論文の内容の要旨

論文題目 Passenger Forecast and Staffing at Airport Immigration
(空港の入国審査場における到着客予測とスタッフ配置に関する研究)

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Over the last few decades Narita Airport has lost its position as Asia's main transfer hub. Its Asian competitors have increased their capacity while Narita's capacity has stagnated. In addition its Asian competitors have consistently won airport awards for the best service. Immigration at Narita Airport has received complaints from passengers about long waiting times during peak hours. The purpose of our research is to reduce the waiting times for foreign passengers at Narita Airport immigration by optimizing the staffing levels. To do so we have developed three models: an arrival forecasting model, a queueing model and a staffing model. Based on the flight schedule and the number of passengers on each flight we first make a distributional forecast. The arrival forecast is then used as input for the staffing model. To meet a certain service level requirement the staffing model gives the staffing function, i.e. the required number of staff during the day. We can then simulate the performance of the staffing function with the queueing model.

The first step is to forecast the number of passenger arrivals at immigration. In the literature statistical models and discrete-event simulation models are commonly used. Statistical models require a large amount of historical data and simulation models generally require many iterations. We have developed a different approach to determine the arrival probabilities by using the sum of random variables. For a flight it is assumed that the walking time probability distribution is the same for each passenger. Then the arrival probabilities for the passengers of the flight without delay uncertainty are determined by the convolution of the distribution functions of every passenger at each time interval. Adding delay uncertainty to the flight requires the convolution of the arrival probabilities and the delay probability distribution. To calculate the arrival probabilities of the combined passengers of multiple flights we again apply the convolution operation. We call this forecasting model the convolution model.

The forecasting model requires knowledge of the probability distributions of the flight delay, the disembarkation delay, the disembarkation rate and the walking speed. To determine these probability distributions we gathered data at Narita Airport. Flight delay is defined as the difference between the estimated and the actual flight arrival time. In the literature on flight delays the scheduled arrival time is used as the estimated arrival time. However we estimate the flight delay with the more accurate estimated arrival time from the real-time online flight schedule which is updated every 10 minutes. We have collected every flight schedule update for more than 1 year. We found that the delay probability distribution of a flight depends on the length of time between the estimated time of arrival and the flight schedule update time. The second uncertain parameter is the disembarkation delay. After an aircraft arrives at the gate, the passengers have to wait a certain time before disembarkation. We have recorded the time when the first passenger leaves the aircraft for 41 flights. A Markov Chain Monte Carlo algorithm was used to infer the distribution of the mean and the standard deviation of the disembarkation delay. For 10 flights the disembarking passengers at the gate were recorded on video. We found that the disembarkation rate is relatively constant for all flights. After disembarkation the passengers walk from the gate to immigration. Because the walking times could not directly measured we assumed that the walking speed is normally distributed and we inferred the walking speed mean and standard deviation from the observed arrival rates of 10 isolated flights.

In addition we have developed a Monte Carlo simulation model and a deterministic approximation. All three arrival forecasting models give reasonable results when compared to the observed arrival rates of a single flight and multiple flights. For use in practice the convolution model can give the decision makers at Narita immigration a good indication of the trend, the variance and the upper bound of the arrival rates while the deterministic approximation can give a sample path of the arrival rates. The Monte Carlo simulation model can be used to provide the arrival rate samples for the performance simulation of the staffing function.

The second step in our research is to develop a queueing model for the immigration service of foreign passengers. The purpose of the queueing model is to estimate the waiting time if the number of arrivals and staff are known. Traditional queueing theory studies the steady state of a queueing system. However at immigration the arrival rate is non-stationary and uncertain. Traditional queueing theory also assumes that the system is non-overloaded, i.e. the average arrival rate is less than the service capacity. However at immigration overload occurs frequently. In the literature there are various queueing approaches that can deal with overload. We have implemented three queueing models: the numerical integration of the Kolmogorov differential equations, the deterministic fluid approximation and the stationary backlog-carryover approach. In the literature there has not been a comparison of these three models. Also artificial arrival rates are commonly used in the literature to compare queueing models. Instead we used actual arrival rates and validated the models with actual waiting times.

To compare the three queueing models we gathered data at Narita Airport. We recorded videos of the queues to determine the waiting times and service times. We also counted the number of arrivals and the number of staff during five afternoons. The input of the queueing models is the observed arrival rate, the observed number of staff and the observed service time. The output is the waiting time at each time of the day. We compared the output of the queueing models with the observed waiting times. All three models give good estimations of the waiting times. The numerical integration approach however requires long computation times. The deterministic fluid approximation is easy to implement, the fastest and accurate if a time interval of 1 minute is used. It is our preferred queueing model for the performance evaluation of the staffing function.

The final part of our study is to determine the staffing requirements for foreign passengers in order to support the decision makers at Narita immigration. In the call center and hospital staffing literature there are two approaches to determine the staffing function: the optimization approach and the constraint satisfaction approach. The optimization approach is rarely used in practice because of the difficulty of quantifying the waiting cost. For our staffing model we use the constraint satisfaction approach where the objective is to minimize the number of staff while meeting a service level requirement. The service level is defined as the excessive waiting time $\mathrm{SL}(t) = P(W(t) > W_{\max})$. We want to keep the daily service level $\mathrm{SL} = \sum \lambda(t)\mathrm{SL}(t) / \sum \lambda(t)$, i.e. the service level weighed by the arrival rate $\lambda(t)$ over the remainder of the day, under a certain percentage. For the foreign passengers the performance constraint is $\mathrm{SL} \leq 0.01$ with $W_{\max} = 10$ minutes. The performance evaluation is done with the deterministic queueing model and the arrival rate samples generated by the Monte Carlo simulation model.

In the staffing literature of call centers it is frequently assumed that the system is in steady-state during each staffing interval or that there are customer abandonments in the case of overload. At immigration there are no abandonments and the steady-state assumption is inappropriate because of severe overload. In the airport staffing literature a deterministic fluid model has been applied for immigration staffing but uncertainty in delay was not taken into account. We analyzed the waiting time performance of the deterministic fluid model with uncertain demand and we concluded that the performance is inadequate. We have extended the deterministic fluid model with delay uncertainty by converting the deterministic staffing function into staff probabilities. The staffing levels are then set by determining the appropriate quantiles of the staff probabilities. In addition we also applied the square-root staffing approach, $s = r + \beta\sqrt{r}$, to our problem and determined the appropriate values of β to meet the service level requirement. With both methods we can satisfy the daily service level SL requirement. However during periods with low arrival rates and at the end of the day the service level in an interval $\mathrm{SL}(t)$ can reach unsatisfactory levels. We propose a new service level constraint: the service level during any interval $\mathrm{SL}(t)$ should be at most 0.03. To meet this new constraint we have developed an iterative algorithm. The initial staffing levels can be set according to the deterministic fluid model, the staff probability quantiles or the square-root staffing formula. Then the service level in each interval $\mathrm{SL}(t)$ is calculated. If the constraint is violated in any staffing interval, the number of staff in that interval is increased by one. We do this iteratively until the performance constraint is satisfied in each staffing interval.

In practice we can support the decision makers at Narita immigration with our models. First we can provide the arrival forecast with the arrival probabilities, the expected arrival rate, the 95% upper bound and a sample path with the deterministic approximation. Second we can provide a staff forecast with the staff probabilities and the upper bound of the required number of staff. Using the quantiles for the staff probabilities or the square-root staffing formula we can also give a recommendation for the staffing function such that the daily service level requirement is met. If a more robust solution is desired then the iterative algorithm can be used but it will require longer computation time to generate arrival rate samples and to simulate waiting time probabilities of the queueing system.