0.01399	0.01084	-1.3	0.19664	
day5	-0.03368	0.01089	-3.1	0.00199	**
day6	-0.02549	0.01142	-2.2	0.02559	*
day7	0.02609	0.01099	2.4	0.01759	*
hour6	-0.00028	0.05836	-0.0	0.99617	
hour7	-0.09520	0.05863	-1.6	0.10443	
hour8	-0.06957	0.05873	-1.2	0.23618	
hour9	-0.04462	0.05891	-0.8	0.44881	

hour10	0.06351	0.05921	1.1	0.28342	
hour11	-0.10280	0.05958	-1.7	0.08451	.
hour12	0.00096	0.05957	0.0	0.98717	
hour13	-0.07199	0.05938	-1.2	0.22543	
hour14	-0.07673	0.05886	-1.3	0.19245	
hour15	-0.10360	0.05883	-1.8	0.07836	.
hour16	0.00035	0.05830	0.0	0.99524	
hour17	0.02563	0.05815	0.4	0.65935	
hour18	-0.04279	0.05877	-0.7	0.46662	
hour19	-0.18760	0.05889	-3.2	0.00145	**
hour20	-0.31080	0.06008	-5.2	2.33E-07	***
hour21	-0.49500	0.06141	-8.1	8.13E-16	***
hour22	-0.65950	0.06273	-10.5	< 2e-16	***
hour23	-0.85660	0.06954	-12.3	< 2e-16	***

Multiple R-squared: 0.657. DW = 2.0004, p-value = 0.4479.

We make the following observations.

- "Open.lanes","laglane" and "laglane2" are the number of open lanes in the current period (at time t), 15 minutes before (t-1) and 30 minutes before (t-2). The parameters for the lagged variables are very significant.
- These parameters imply that an increase in the number of open lanes at time t reduces the waiting time at time t+1. The effect is reduced but still very significant at time t+2. In addition, there is the amplifying effect of the lagged waiting time, this is discussed below.
- "ELoad" and "OLoad" refer to destinations inside Europe and outside, respectively. The numbers refer to forward lags: Thus "OLoad25" is the number of people leaving on planes departing 2 to 5 times 15 minutes, i.e. 30 to 75 minutes, after the current time, for destinations outside Europe. The part of the names "_Sum" can be ignored.
- Demand for destinations outside Europe affects waiting times up to 3 hours prior to departure ("OLoad12"). Demand for destinations inside Europe affects waiting times up to 2 hours and 15 minutes prior to departure. This makes sense as passengers go through security at varying times prior to their departure. Effects beyond these were small and therefore ignored in the model.
- We have included forward lags of demand until the point where the parameters become smaller and less significant.
- All the demand parameters are positive as expected.
- "lagwait" refers to the waiting time at time t-1. The parameter is 0.71, which means that a change in the waiting time, either due to random shocks or due to changes in the independent variables, will persist for some time into the future. The effect of a temporary change will die out over time, while the effect of a permanent change will take time to be fully reflected in the waiting time. This is illustrated below.
- The "day" constants take day-specific effects into account. Monday ("day1") is the base, and hence the constants measure the difference from Mondays. The differences between days, taking into account all the other variables in the model, are small and

only some are significantly different from zero. The waiting time is shorter on Fridays and longer on Sundays for reasons not otherwise explained in the model.

- The “hour” constants take time of day specific effects into account. The hour from 5am to 6am is the base and “hour” constants measure the differences from this hour. The effects are small, except from 7pm where waiting times decrease until the last hour from 11pm to 12pm.
- We have tested the residuals for auto-correlation. The Durbin-Watson test, as well as a range of other tests, do not reject the hypothesis of no serial correlation of the residuals.

A residual plot is shown in the next figure with respect to the log of the number of open lanes.

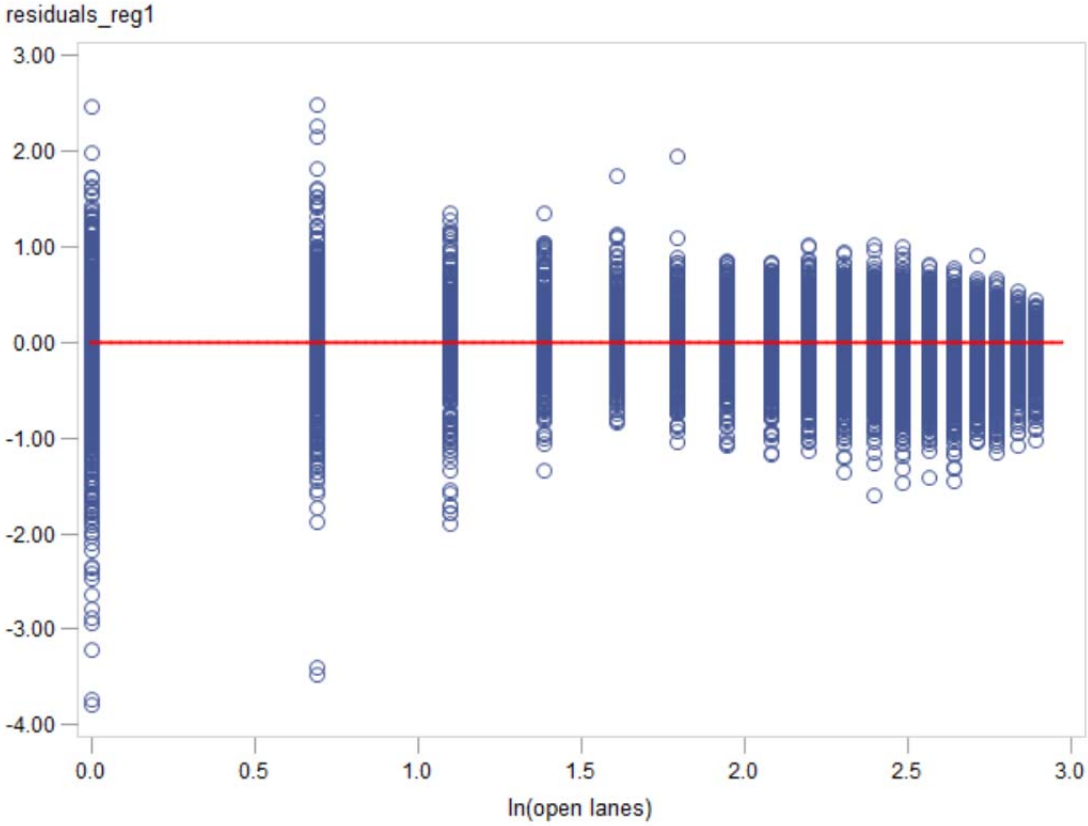

Figure 7 Residual plot against the number of lanes

The model can be solved for the steady-state relationship, where there is no random noise and where all variables are constant. This is useful for checking that the model makes sense. The estimates imply the following steady-state relationship for the waiting time in minutes (Mondays at 5am):

$$W/min = 23.9 \cdot (lanes)^{-1.05} \cdot \exp(0.0023 \cdot ELoad + 0.0049 \cdot OLoad)$$

- As a first sanity check of the model, we compute the steady-state waiting time at sample averages (10.6 lanes, ELoad = 355 pass/15min, OLoad = 51.5 pass/15min), which yields a steady-state waiting time of 5.97 minutes. This is close to the observed average waiting time of 5.43 minutes, which promises well for the model. Note, however, that we do not expect the steady-state waiting time to match the observed average completely, since the observations do not correspond to steady-state. It is still reassuring to obtain a number from the model in the same range as the data.

- The steady-state relationship indicates that an increase in the number of lanes of 10% (say from 10 to 11) decreases the waiting time by 10.5%. An increase in ELoad of 1 passenger per 15 minutes increases the steady-state waiting time by 0.23%, and an increase in OLoad of 1 increases the steady-state waiting time by 0.49%. Thus passengers travelling outside Europe contribute more to the average waiting time than travellers inside Europe.
- The model fits the data well in the range where we have data. It is, however, important to note that the model is not guaranteed to perform well away from the range of data that we observe. If we go to the extreme of zero demand and just one open lane, then the model would predict a very large waiting time, which is clearly unreasonable. This shows that we should not use the model to evaluate situations that are too far from the observed.

The following two figures illustrate the effect from steady-state of a temporary increase in the number of lanes (Figure 8) and in the demand (Figure 9). The effect in both cases persists over a period of 2-3 hours.

The effect of a change in the number of lanes occurs quite quickly.

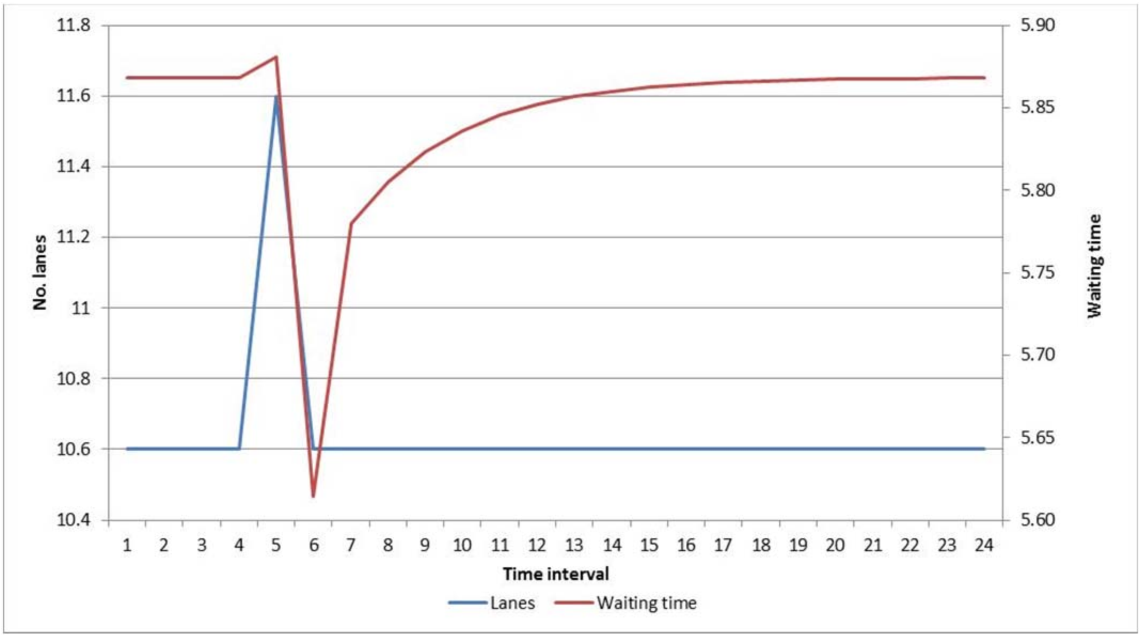

Figure 8 A temporary increase in the number of lanes

In contrast, the effect of a temporary increase in the number of passengers peaks after 45 minutes and then dissipates.

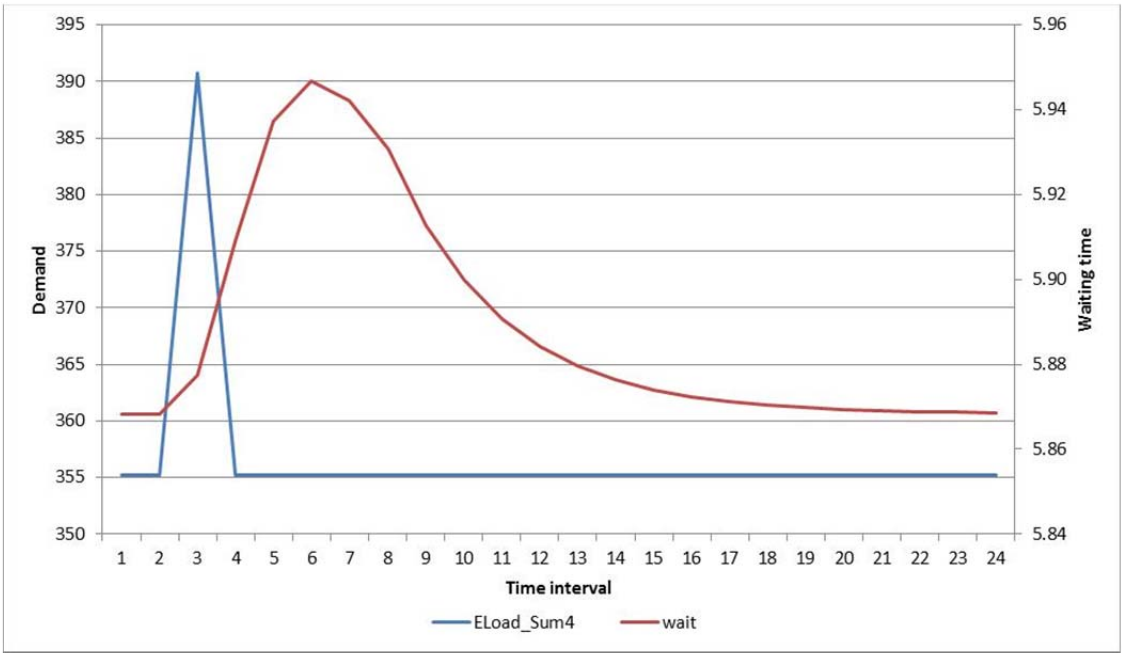

Figure 9 A temporary change in demand

3.3.2 Variance regression

We have then estimated various specifications of (5), arriving at the model with parameters shown in Table 3. Again, the model was extended until the point where the autocorrelation of the residuals could be assumed to be zero.

The dependent variable is the logarithm of the squared residuals from the mean regression. This measures the scale of the variability of waiting times. The unit for this does not have an easy interpretation.

Table 3 Estimation results, variance regression

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-2.01426	0.066515	-30.283	< 2e-16	***
log(Open.lanes)	-0.576	0.027600	-20.869	< 2e-16	***
hour23	0.756652	0.198827	3.806	1.42E-04	***
laglogsquareresiduals_reg1	0.046357	0.007803	5.941	2.89E-09	***

Multiple R-squared: 0.0381. DW = 2.0017, p-value = 0.5401

The following observations can be made.

- Increasing the number of open lanes decreases the variability of waiting time. The effect is very significant.
- The variability is higher in the last hour before midnight.
- There is a tendency that a numerically large residual in one period (higher or lower waiting time than otherwise expected) is associated with increased variability also in the next period.

- The fit of the model, measured by the R-squared, is low. This is expected since the dependent variable is constructed from the random residual from the first-stage regression.
- The Durbin-Watson statistic, as well as a range of other tests, allows us to accept that residuals are not auto-correlated.

A residual plot is shown in the next figure with respect to the log of the number of open lanes.

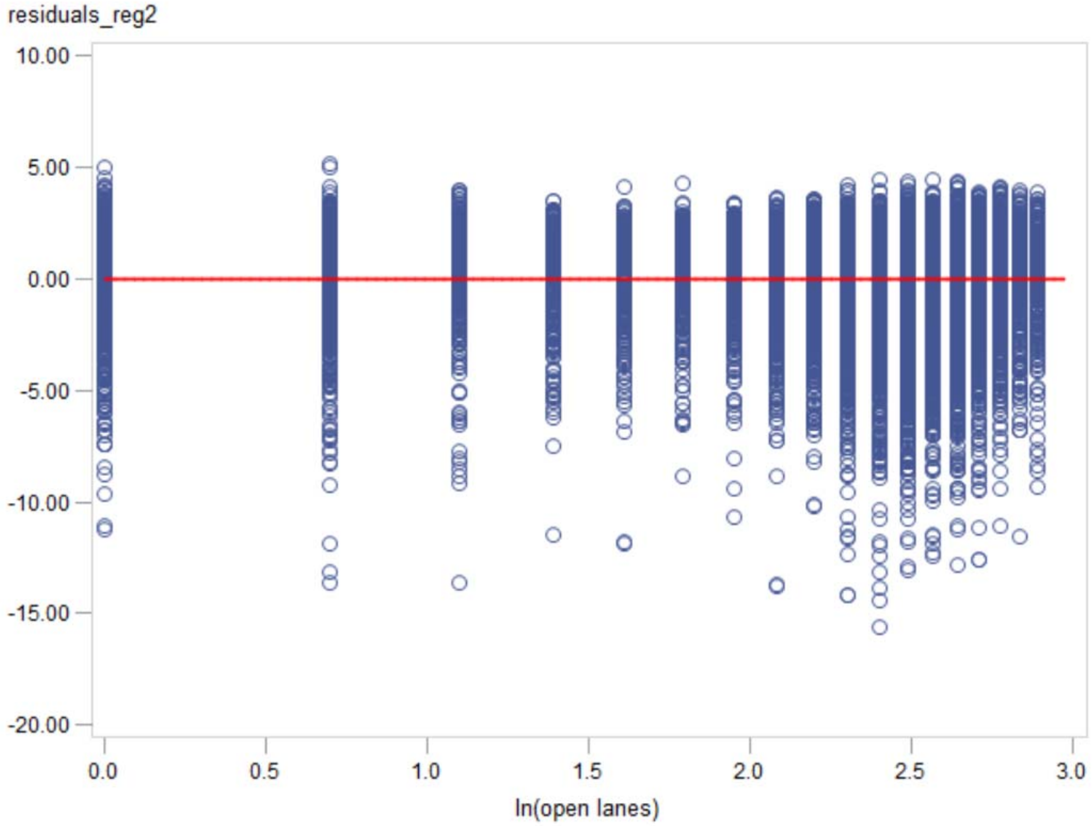

Figure 10 Residual plot against the number of lanes

3.3.3 Model validation using simulation results

Simulation is carried out for an average week, covering the interval from 6am to 10pm. The profiles over the week of demand and the number of open lanes are constructed as the average over the weeks in the data. The construction of the demand variables proceeds as follows.

The data informs about the number of passengers according to the time of departure. These data are used as they are in the estimation and in the simulation of the model. For the purpose of evaluating the waiting time cost we need the number of passengers according to the time they pass through security. We distribute each departing passenger on earlier times using the demand coefficients from the estimated model. These coefficients are normalised to sum to 1, such that each departing passenger is counted exactly once at the central security check.

The resulting demand profile at the central security check is shown in the next Figure 11. We observe a sharp peak in demand in the early morning every day. Most of the demand is for destinations in Europe.

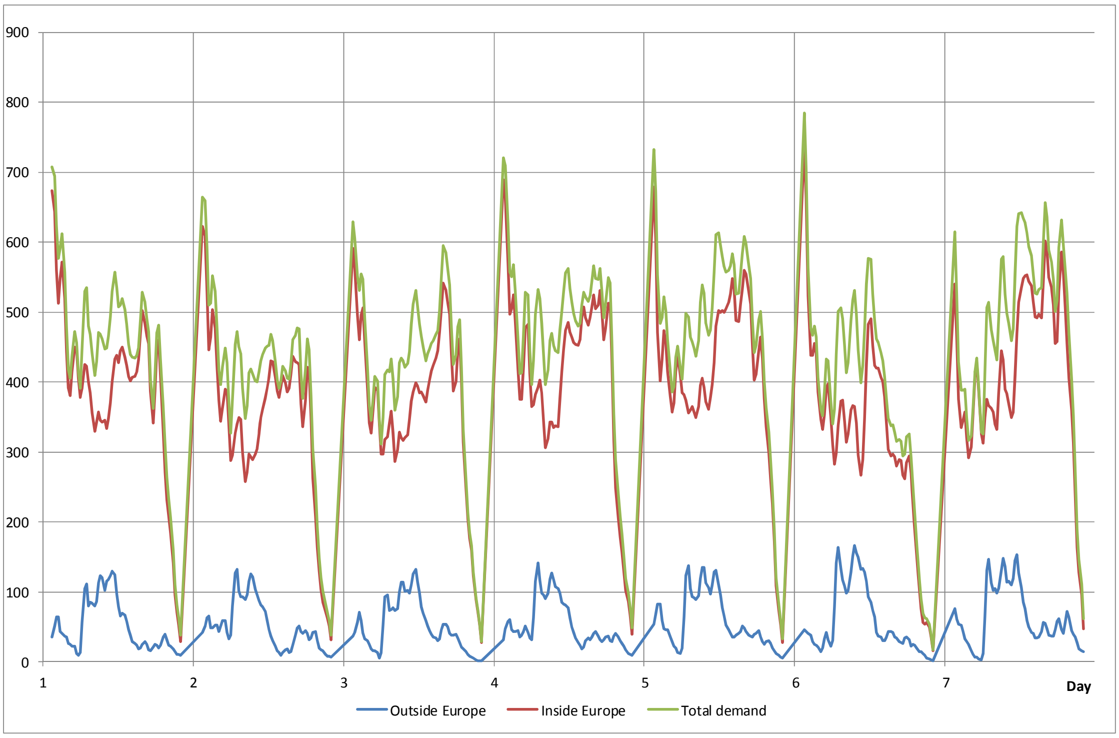

Figure 11 Demand profile at the central security check

The simulations are based on the demand profile and profiled for the number of open lanes in the central security check. The base scenarie 0 is the average number of lanes across the weeks in the data. This is shown in Figure 12.

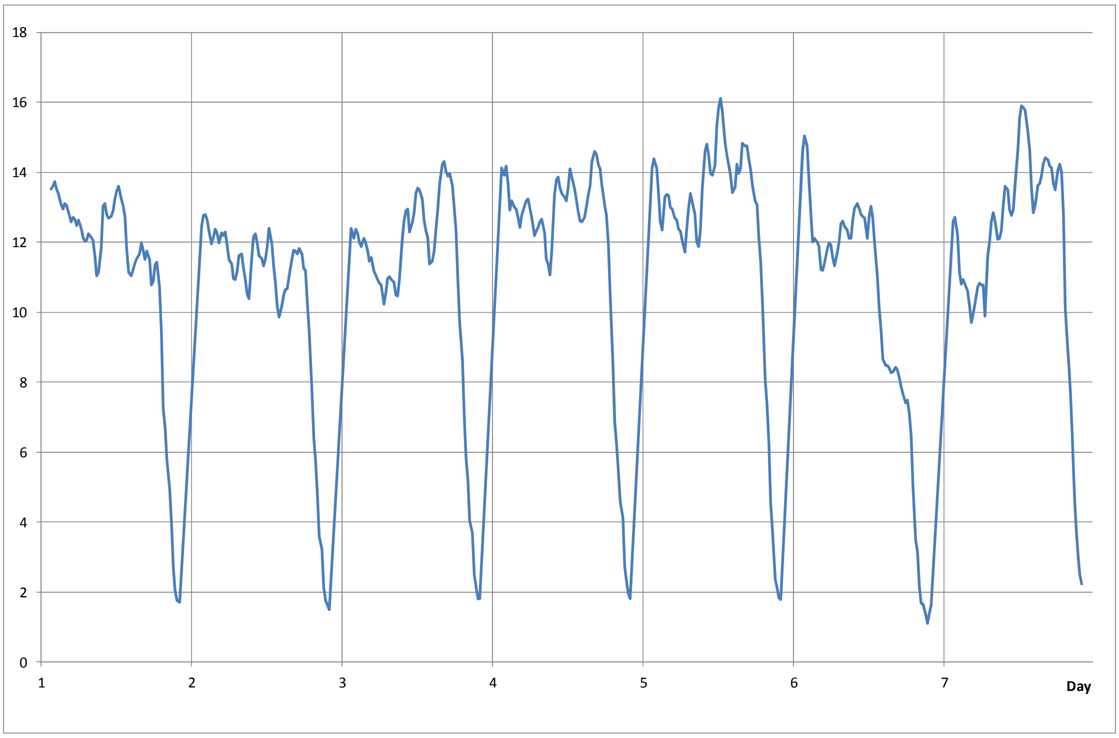

Figure 12 Open lanes, scenario 0

Figure 13 compares the model prediction to the observed mean waiting times. The model tracks the changes within days and over the week quite well. Deviations are to be expected, as there is sampling noise in the observed data. The model has a tendency to under-predict the mean waiting time: the mean predicted waiting time in the base scenario is 5.2 minutes while the mean observed waiting time is 5.5 minutes during the time interval from 6am to 10pm. As mentioned above, this is expected since the model is estimated in terms of log waiting time. The purpose of the model is to evaluate the change in waiting times following an increase in the number of lanes and then the bias does not matter much.

We obtain similar results when we compare the predicted and the observed standard deviation of waiting time, as seen in Figure 14. Larger differences between predicted and observed must be expected for the standard deviation of waiting times than for the mean, since sampling noise matters more for the standard deviation.

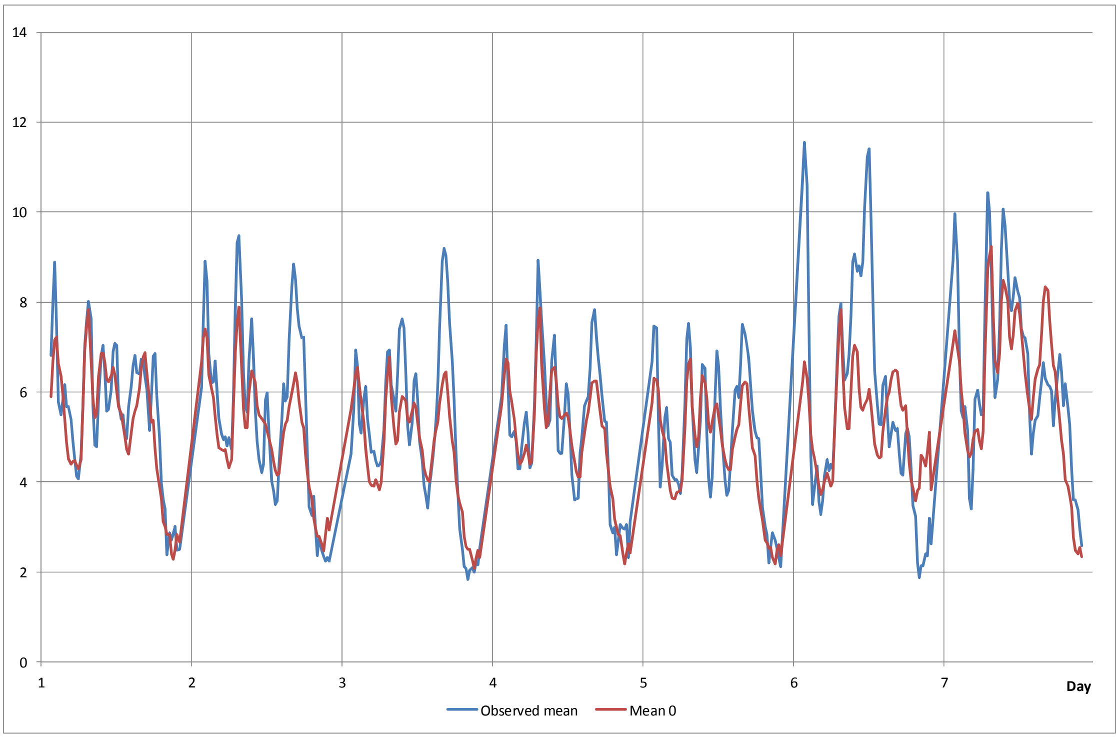

Figure 13 Comparison of predicted mean waiting time to the observed waiting time

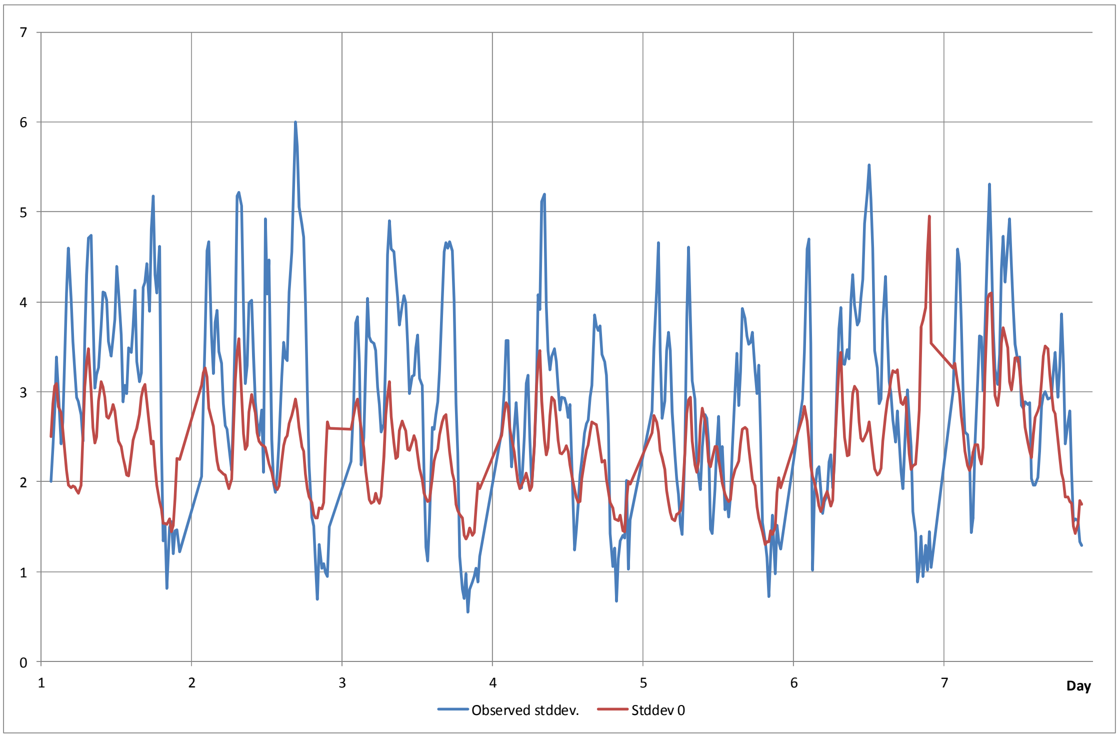

Figure 14 Observed and predicted standard deviation of waiting time

Finally, Figure 15 shows the 5% and the 95% quantile for the observed data and for the base scenario. This shows that the model is able to track the distribution of waiting times quite well. The match is not expected to be perfect, due to sampling noise in the observed data.

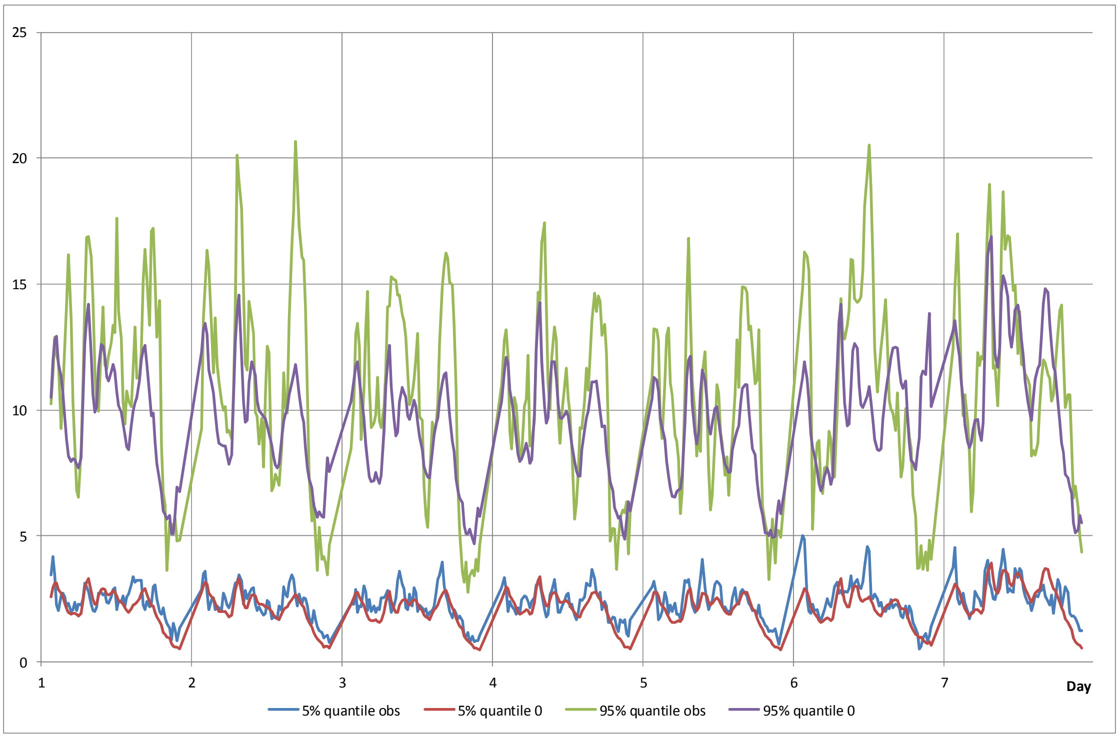

Figure 15 5% and 95% quantiles, observed and base scenario 0

In conclusion, we find that the model matches the observed data quite well: it is able to track the mean, the standard deviation and the range of the distribution of waiting time quite well over the simulated week. This is very satisfactory.

4. Simulation results

We simulate four scenarios, using 50,000 replications, for an average week and from 6am to 10pm every day. When showing results, we omit the interval from 8pm to 10pm as the number of passengers and the number of open lanes are low in that interval; thereby we ensure that the simulation stays within the range of data where the model is most reliable.

The scenarios are based on the demand profile and the profile for the number of open lanes in the central security check. The base scenarie 0 is the average number of lanes across the weeks in the data. Scenarios 1, 2, 3 add 1, 2, and 3 additional lanes, respectively. A cap of 18 lanes is applied, which is the maximum available at the airport.

The following table shows the mean and the standard deviation of waiting time for the four scenarios as well as for the observed data. Adding one lane to the base scenario at all times decreases the mean waiting time by 0.47 minutes. Adding more lanes decreases the mean waiting time further at a diminishing rate, which is as expected and reasonable. Similarly for the standard deviation of waiting time, the first lane added leads to a decrease of 0.27 minutes and more lanes decrease the standard deviation of waiting time further at a decreasing rate.

Table 4 Mean and standard deviation of waiting time 6am-8pm, minutes

Scenario	Mean	Standard deviation
Observed	5.99	3.22
Sim 0	5.55	2.46
Sim 1	5.08	2.19
Sim 2	4.68	1.97
Sim 3	4.34	1.79

Figure 16 shows the predicted mean waiting time for the four scenarios. It is observed that adding more lanes decrease the mean waiting time consistently over the week.

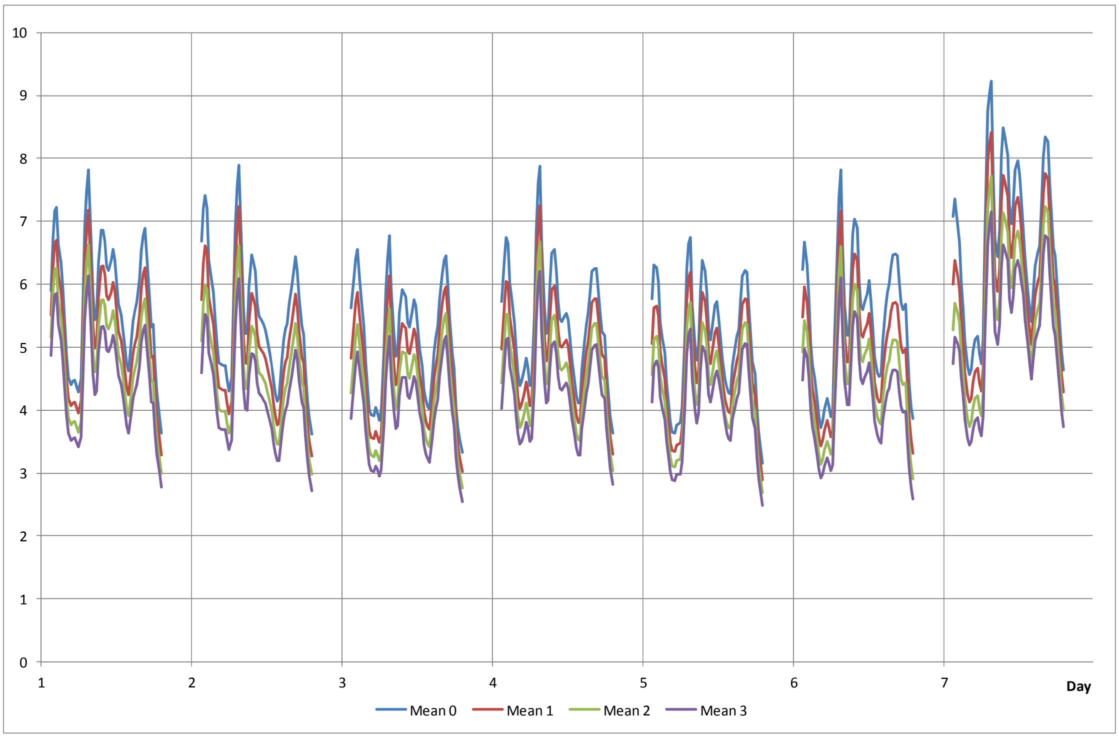

Figure 16 Mean waiting time, scenario 0-3

Figure 17 similarly shows the predicted standard deviation of waiting time for the four scenarios. The predicted standard deviation of waiting time decreases consistently over the week as more lanes are added.

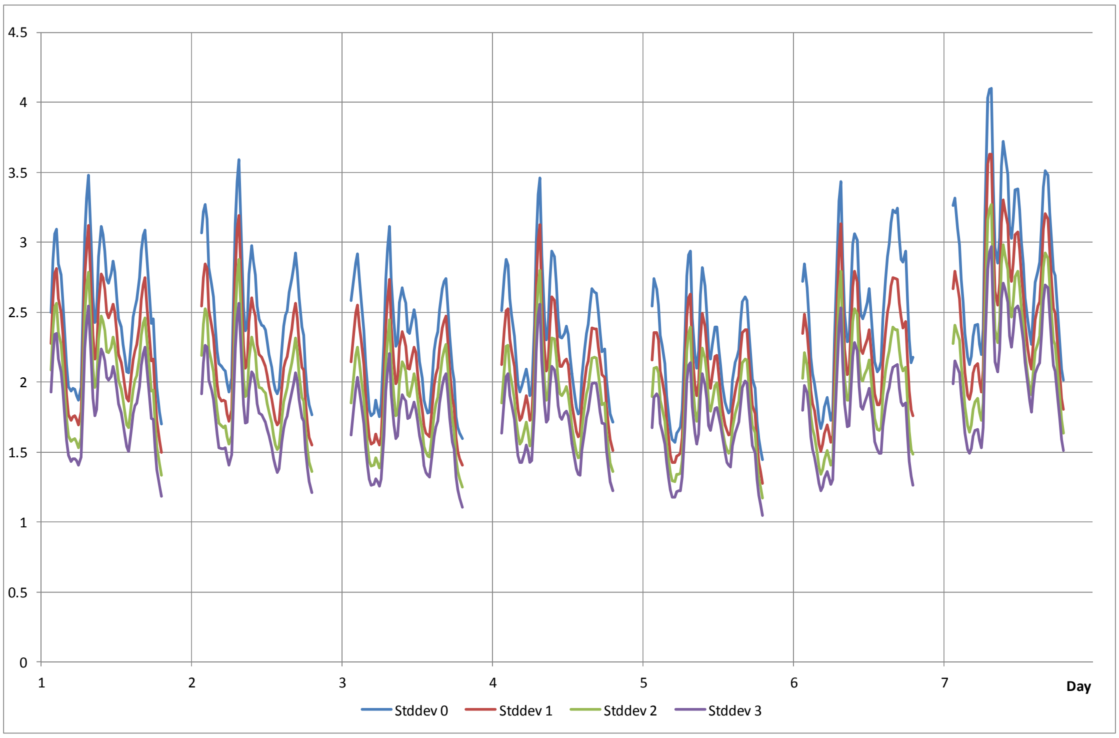

Figure 17 Standard deviation of waiting time, scenario 0-3

Another perspective on the reduction of the random variability of waiting times is provided in Figure 18. Adding lanes decreases the extreme waiting times consistently across the day and more as more lanes are added.

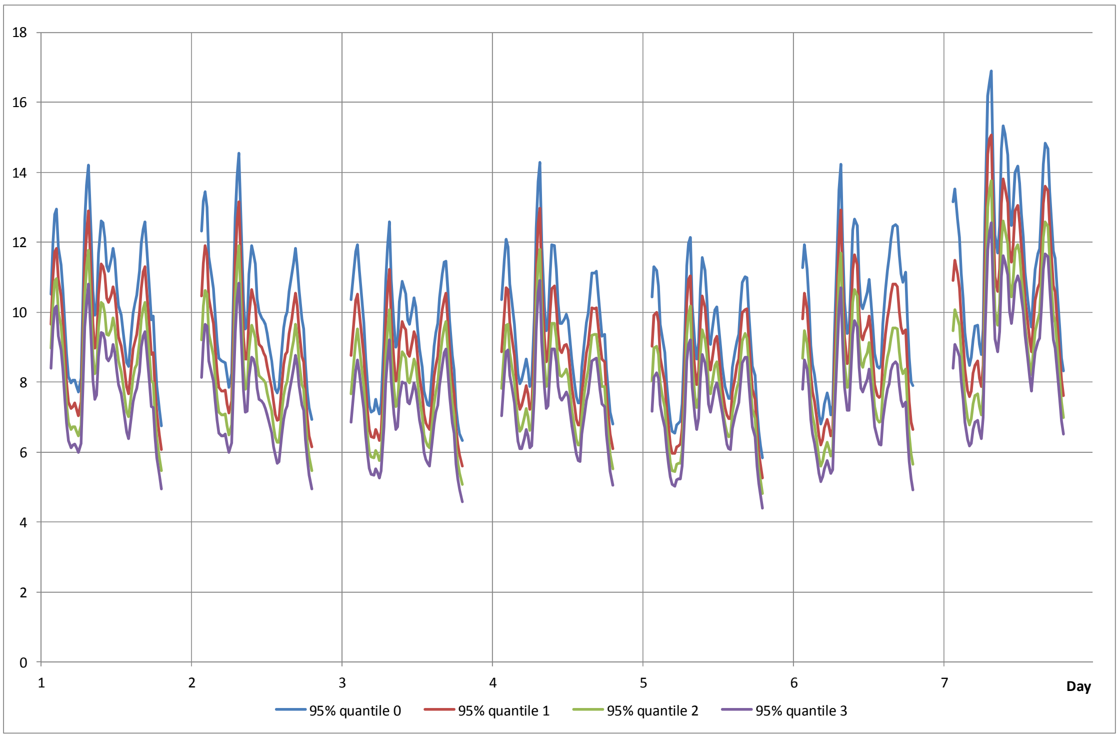

Figure 18 The 95% quantile of waiting time. At each time of day, the waiting time is below the 95% quantile 95% of days.

5. Economic evaluation of a capacity increase

5.1 The value of time and reliability

The Ministry of Transport maintains a list of unit values for cost-benefit analyses in the transport sector. These unit values comprise the value of travel time and delay time in car and public transport. They do not comprise values for air travel and hence they do not comprise values for waiting time in the security check. They do also not comprise values for reliability. For ordinary surface travel, travel time variability is handled via a simple markup on the delay relative to free flow travel time.

Therefore we look elsewhere to obtain valuations of waiting time and reliability. We seek a value of waiting time as well as values of schedule delay that are used in the calculation of the waiting time cost as described in section 3.1. The waiting time cost comprises both the cost related to the mean waiting time as well the variability of waiting time.

The table below summarises values from various studies that provide estimates of the willingness to pay to save time for air travellers. Two studies provide specific willingness to pay values for reduced waiting time in security, i.e. the value of time (VoT) in security, whereas the remainder provide values of access time (VoAT) to airports in general.

Table 5 Value of time related to airports, from various studies

Reference		VoT in security			VoAT overall		
		Business	Leisure	Mix	Business	Leisure	Mix
Incentive [4]	2009	6.6	2.8	4.3			
Furuichi & Koppelman [5]	1993				8.0	4.7	
Pels et al. [6]	2003				19.9	13.5	
Hess et al. [7]	2007				8.6	4.4	
Koster et al. [8]	2011				5.4	3.9	
Landau et al. [9]	2015	4.3	3.3	3.7	2.1	1.9	2.0

In Landau et al. [9], costs are measured in 2013 dollars. The year has not been validated for the other sources. We have used exchange rates (6.86 and 7.5) to transfer values into DKK/min.

Below we present the results from Koster et al. [8] who apply the scheduling model to airport departures. The measures are value of access time (VoAT), Value of schedule delay early (VSDE), Value of schedule delay late (VSDL), and Value of probability to miss next flight (VoPMF).

Table 6 Scheduling parameters from Koster et al. [8]

	Business (DKK/min)	Non-business (DKK/min)
VoAT median	5.0	3.6
VSDE median	4.0	2.9
VSDL median	5.9	4.3
VoPMF median	1.1	0.8
VoAT mean	5.4	3.9
VSDE mean	8.2	6.0
VSDL mean	23.3	17.0
VoPMF mean	6.9	5.0

Based on the evidence above we will use $\alpha = 3\ kr/min$. This value is in line with the leisure value estimate by Incentive [4]. Given the fact that the security will also include business travellers and that values may have increased since 2009, we see this as a conservative estimate. Our estimate reflects a mixture of 5% business travellers for the central security check, while the mixture value calculated by Incentive [4] reflects a mixture with 40% business travellers for all travellers.

To derive our value for SDE and SDL, we apply the ratios between the mean values for non-business travel estimated by Koster et al. [8]. We round these and use 1.5 and 4.5. This gives us the three coefficients

$$\alpha = 3\ DKK/min, \beta = 4.5\ DKK/min, and\ \gamma = 13.5\ DKK/min$$

These are also conservative estimates, since the Koster et al analysis includes a cost associated with the probability of missing a flight that we omit here.

5.2 The cost of capacity

The cost of adding an additional lane for 1 hour with 4 employees has been calculated by the Danish Transport and Construction Agency [10] to be DKK 274 *4 = DKK 1096 with an uncertainty of +-10%.

The cost-benefit analysis is carried out in market prices, which corresponds to the willingness-to-pay of leisure travellers. The cost to the airport is in factor prices and must be converted to market prices. We use the standard factor of 1.325, which yields a cost of an additional lane in market prices of 1452 DKK per hour.

5.3 Comparing costs and benefits of a capacity increase

Figure 19 shows the waiting time cost per passenger in DKK for the four scenarios. We observe a consistent decrease over the week as more lanes are added.

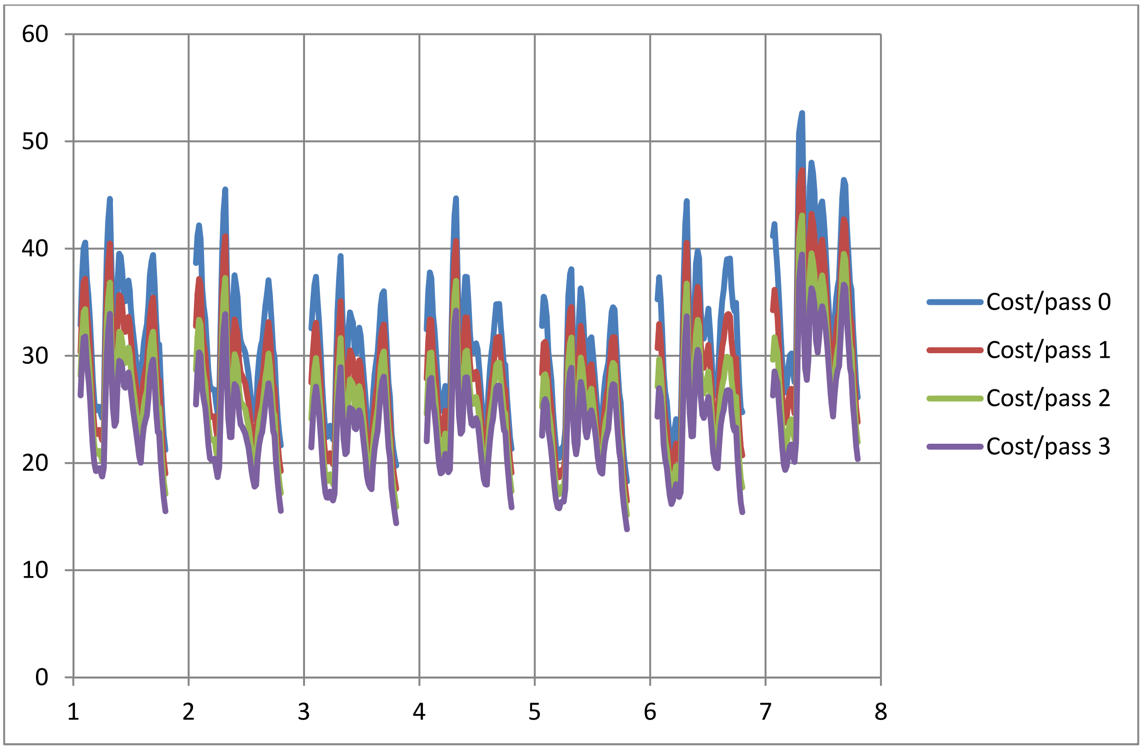

Figure 19 Waiting time cost per passenger, DKK

The average reduction in waiting time cost per passenger in the four scenarios is shown in the following table.

Table 7 Waiting time cost per passenger, DKK

Scenario	Cost per passenger, DKK	Change from previous
Sim 0	31.6	
Sim 1	28.6	3.1
Sim 2	26.0	2.5
Sim 3	23.9	2.1

The cost per passenger is multiplied by the number of passengers passing security every 15 minutes, estimated from flight departure data as explained above. The following Figure 20 shows the total savings from adding lanes in the central security check, comparing scenarios with additional lanes to the base scenario 0.

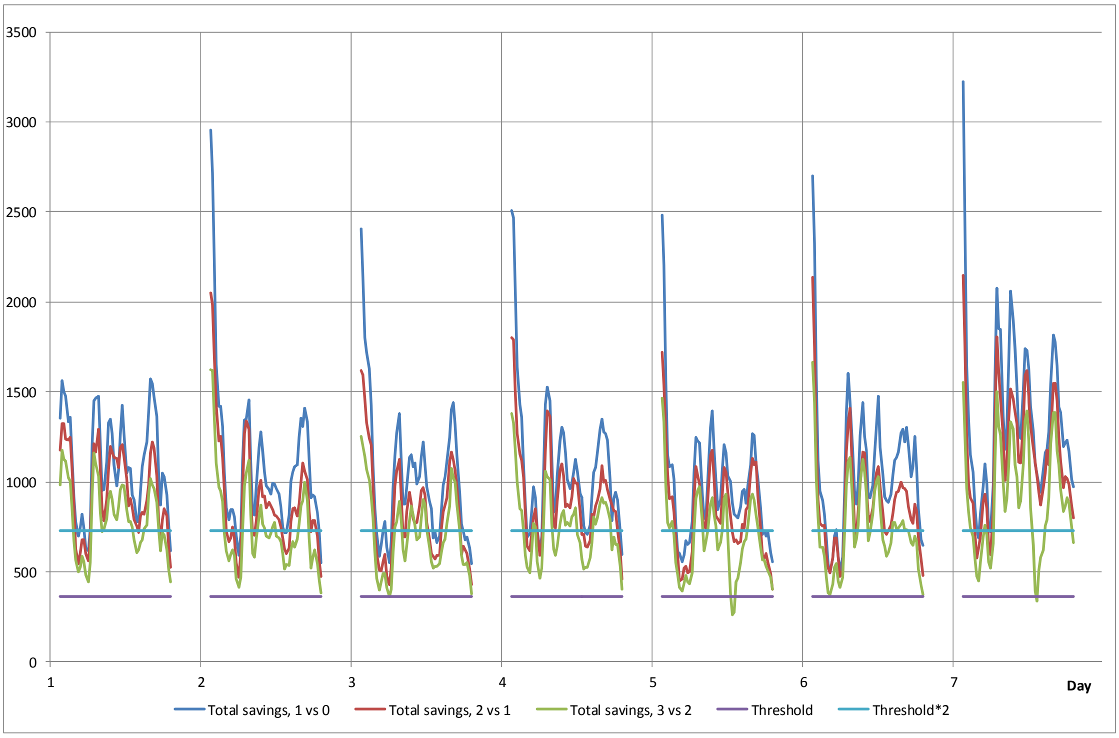

Figure 20 Total cost savings for passengers over an average week. The figure shows the benefit to passengers in 15 minute intervals of adding one lane. "1 vs 0" compares one additional lane to the baseline, "2 vs 1" compares two additional lanes to one additional lane, and "3 vs 2" compares three additional lanes to two additional lanes. The threshold lines indicate the corresponding cost to the airport per 15 minutes and twice that amount.

Adding 1 or 2 lanes yields a net benefit at all times during the week. Adding three lanes yields a substantial net benefit in general, but there are a few 15 minute intervals during the week where the net benefit of the third lane becomes negative.

Table 8 Benefits and costs per hour due to an additional lane open at all times during the day

	Savings to passengers	Savings due to mean waiting time	Cost to airport	Net benefit
From 0 to 1 extra lanes	3358	1572	1452	1906
From 1 to 2 extra lanes	2801	1326	1452	1349
From 2 to 3 extra lane	2310	1103	1452	858

Opening one additional lane yields an average benefit to passengers of 3358 DKK per hour with a corresponding cost to the airport of 1452 DKK per hour. A bit less than half of the savings to passengers, 1572 DKK, is due to reduction in the mean waiting time, the rest is due to reduced variability. This means that adding one lane is justified even without taking the reduction in variability into account.

Opening a second additional lane yields an additional average benefit to passengers of 2801 DKK per hour, which is still larger than the cost to the airport of 1452 DKK per hour of manning a second additional lane. The saving due to mean waiting time is 1326 DKK, which is close to the hourly cost to the airport of manning a lane.

Opening a third additional line yields an additional average benefit to passengers of 2310 DKK per hour, out of which 1103 DKK per hour is due to reduction of the mean waiting time. The benefit to passengers clearly outweighs the cost to the airport of 1452 DKK per hour, also in this case going from two to three additional lanes.

In conclusion, the calculations indicate a clear net benefit of opening three additional lines at all times during the day. Section 6.1 discusses uncertainties related to the analysis. The main points relevant for assessing the robustness of the conclusion are the following.

The benefits are proportional to the values of time and reliability. The values used are on the low side of the available evidence, which indicates that the actual benefit of a capacity increase is likely to be larger than the calculated benefit.

The cost per lane hour is directly proportional to the estimate from the Danish Transport and Construction Agency. The cost per lane hour would thus need to be more than 50% larger in order to change the conclusion.

We therefore find that the conclusion that there is a clear net benefit of opening three additional lines at all times during the day is quite robust.

6. Conclusion

The purpose of this project is to

- Undertake an economic evaluation of waiting times in the central security check at Copenhagen Airport.
- Compare the cost of additional capacity in the central security check to the economic benefit to passengers of reduced and less variable waiting times.

- Define the optimal capacity in the central security check.

We have found that there is a clear net benefit from increasing capacity in the central security check. The cost savings to passengers clearly outweigh the corresponding cost to the airport.

The uncertainty inherent in the model predictions increases as we add lanes and move away from the range we observe in the data. We therefore do not investigate capacity increases beyond three additional lanes as we would then be less confident about the model predictions. The implication is that the net benefits are so large that we are not confidently able to identify the break-even point where additional capacity no longer yields a net benefit.

The capacity in the baseline scenario is the average number of lanes that was open during the period observed in the data. The airport varies the number of open lanes day by day and during the day according to their expectations regarding the number of passengers. The number of open lanes is also influenced by the short term availability of staff. The baseline is thus a moving target and it does not make sense to impose requirements on the airport in terms of the number of open lanes.

The table below presents the mean waiting time, the standard deviation of waiting and the 95% quantile of waiting time. 95% of waiting times are smaller than the 95% quantile. The first line in the table presents the observed data, while the next four present the baseline scenario 0 and the three scenarios where additional lines are opened. The numbers concern the period 6am to 8pm for an average week.

As has been discussed, the baseline scenario does not reproduce the observed data exactly. We therefore provide recommendations in terms of the changes that are achievable according to the model predictions.

Table 9 Summary statistics, average week, 6am to 8pm

Scenario	Mean waiting time	Standard deviation of waiting time	95% quantile of waiting time
Observed	6.0	3.2	11.7
0	5.6	2.5	10.1
1	5.1	2.2	9.1
2	4.7	2.0	8.3
3	4.3	1.8	7.6

The analysis predicts that adding two or three lanes at all times will reduce the mean waiting time for passengers between 0.9 and 1.2 minutes. The standard deviation is reduced between 0.5 and 0.7 minutes. The 95% quantile is reduced between 1.8 and 2.5 minutes. The corresponding reductions in waiting time costs for passengers clearly outweigh the cost to the airport of opening more lanes.

The airport is able to allocate capacity more efficiently than the present simulations indicate, by adapting capacity to the variation in demand that they observe from day to day and during each day.

Requiring that the airport reduces the mean waiting time and some convenient measure of the size and frequency of large waiting times seems very operational.

Using round numbers, a requirement that the airport reduces the mean waiting time by one minute and the 95% quantile by two minutes would clearly lead to a net societal gain, accounting for the benefit to passengers as well as for the cost to the airport.

6.1 Uncertainties

There are a number of uncertainties in the evaluation carried out in this report. Generally, we have chosen to be conservative, such that the benefits that we compute resulting from capacity increases in the central security check will be on the low side. We have discussed uncertainties at various points in the report and provide a summary of these discussions here.

- The valuation measures that we derived in section 5.1 were chosen as conservative values based on leisure values from 2009. A share of travellers are business travellers who should ideally be assigned higher valuation measures. Not accounting for this implies that our valuation measures will tend to be on the low side.
- Furthermore we did not include the cost associated with the probability of missing a flight. This will also imply that the measures are on the low side.
- Our computation of the waiting time cost assumes that travellers know the waiting time distribution and that the waiting time distribution varies slowly over time. However, there is a lot of variation at the 15 minute time resolution, and it seems not realistic that travellers are able to anticipate this. This means that some of the variation that the model considers to be just variation in the mean waiting time will be perceived as random variability by travellers. We do not account for this, and hence we underestimate the waiting time variability. This is likely to mean that we also underestimate the decrease in waiting time cost that follows a capacity increase.
- Our model is most reliable where we have most data. The model is less reliable in the evenings when demand and the number of lanes is lower. Therefore we omit the period 8pm to 10pm each day when reporting results.
- The simulation is based on an average week. This omits variation between weeks in the demand and the number of open lanes. Therefore the cost to travellers of waiting time variability that we compute is lower than it would have been if we had accounted for that variation.

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