Application of Discrete Event Simulation in Measuring Pollutant Emissions: A case study for London Heathrow (LHR)

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ABSTRACT

The aim of this paper is to explain the relationship between air pollutant-emissions and waiting times whilst aircrafts queue to access London Heathrow (LHR) runways. The approach to this problem is to develop a discrete-event simulation that describes the current landing and take-off operations, aircraft inter-arrivals and inter-departures, runway utilisation, and average waiting times for the aircrafts to access the runways. The proposed models cover three runway operational scenarios: segregated mode, mixed mode and mixed mode with third runway. The produced stochastic model will then estimate the average number of approaching aircrafts awaiting resources for access to runways (analogous to work-in-process in manufacturing environments). The emission estimation model takes into consideration the number of aircrafts at different altitudes and on land, and relates the information to the average emission for each aircraft at each state.

This paper does not deal with measuring the quality of air and neither has it considered any other factors such as wind, humidity and rain patterns that affect air quality around the airport. The input data gathered for this project are from sources available to the public and does not include complex landing rules based aircraft type or weight. The only contribution sought is to relate demonstrate the capabilities of Discrete Event Simulation and modelling techniques for capturing the relationship between aircraft waiting times and flow with emissions in a real case study.

Keywords

OR in airlines, Environmental Impact, Queuing Models, Airport Operations, Discrete Event Simulation, Aircraft Emissions

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1. Introduction

The controversy of the 3rd runway can be described as one of the most engaging discussions currently taking place in the United Kingdom (UK). The new government has postponed any decision to expand London Heathrow's runway capacity, but the discussions will resume in a later time. The policy and decision makers are dealing with strong feeling on both sides of the London Heathrow (LHR) expansion argument. Provided a 3rd runway is built at Heathrow airport, the annual Air Transport Movement (ATM[†]) will increase from the current level of 480,000 to at least 655,000 per year (Department of Transport, 2008).The UK business will benefit from a highly advanced airport with the appropriate capacity to deal with the expanding aviation industry. However, this expansion of capacity at LHR impacts the air pollution at the vicinity of the airport. At the moment it is difficult to accurately estimate such impact. Especially, we cannot be confident that with the increase in number of aircrafts the key conditions to meeting the air quality constraints can be met.

In this research paper Discrete Event Simulation (DES) and the associated modelling techniques (Askin and Standridge, 1993 and Kelton et al, 2010) have been applied to collect, format, and model the landing and departure operations at LHR. Data was collected on the availability of the two runways, flight inter-arrivals and departures, aircraft types, and pollutant emission profiles of various aircraft engine types at different altitude levels. The performance factors such as the number of aircrafts waiting for available resources (or work-in-process), aircraft average waiting time, resource (runway and taxiway) utilisation, and number of aircrafts in queues were derived from the implementation of Little's law (Askin and Standridge, 1993) and the introduction of the principles of analytical queuing models (Cassady and Nachlas, 2009). The overall emission function is described in this paper as the product of average waiting times with respect to aircraft state (at various stages of the flight or on the ground i.e. taxing and waiting to access a runway) and the subsequent emission rates.

In the first step two DES models were developed to measure the current performance of the system and the emissions of air pollutants of aircrafts waiting to land and depart from LHR. The models simulate two modes of runway usage; segregated and mixed mode. In the segregated mode scenario, the one mainly used, the current levels of traffic (i.e.

[†] An aircraft take-off or landing at an airport. For airport traffic purposes one arrival and one departure is counted as two movements

approximately 1300 aircrafts/day) were modelled. Based on BAA and DfT reports on mixed-mode operations, we uniformly increased the traffic to the predicted (approximately 1480 aircraft/day). The arrival and departure data was monitored, collected and analysed for 4 weeks of 7 days a week.

In the next step a third runway was introduced to the model and accordingly we increased the number of aircrafts expected to be handled by the airport to (over 2200 aircrafts/day) to demonstrate and compare the possible environmental impact of the increased traffic and runway capacity from the current levels. It is worth noting that the descriptive models developed for this purpose used available information in public domain and is bound to some assumptions made by the modellers. This may affect the accuracy of the estimated figures; however, it does not have a significant effect on the research methodology and the overall conclusions of the study.

The raw data on aircraft models and airport operations at LHR were obtained from British Airport Authority (BAA) data depository (BAA, 2009 and Department for Transport, 2008) over a specified period of time. Furthermore the information about operational modes and layouts of the runways were obtained from reports published by the Department of Transport [Department for Transport, 2008 and 2009).

2. Research Method

The parameters specified in this study are restricted to the minimum requirements for a valid DES model. They include data about the types, emission profiles and LHR aircraft processing logic during landing and departure periods.

The main objectives pursued in this study are:

1. To report and appraise and extract the literature about air pollutant emission models and relate them to DES models of LHR.
2. To design, build and validate a DES model using an existing DES software tool (in this case Arena^{TM} (Kelton et 2010).
3. To validate and verify key performance factors on air pollutant emissions resultant from the DES and analytical queuing models with respect to the current runway operation modes i.e. Landing and Take-Off (LTO) cycles.
4. To investigate the introduction of a 3rd runway and its impact on the air pollution around LHR.

In addition to a literature review about the subject, figure 1 provides a snapshot of the sources of information the authors reviewed to set out their research plan.

[Figure 1]

2.1 The LTO cycle and operations

According to the International Civil Aviation Organisation (ICAO), LTO cycle is all operations near the airport below the 3000 feet (1000m) altitude. The operations specified as part of the LTO cycle and important in modelling the operations are divided into: taxi-out, hold, take-off roll, initial climb (wheels off the runway to throttle back, assumed to happen at (450m), climb out (1000m), approach (1000m to touch down), landing roll, and taxi-in. The aircraft engine thrust settings at LTO are used in this study to relate LTO to levels of emissions. Table 1 in the appendix, describes the relationship between various LTO modes with the default thrust settings (Watterson et al, 2004).

2.2 Emission models and air pollution estimation

The Intergovernmental Panel on Climate Change (IPCC) proposes a decision flowchart as part of good practice on estimating emissions (Penman et al, 2000). The guideline is a suitable approach to selecting and comparing various techniques suggested in the literature. In this section we will briefly discuss a number of methods and select the best model that seems to be the most suitable for analytical and simulation models purposes.

Analytical methods for measuring emission levels such as the extensive list described by (Romano et al, 1999 and Dopelheuer and Lecht, 2000) are not in the scope of this study. Aircraft emission measurements used in this study are derived from the models proposed in Woodmansey and Patterson, 1994) and further extended and customised for UK airports by Watterson et al (2004). The revised calculation method proposed in (Watterson *et al* 2004) has been adopted in this study for the following reasons:

- The models are customised for UK airports,
- Makes distinctions between the CO emissions of domestic and international flights,
- It provides a more accurate estimate of fuel consumption for the LTO cycles,
- Provides a strong logical basis for improved estimation of total emissions with respect to aircraft specifications during the LTO cycle,

– Allows for the changes in the aircraft fleet over time, and

– Flexibility to deal with changes in the LTO process if they occur.

Equation 1 reproduced here calculates the emission levels (and fuel consumption) of pollutant ρ, where m is a particular LTO mode of operation (excluding auxiliary power unit[‡]), for aircraft type s (Watterson et al, 2004). Therefore the instant emission levels in mode *m* is:

$$E_{LTO_{a,m,\rho,s}} = N_s \times T_{a.m,s} \times F_{a,s}(t_{a,m,s}) \times I_{a,\rho,s}(t_{a,m,s}) \qquad (1)$$

Where:

$E_{LTO_{a,m,\rho,s}}$	Level of emission in mode m for pollutant ρ for aircraft type s and airport type a
a	Airport type
m	The LTO mode
ρ	The type of pollutant
s	Aircraft type
N_s	Number of engines on aircraft type s
$T_{a,m,s}$	The length of time that an aircraft s is in mode m at airport a. The value is the average waiting time in the proposed DES model.
$t_{a,m,s}$	The thrust setting of aircraft s at airport a in mode m
$F_{a,s}(t)$	The weighted average flow of fuel for an engine on aircraft type s at airport a, with thrust setting of t (kg/s)
$I_{a,\rho,s}(t)$	Average emission factor for pollutant ρ of each engine on aircraft s at airport a at thrust setting of t.

[‡] Auxiliary Power Unit (APU) is the power provided when the aircraft is on the ground and the main engines are switched off.

The fuel consumption on an aircraft with respect to $I_{a,\rho,s}(t)$ can be calculated using equation 2 0:

$$T_{a,m} = 0.1 \times R_a \qquad (2)$$

Where:

R_a The length of the longest runway in airport a

$T_{a,m}$ The time in modes Taxi-in or Taxi-out at airport a

According to Chin and Melone (1999) levels of engine emissions and calculations vary at different stages of the flight. The altitude of the aircraft is an important factor in estimating emissions. For example, the maximum levels of NOx, CO and unburned HC are generated above 3000ft where 83% of the fuel is consumed. Although, surface operations consume the least amount of fuel but produce the highest ratios of CO and HC to fuel burnt. To capture the levels of emissions during the LTO Cycle which is the focus of this study, the weighted average emission to fuel consumption suggested in Celikel et al (2004 and 2005) is adopted (see equation 3).

$$Emissions = No.\ of\ engines \times Time \times Fuel\ Flow \times Emission\ Index \qquad (3)$$

The Emission Index (EI) is normally obtained from the aircraft engine manufacturer. Using the EI, the aircraft emissions are estimated at idle, taxi, and altitudes below 3000ft.

Due to the fact that it was not possible for the modellers to obtain the data on how long an aircraft remains in a specific flight mode, equation (3) has been selected by the modellers over equation (1). It represents an overall average emission and can be considered as a reasonable simplification and estimation for the DES model. Provided the information on length of time an aircraft remains in a mode can be obtained the model can be adjusted to use equation 1 for instantaneous emission calculations.

2.2.1 Air Pollution at London Heathrow (LHR)

The potential sources of emissions in and around LHR can be attributed to:

1. Aircrafts in various LTO modes,
2. Road Traffic,
3. Fire Training Grounds, and
4. Airport heating plant.

This paper focuses solely on item 1 of this list; however, in future there is a possibility to include other sources of pollution to demonstrate the total environmental impact of LHR and its expansion.

BAA performs assessments of the air quality at LHR using mobile sites situated at different locations in and around LHR (BAA, 2009). According to BAA reports, aircrafts are the major sources of NOx emissions (84%), in which take-off and climb contributing 78% of the total. Moreover, 66% and 78% of the total HC and CO are respectively from aircraft emissions at idle and taxi modes.

In addition to direct measurements there are the air quality models (AQM) explained for example in (Idriss , 2003; Godish, 2004; Metcalfe and Derwent, 2005).

2.2.2 The principles of Discrete Event Simulation (DES) modelling at LHR

Figure 2 provides an overview of the key parameters that were considered in creating the DES model of LHR runway operations.

[Figure 2]

Figure 2 shows how the information was classified into 4 categories so that the logic of using the land and air resources by the aircraft can be captured. The "Arrival" category was defined to describe the rules of aircraft arrival, in Hold-Signal feature of simulation modeller (in this case Arena Software) was used to manage the landing process, capturing the arrival of the aircraft into the landing zone and permissions to land with respect to clearance between consecutive aircrafts requesting to access a runway. This allowed the logic of the model to encapsulate the approach time, taxi roll times and clearance of the runway (runway becoming available for the next landing request).

The "Departure" category covers the processes of an aircraft using taxi corridors to access the available runways for take-off. The logic of access based on the Hold-Signal criteria and the buffers for access to the runways were used to model the departure process and also relate the different aircraft emission profiles at various states (i.e. idle, take-off roll, initial climb, and climb out).

The "Hub of Airport Operations" and "Terminal Runways" categories deal mainly with the layout of the airport, positions of terminals, gates, taxi ways, the two existing runways, and their proximities.

In addition to the key parameters shown in Figure 2, information the following information was collected:

- Departure: flight information for specified periods, departure times, destinations, aircraft type, and the allocated terminal.
- Runway operations: mode of operation and maintenance.
- Arrival: approach distance, inter-arrivals, terminal, and taxi-in times.
- The Celikel *et al* (2005) emission calculation methodologies were adopted.

3. Modelling Principles, Assumptions and Constraints

In this section the authors attempt to clarify the principles of the models chosen and reasons for some of the key assumptions. We hope that the explanations help the reader to appreciate the framework and research constraints in this study.

3.1 The Runway Operations Queuing Rules

There are three basic models:

- Model 1 simulates the current dominant scenario of the two runways in which the runways function in segregated mode. This means that one runway is allocated to landing and the other to departure and they can alternate. Therefore the most appropriate queuing model that applies to this form of operation would be *M/M/1*. The access rule to the runways waiting for landing and departure was assumed to be *First-in First-Out (FIFO).* It would have been ideal to be able to capture any priority rule such as *emergency landings* but due to the sensitivity of the data, the modellers chose not seek such information.
- Models 2 and 3 simulate the Mixed-Mode (using two and a third runways for both landing and departure). In this model the aircrafts join an imaginary storage (*hold logic in simulation language)* and based on their request i.e. land or depart, and based on their priority (aircrafts in landing mode take priority over ground aircrafts) access to one of the designated runways is granted.

3.2 Aircraft Arrival /Departure Rate, Types and Emission Levels

- The aircraft landing and departure rates and the actual meantime between arrivals and departures were obtained through the information available in public domain. The best-fit probability distribution tests were applied to the data to and the best-fit inter-arrival and departure of the aircrafts were measured with 95% confidence interval (results are shown in figure 3).
- In order to measure emission levels by aircraft type as accurately as possible, we estimated the number of various types of aircrafts that arrive and depart from LHR by studying the airlines fleet and percentage of each aircraft type that they may use in Heathrow. At occasions we were able to directly obtain the information on the type of aircraft so we conducted some simple evidence-based cross correlations (i.e. assuming a specific type of aircraft and then checking actual tickets). It was the best option at the time that was available to the authors. However, if the exact information is provided it can be directly feed into the models. The authors do not believe there would be a significant difference between the assumed (applied here) and the exact aircraft types.
- The emission models were borrowed from the latest development research results by experts in the area (Watterson et al 2004; Celikel et al 2004).

4. Data Collection and Implementation

In this section of the paper the approach to data collection and implementation of the DES models and the inherent limitations of this approach to projecting emissions at LHR will be explained.

4.1 Data Collection

In this study, the information in the public domain regarding LHR operations has been used. No extra or supporting information was provided by any airline or the BAA. Our approach in collecting data and building the LHR DES model follows the guidelines of IPCC, ICAO and EMEP/CORINAIR (2007). The tools used for compiling and processing of the collected data are listed in table 2 of the appendix.

The substances that were included for emission measurement purposes in this study were CO, NOx and HC, the so-called Green House Gasses (GHG). The measurements will be focused on the LTO cycle (excluding cruise mode), and will include both domestic and international flights (Airfleet website, 2009).

3.1.1 Information on day-to day flight patterns at LHR

The data on flight inter-arrivals and departures, the allocated terminals to aircrafts, flight numbers, and origins and destinations of the flights were gathered from the BAA official website (BAA, 2009). The information on inter-arrivals and departures which determines the usage of runways, taxi-ways and the terminals at LHR were fed into the stochastic input analyser. Figure 3 shows the best-fit curve on the aircraft inert-arrival and departures from LHR.

[Figure 3]

Moreover aircrafts types and their key attributes were also collected using the NATSCAT categorisation (Airfleet website, 2009). Table 3 provides a snap shot of the excel spreadsheet generated for data collection on aircraft categories and emission profiles.

3.1.2 Aircraft Classification at LHR

An important factor in estimating emission levels at the airports is the aircraft type. The aircrafts are categorised based on their key characteristics and age. The approach we adopt in this study is similar to that proposed by Watterson et al (2004). The information for this section was acquired and statically derived from the data provided by a selection of airlines that use LHR (see Little, 1961). A statistical analysis was conducted based on the type of aircraft operating in the fleet of airlines that use LHR and estimations were made of the probability of the aircraft type to be allocated by the airline to LHR on a busy day. Tables 3-1 to 3-4 of the appendix list the sample aircrafts and their corresponding airlines that land and depart from LHR on a typical busy day.

3.1.3 DES and Analytical Queuing model for LHR

The LTO cycle is analogous to a manufacturing system where parts arrive at a random rate (proved in the data collection process), delayed for processing (in this case access taxi ways and runways), and leave the system (depart or terminate at terminals). Using equation 4 it seems logical to adopt and interpret the First Law of Manufacturing Systems, the Little's Law (1961) for this case as:

$$\text{Work-}\textit{in-Process (WIP) = Aircraft LTO Rate (ALTOR)} \times \textit{Average LTO Cycle Time} \quad (4)$$

Assuming that the LTO to be considered as a single process and if the steady-state ALTOR is *X*. There are *N* aircrafts requesting access to the airport resources (i.e. runways) and every aircraft arrives to the resources at a rate of 1/*X* and each aircraft advances 1 space and spends 1/*X* time units at each spot to access the runway then the total LTO time will be: $T = N/X$. Therefore, adding more aircrafts into the system will increase the LTO cycle time. As the ALTOR approaches capacity or in other words full utilisation of the runway, any ALTOR increase diminishes and the WIP increases leading to higher levels of emissions of aircrafts due to waiting. This can be further explained using the M/M/1 concept in analytical queuing models (Askin and Standridge, 1993). In which the rate of aircraft arrivals follows the random Poisson distribution or Exponential time between arrivals and departures (see LHR data collection figure 3) with respect to a single server (i.e. runway) system having random LTO process times. Heathrow runways in actual terms follow this rule. There was no information available for priority access rules; henceforth, an assumption was made that the queuing rules in this case to be First-Come First-Out (FCFO).

Let the average rate for requesting access to one of the runways at LHR to be λ, μ to be the average time that the runway is allocated to an aircraft for the LTO cycle, and c to be the number of runways used in parallel, then the runway utilisation factor denoted by *U* can be defined as: $U = \lambda / c\mu$. Therefore with respect to Little's Law and the M/M/1 queuing models one can calculate the following:

$$L_q = \frac{U^2}{1-U} \tag{5}$$

$$L = \frac{U}{1-U} \tag{6}$$

$$W_q = \frac{U}{\mu(1-U)} \tag{7}$$

$$W = \frac{1}{\mu(1-U)} \tag{8}$$

Where:

L_q Expected number of aircrafts waiting in the queue to access the runway

L Expected number of aircrafts at the runway

W_q Queuing time

W Expected LTO cycle time

5. The Heathrow Runway Simulation Model

The descriptive model on LHR was developed based on the following assumptions and constraints:

- On a typically busy day at LHR around 1300 planes should arrive and depart at a random rate.
- There are two parallel runways for landing and take-off which operate in segregated modes. Access to the runway, taxi-ways and terminals were based on FCFO queuing logic. In future provided the information is made available by the airport management, priority access can also be modelled.
- The runway operational modes are significant factors in determining the utilisation of the runways. Simulation studies were conducted on the segregated, mixed, and mixed with 3rd Runway modes of operations.
- Aircraft type are also considered, their state in the LTO phases and thrust settings were important factor in estimating the emission levels with respect to WIP.
- The LTO cycle times are divided into eight modes in which the emission factors, thrust and fuel consumption settings are defined for each mode.
- The plane arrival and departures processes are modelled in separate sections of the model in which specific attributes and logic around accesses to terminal gates and runways are incorporated into the DES model.
- The distances between terminals and runways are also included in the model for accuracy of time factors and plane movements.
- The central control and management of operations for aircraft handling are captured via, control directions, terminal designation and queuing logic.

The Arena™ DES software package was used to model the descriptive LHR model. The claculations regarding levels of emission are based on LTO modes (ie.e circling, approach, landing roll, landing, Taxi-in, Taxi-out, and take-off, climb) with respect to the time they spend on that specfic mode. Equation 1-4, 7 and 8 were used to measure the levels of emissions based on the instantaneous utilisation of resources. For example to estimate the emission levels of CO during circling the following formula was adopted using the NATCAST (2009) classification criteria:

$$\textit{CO Circling Emission Level} = \textit{No. Engines} \times \textit{Fuel Flow} \times \textit{CO Emission Index} \times \textit{Average Circling Time}$$

Figure 4 shows a simple overview of the model and the prevailing control logic.

[Figure 4]

The average circling time information is collected for a full simulation time span and Arena Tally Variable (Kelton et al, 2010). Similarly, emission levels for other substances i.e. NOx and HC were calculated with respect to their corresponding parameters and at various LTO modes.

6. Results and Analysis

In this section we report the results of the simulation exercise based on the current operational capacity using two runways in both segregated and mixed operational modes. We will then introduce a 3rd runway and use the increased number of aircrafts from the current 1300 to 2200 (envisaged expansion by 2016) a day. The results will only concentrate on the estimated emissions of CO, NOx and HC from ground level to 3000ft.

Table 4 (appendix) reports on the estimated emissions with respect to the existing LHR runway operational mode (segregated) at current traffic levels (approximately 1300 aircrafts per day), and utilisation of 98% of the resources capacity.

Table 5 (appendix) reports on the levels of emissions using the mixed mode of operation for LHR two runways at an average traffic of 1,480 aircrafts per day, and utilisation of 98% of the resources capacity.

Table 6 (appendix) reports on the average waiting times of the segregated and mixed modes.

In the next model we introduce the 3rd runway and measure emissions with the projected number of aircrafts to be around 2,219 per day, at 98% of the available airport capacity. In other words this hypothetical scenario discusses the affect of expanding the runway capacity and its effect on aircraft handling at LHR.

Table 7 reports on the levels of emissions at traffic levels of 2,219 using the mixed mode with the additional 3rd runway.

Table 8 reports on the average waiting times at various LTO stages if there is a 3rd runway and the average daily number of aircrafts is around 2,219.

A summary of the emission figures are shown in figure 5. In figure 6 we demonstrate the average aircraft waiting time for the three scenarios, 2 segregated runways, 2 runways in mixed-mode and mixed mode 3 runways.

[Figure 5]

[Figure 6]

The results of the queuing models and simulation runs reveal some interesting outcomes.

- Firstly, better management of the two runways operations and moving towards segregated mode to mixed mode reduces the average waiting time by nearly 40%.
- Secondly, by comparing the segregated mode with the mixed mode operations, despite the increase by 13.8% in number of aircrafts handled the total of CO emissions can be reduced by approximately 21%. The approximate reduction in NOx emissions will be by about 56%, and the total reduction in HC emissions will be about 19.2%.
- Provided a third runway is introduced in mixed mode of operations the number of aircraft handled in LHR is expected to increase by nearly 70% of the current levels. Despite the increase in number of aircrafts when a third runway is introduced, average waiting times for each aircraft will be reduced by 94% and 85.6% compared to the segregated and mixed modes respectively when two runways are used.
- Provided that a third runway is introduced, the average estimated reductions in emissions compared with the two runway mixed mode operations will be CO 6%, NOx 8.4%, and HC by 6.7%.
- However, by no means the analysis here tries to promote the idea of a third runway at LHR since there are other factors that need to be taken into consideration. For example:

(1) Noise emissions due to the increase in the projected number of aircrafts landing and departing from LHR,

(2) The overall air quality which requires the inclusion of a larger number of parameters rather than the 3 substances explored in this study,

(3) Quality of life of the population that live in the close vicinity of LHR including (road traffic, demolishing of homes and businesses in the areas of expansion, and relocation communities, and

(4) Destruction of the natural surrounding, greenery and wildlife habitats.

Nevertheless the proposed model can be a starting point to incorporate the other important factors in expansion of the airports throughout the UK. A clear cost-benefit analysis can be developed using the proposed modelling approach to identify the best options to expand the transport systems that will guarantee the economical growth. Moreover, the current model can be enriched with more accurate information on the airport control logic and aircraft-passenger handling. Also proposed models can be integrated into a larger transport planning strategy in which the rail network can also be incorporated and the best solutions using what if scenario-base simulations to find solutions that has the minimum impact on the environmental.

The next step is to incorporate the model into the proposed real-time data acquisition and modelling so that the most accurate information can be feed into our modellers automatically for best scenarios to be developed and subsequently help to simultaneously improve transport planning, improve quality of service and reduce environmental impact Mousavi et al 2007; Tavakoli et al 2008a 2008b).

7. Results Validation and Verification

The best method to validate and verify the results is to compare the results of the simulation model with that of the actual measurement/observation of the system. In cases where comparisons between the results of DES models) and actual observation (e.g. real emissions value at various altitudes) is not possible, secondary observable evidence were used for validation. The key performance indicators that were available to assess the accuracy of results were the actual and available information regarding runway utilisation, total number of aircrafts handled daily Throughput) and average work-in-process. This comparison between the key operational performance indicators and the simulation results demonstrates that the simulation models accurately represent the processes at LHR.

8. Conclusions

This aim of this study was to explore the relationship between aircraft air-pollutant emissions with respect to queues and waiting times to access the existing London Heathrow (LHR) runways. It then investigated the possibility of adding a third runway and estimating the impact on emissions of three key substances, CO, NOx and HC.

The approach proposed for our analysis was to develop a discrete-event simulation and analytical queuing models that describe and measures the current landing and take-off operations, aircraft inter-arrivals and inter-departures, runway utilisation, and average waiting times for the aircrafts to access the runways and taxi-ways. The produced stochastic models were then used to relate the information to the average emission of each aircraft at different altitudes and on land. The completion of the simulation runs for three predefined scenarios i.e. the segregated mode (the current), the mixed mode and addition of a third runway revealed interesting results.

The suggestion that can be made at this stage is that the LHR operations management should concentrate on developing and implementing the mixed mode model for the runways which will have significant impact on the emissions of the three substances (CO, NOx and HC). It is also possible to increase the number of aircraft handling by 14%, a reasonable business case, since it not only reduces the environmental impact but improves passenger satisfaction due to reduced waiting times and produces further income due to increase in number of aircrafts using LHR.

Even though the introduction of a third runway at LHR may reduce the emission levels despite sharp increases in the number of aircrafts that can be handled at LHR, further studies with incorporation of more parameters to the proposed model in this paper are required. The direction of the future work will be to introduce the real-time data acquisition and scenario modelling to accurately investigate environmental impacts on transport systems expansion in specific evaluating the trade-offs between improving the usage of the current two runways against the introduction of a third runway at LHR. Furthermore, the model will also be expanded to cater for other environmental impact parameters such as noise emissions, air quality and socio-economic dynamics.

Similar studies can be introduced for other UK airports. The proposed modelling approach can also incorporate other transport systems such rail and road to find best solutions for expansion of the transport network with minimum environmental impact and improved quality of service.

References

Airfleet website, http://www.airfleets.net/home/; 2009 (accessed August 2009).

Askin R. G. and Standridge C. R. (1993), *Modelling and analysis of manufacturing systems*, John Wiley & Sons Inc, Part I and Part IV.

BAA Official Website, http://www.heathrowairport.com/; 2009 (accessed online July, 2009).

BAA Terminal 5 Heathrow Environmental Statement (2009), **1** and **2**, ERL UK.

Cassady C. R. and Nachlas J. A. (2009), *Probability models in Operational Research*, CRC Press, Taylor & Francis Group, Chapter 8: 181-200.

Celikel A., Peeters S. and Silue M. (2005), Airport Local Air Quality Studies (ALAQS) - Concept Document Issue 2.1, EEC/SEE/2005/003: http://www.isa-software.com/Alaqsstudy (accessed online August 2009).

Celikel A., Peeters S., and Silue M. (2004), Perspective for airport emission and dispersion – Lyon Pilot study. ISA software studies - Airport local air quality studies (ALAQS), http://www.isa-software.com/alaqsstudy (accessed online August 2009).

Chin D. K and Melone F. (1999), Final Report: *Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft. USA Environmental Protection Agency*, EPA420-R-99-013.

Department for Transport: Britain's Transport Infrastructure. Adding Capacity at Heathrow (2008).

Department for Transport: Britain's Transport Infrastructure. Adding Capacity at Heathrow: Decisions Following (2009): 1-28.

Dopelheuer A. and Lecht M. (1999), Influence of engine performance on emission characteristics, *Proceedings RTO Meeting – Gas Turbine Engine Combustion, Emissions and Alternative Fuels, NATO Research and Technology Organizatio*n. RTO-MP-14 AC/323 (AVT) TP/10.

Godish T., *Air Quality 4th Edition*, Lewis Publishers, USA (2004).

Idriss A., Air quality model guideline. Alberta environment, (2003), environment.gov.ab.ca/info/library/6709.pdf (accessed online August, 2009).

Kelton W. D., Sadowski R. P. and Sturrock D. T. (2010), *Simulation with Arena, Fifth Edition,* McGrawHill Higher Education, , Chapters 1-8.

Little J. D. C. (1961), *A proof for the queuing formula L = λW, Operations Research*, 1961, **9: 3:** 383-387.

Metcalfe S. and Derwent D. (2005), *Atmospheric pollution and environmental change*, Hodder Arnold, UK.

Mousavi A., Devagiri R. and Broomhead P. (2007), A generic platform to address event-based problems for universal applications: supervisory control and simulation, *International Journal Industrial Systems Engineering,* **Vol. 3, No. 3:** 257-276.

NATCAST air traffic control services online information (2009), http://www.nats.co.uk/, (accessed August 2009).

Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., and Tanabe K. (2000), IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*.

Romano D., Gaudioso D. and De Lauretis R. (1999), *Aircraft emissions: A comparison of methodologies based on different data availability. Environmental monitoring and assessment*, **56:** 51-74

Tavakoli S. and Mousavi A., Flexible Data Input Layer Architecture (FDILA) for Quick-Response Decision Making Tools in Volatile Manufacturing Systems (2008), *Proceedings of* 2008 *IEEE International Conference on Communications*, Beijing, China, May 19-23.

Tavakoli, S., Mousavi, A., Komashie, A. (2008), A Generic Framework for Real-Time Discrete Event Simulation (DES) Modelling, P*roceedings of Winter Simulation Conference 2008,* Miami, USA.

Watterson J., Walker C. and Eggleston S., Revision to the method of estimating emissions from aircraft in the UK Greenhouse Gas Inventory. Report to Global Atmosphere Division, DEFRA, netcen/ED47052; July (2004).

Woodmansey B.G. and Patterson J. G. (1994), New Methodology for Modeling Annual Aircraft Emissions at Airports. *Journal of Transportation Engineering*, **120:** 339-357.

Appendix

Table 1: The thrust setting for each LTO modes [10].

LTO modes	Default Thrust Setting
Taxi-Out, Hold and Taxi-In	7%
Take-Off	100%
Initial Climb	100%
Climb-Out	85%
Approach	30%
Landing Roll	7%

Table 2: List of tools and the reasons for their adaptation in this study to collect, store and process data

Tools	Reasons for Use
BAA Heathrow official website	Online aircraft arrivals and departure times for a typical busy scheduled day
MS Excel	To store and process the data obtained from BAA website for the inter-arrival times and the time-in mode evaluation
ARENA's Input analyser	To measure the probability distribution and best-fit curve fitting of data such as the inter-arrival and departure timings of the entities
Report on LHR by Watterson et al 2005	A report on the Green House Gas Tier levels within various airports in the UK. It provides the basis for incorporating information on aircraft types using NATSCAT categorisation, theoretical basis for the calculations, emission factors, thrust settings and number of engines for every aircraft

Table 3-1 to 3-4: Provides a list of aircraft types and fleets that constitute the majority of aircrafts using LHR.

Airline	Number of flights	Percentage per flight
British Airways	322	26.3%
BMI	112	10%
American Airline	141	12%
Lufthansa	87	7.1%
Others	560	45%

Table 3-1

Aircraft Type	Category	Number of Aircrafts	Percentage of total aircrafts	Percentage per category
Airbus A319/320/321	Group 5	81	36%	9.36
Boeing 737	Group 5	21	9%	2.34
Boeing 747	Group 1	55	23%	5.98
Boeing 757	Group 4	9	4%	1.1
Boeing 767	Group 2	21	9%	2.34
Boeing 777	Group 1	46	19%	5.18

Table 3-2

Aircraft Type	Category	Number of Aircrafts	Percentage of total aircraft	Percentage per category
Airbus A319/320/321	Group 5	30	41.5	2.85
Boeing 757	Group 4	1	1.3	0.1
Airbus A330	Group 1	3	4.2	0.3
Embraer 135/145	Group 7	20	27.5	1.95
BAe 146 / Avro RJ	Group 7	18	25.5	1.80

Table 3-3

Category	Percentage (%)	Discrete (Cumulative Percentage %)
Category 1	16.45	16.45
Category2	7.49	23.94
Category3	3.75	27.69
Category4	7.51	35.2
Category5	31.1	66.3
Category6	3.75	70.05
Category7	11.2	81.25
Category8	3.75	85
Category9	3.75	88.75
Category10	3.75	92.5
Category11	3.75	96.25
Category12	3.75	100

Table 3-4

Table 4: Emission levels of the current LHR operations (segregated mode)

CO	Existing operation (Kg)/day	% of emission
Emission level circling	4.81M	19%
Emission level of Approach	4.82M	19%
Emission level of Landing	1.18M	5%

Emission level of Taxi in	11.6M	45%
Total Emission level for Arrival	**25.5M**	
Emission level of taxi out	18.2M	60%
Emission level of hold for runway	5.2M	17%
Emission level of take off	1.8M	6%
Emission level of initial climb	3.6M	12%
Emission level of climb out	1.8M	4%
Total emission level for Departure	**30.4M**	
Total emission for Arrival and Departure	**56M**	
Total Emission level for Arrival		**46%**
Total emission level for Departure		**54%**
NOx		
Emission level circling	23.5M	70%
Emission level of Approach	2.8M	8%
Emission level of Landing	0.084M	0%
Emission level of Taxi in	0.074M	2%
Total Emission level for Arrival	**33.9M**	
Emission level of taxi out	1.3M	7%
Emission level of hold for runway	0.37M	2%
Emission level of take off	5.3M	29%
Emission level of initial climb	6.3M	35%
Emission level of climb out	3.7M	20%
Total emission level for Departure	**18.2M**	
Total emission for Arrival and Departure	**52.1M**	
Total Emission level for Arrival		**65%**
Total emission level for Departure		**35%**
HC		
Emission level circling	0.38M	7%
Emission level of Approach	0.79M	14%
Emission level of Landing	0.37M	7%
Emission level of Taxi in	3.7M	64%
Total Emission level for Arrival	**5.7M**	
Emission level of taxi out	5.9M	70%
Emission level of hold for runway	1.7M	20%

Emission level of take off	0.17M	2%
Emission level of initial climb	0.33	4%
Emission level of climb out	0.088M	1%
Total emission level for Departure	**8.3M**	
Total emission for Arrival and Departure	**14.1M**	
Total Emission level for Arrival		**41%**
Total emission level for Departure		**59%**

Table 5: Emission levels of the current LHR operations mixed mode

CO	**Mixed mode operation (Kg)/day**	**% of emission**
Emission level circling	0.14M	1%
Emission level of Approach	5.0M	27%
Emission level of Landing	1.2M	7%
Emission level of Taxi in	12.0M	65%
Total Emission level for Arrival	**18.6M**	
Emission level of taxi out	17.9M	70%
Emission level of hold for runway	1.9M	7%
Emission level of take off	1.7M	7%
Emission level of initial climb		0%
Emission level of climb out	1.1M	5%
Total emission level for Departure	**25.6M**	
Total emission for Arrival and Departure	**44.2M**	
Total Emission level for Arrival		**42%**
Total emission level for Departure		**58%**
NOx		
Emission level circling	0.14M	3%
Emission level of Approach	2.9M	57%
Emission level of Landing	0.09M	2%
Emission level of Taxi in	0.7M	15%
Total Emission level for Arrival	**4.9M**	
Emission level of taxi out	1.4M	8%
Emission level of hold for runway	0.14M	1%

Emission level of take off	5.3M	29%
Emission level of initial climb	6.3M	34%
Emission level of climb out	3.7M	20%
Total emission level for Departure	**18.3M**	
Total emission for Arrival and Departure	**23.3M**	
Total Emission level for Arrival		**21%**
Total emission level for Departure		**79%**
HC		
Emission level circling	0	0%
Emission level of Approach	0.83M	17%
Emission level of Landing	0.39M	8%
Emission level of Taxi in	3.8M	76%
Total Emission level for Arrival		
	5.0M	
Emission level of taxi out	5.8M	84%
Emission level of hold for runway	0.6M	9%
Emission level of take off	0.17M	2%
Emission level of initial climb	0.32M	5%
Emission level of climb out	0.09M	1%
Total emission level for Departure	**6.8M**	
Total emission for Arrival and Departure	**11.9M**	
Total Emission level for Arrival		**42%**
Total emission level for Departure		**58%**

Table 6: Waiting times in the segregated and mixed mode per aircraft at LHR

State per aircraft	Segregated mode (seconds) 1300 per day	Mixed mode (seconds) 1480 per day
Waiting time to access runway 1 for landing (circling time)	550	100
Waiting time for take off from runway 1	N/A	123
Waiting time for take off from runway 2 (Hold)	330	64

Waiting time to access runway 2 for landing (circling)	N/A	100
Total	**880**	**387**

Table 7: Emission levels of LHR operations in mixed mode with the 3rd runway

CO	**Mixed mode operation with third runway(Kg)/day**	**% of emission**
Emission level circling	0	0%
Emission level of Approach	5.0M	27%
Emission level of Landing	1.3M	7%
Emission level of Taxi in	12.0M	65%
Total Emission level for Arrival	**18.3M**	
Emission level of taxi out	17.9M	70%
Emission level of hold for runway	0.4M	2%
Emission level of take off	1.7M	7%
Emission level of initial climb	3.4M	13%
Emission level of climb out	1.1M	5%
Total emission level for Departure	**23.1M**	
Total emission for Arrival and Departure	**41.4M**	
Total Emission level for Arrival		**44%**
Total emission level for Departure		**56%**
NOx		
Emission level circling	0	0%
Emission level of Approach	2.9M	77%
Emission level of Landing	0.09M	2%
Emission level of Taxi in	0.75M	15%
Total Emission level for Arrival	**3.7M**	
Emission level of taxi out	1.3M	7%
Emission level of hold for runway	0.03M	0%
Emission level of take off	5.3M	29%
Emission level of initial climb	6.3M	35%
Emission level of climb out	3.7M	20%
Total emission level for Departure	**16.8M**	
Total emission for Arrival and Departure	**20.5M**	

Total Emission level for Arrival		**18%**
Total emission level for Departure		**82%**
HC		
Emission level circling	0	0%
Emission level of Approach	0.8M	17%
Emission level of Landing	0.39M	8%
Emission level of Taxi in	3.8M	76%
Total Emission level for Arrival	**5.0M**	
Emission level of taxi out	5.7M	84%
Emission level of hold for runway	0.14M	2%
Emission level of take off	0.17M	2%
Emission level of initial climb	0.32M	5%
Emission level of climb out	0.09M	1%
Total emission level for Departure	**6.4M**	
Total emission for Arrival and Departure	**11.5M**	
Total Emission level for Arrival		**44%**
Total emission level for Departure		**56%**

Table 8: Waiting times in the mixed mode per aircraft at LHR with 3rd runway with daily traffic of 2,219 aircrafts at 98% of the available airport resource capacity

State per aircraft	**Mixed mode operation with a third runway(seconds)**
Average waiting time for runway 1 for circling	0
Average waiting time for runway 2 for circling	0
Average waiting time for runway 1 for takeoff(Hold)	33
Average waiting time for runway 3 for circling	0
Average waiting time for runway 2 for takeoff(Hold)	13
Average waiting time for runway 3 for Take-off	10
Total	**56**