Institution: University of Nottingham		
Unit of Assessment: 11		
Title of case study: Improving Operations at London Heathrow and Geneva Airports Through Modelling and Optimisation		
Period when the underpinning research was undertaken: 2004 - ongoing		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Jason Atkin	Associate Professor	2004 - ongoing
Period when the claimed impact occurred: August 2013 – December 2020/Ongoing		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Algorithms to predict Target Take Off Time (TTOT) and Target Start-Up Approval Time (TSAT), developed at the University of Nottingham, are in use at two international airports, London Heathrow, UK (LHR) and Geneva, Switzerland. Adoption of the University of Nottingham systems has improved operations at both airports and had environmental benefits. Following the implementation of the University of Nottingham systems in 2013 (LHR) and 2016 (Geneva), and prior to March 2020 and the COVID-19 pandemic, departure punctuality and predicted take-off time accuracy dramatically improved at both airports (at LHR TTOT accuracy has been reduced from an average of 8.7 minutes to 30 seconds per flight), in turn enhancing the efficiency of the control of airspace and facilitating faster recovery from disruption. Aircraft spend less time in the runway queue, in turn lowering fuel burn and associated emissions. For operations from London Heathrow, British Airways have estimated that this change saves them GBP2M in fuel each year, 16,000 tonnes of CO_2 emissions and 4,200 kg of SO_2. The University of Nottingham's TTOT and TSAT algorithms have enabled both airports to achieve compliance with Airport Collaborative Decision Making (A-CDM), a globally recognised standard for airports that aims to improve the efficiency and resilience of operations by optimising the use of resources and improving the predictability of air traffic. A key requirement of A-CDM is for airports to provide TTOTs for aircraft soon enough and accurately enough for this purpose. [redacted text].

2. Underpinning research

Research by Atkin and team in the School of Computer Science seeks to model airports in a realistic way, and to produce algorithms that can be used to improve operations. Airports have several computationally challenging problems to solve. For example, changing the runway sequence can greatly affect throughput, but is limited by the structure of the runway queues and/or taxiways. At LHR, there are multiple complex individual problems, such as runway sequencing and aircraft routing, but the combined problem is orders of magnitude more complex. By collaborating with the stakeholders and eventual users of the algorithms at the airports, Atkin and team have produced usable systems that provide huge cost, workload, and environmental benefits. The key findings from initial work were that a custom-designed solution method to re-sequence aircraft at the runway using state-of-the-art algorithms was able to find runway sequences that reduced queuing time by up to 40%, with search times that were fast enough for real-time use even with models that considered the full constraints rather than the usual academic simplifications **[1]**.

Further work helped to understand the system behaviour in a dynamic, uncertain environment **[2]**, studied the various constraints upon the system **[3]**, and the trade-offs between the various objectives, such as the delay for individual aircraft and the overall delay for all aircraft **[4]**.

Funding from National Air Traffic Services (NATS) **[9, 10]** allowed investigation into the feasibility of performing the runway sequencing operations at LHR with aircraft at the stands. Predicting delays in advance and holding aircraft on the stands for longer to absorb necessary delays before engines are started has consequent reductions in fuel consumption. The resulting algorithms predict Target Take Off Times (TTOTs) and allocate Target Start-Up Approval, or pushback times (TSATs), before aircraft leave the stands. Both are vital for decision makers at airports, airlines and managers of airspace.

Creating sufficiently detailed and realistic models of airports is vital, including the ways in which aircraft block and delay each other at the stands, as well as solving the runway-sequencing problem itself. The hybrid exact-heuristic algorithm developed to solve this problem was detailed, with an analysis of the effects of the various system parameters **[6]**. Comparisons between the new algorithms and the original system **[1-4]** predicted that the same delay reduction benefits were possible with both systems, but the new system allowed an additional 10-15% of delay to be absorbed at the stands **[5]**.

The benefits for Heathrow of the live system were evaluated in 2016, and NATS have continued to fund further research to enhance this system **[10]**. Additional research projects included the automation and integration of stand/gate allocation, ground movement, runway sequencing and resource allocation problems **[11, 12, 13]**. [redacted text].

Geneva Airport deals with fewer flights each day than Heathrow and aircraft are directly allocated to slots on the runway. However, as the situation evolves over time, with airlines constantly declaring the times at which new aircraft will be ready to set off, the system has to update decisions, handle problems, take the greatest advantage of the situation (e.g. filling any gaps which appear), and deal with any timeslot requirements which new aircraft may have. The aim is therefore the same, to predict TTOTs and allocate TSATs, but this time the focus is on fairness and transparency of decision making, with the take-off sequence and movement around the airport being comparably less important. All stakeholders (e.g. airlines and airport staff) have to understand why decisions are fair, and agree in advance to a set of rules that the system applies, for example, when is it permissible to change the planned times for an aircraft and how many times can these be changed. The design and requirements challenges which arose during our development of the resulting pre-departure sequencer (PDS) system for medium sized international airports are described in **[7]**. In 2016, our algorithms were incorporated into ADB Safegate's system at Geneva and are currently running live, improving airport efficiency.

3. References to the research

Publications:

[1] J.A.D. Atkin, E.K. Burke, J.S. Greenwood, D. Reeson, "Hybrid Metaheuristics to Aid Runway Scheduling at London Heathrow Airport", Transportation Science, Volume 41, Number 1, pages 90-106, 2007. DOI: 10.1287/trsc.1060.0163

[2] J.A.D. Atkin, E.K. Burke, J.S. Greenwood, D. Reeson, "On-line Decision Support for Take-off Runway Scheduling with Uncertain Taxi Times at London Heathrow Airport", Journal of Scheduling, Volume 11, Number 5, pages 323-346, 2008. DOI: 10.1007/s10951-008-0065-9

[3] J.A.D. Atkin, E.K. Burke, J.S. Greenwood, D. Reeson, "An examination of take-off scheduling constraints at London Heathrow Airport", Public Transport, Volume 1, Number 3, 169-187, 2009. DOI 10.1007/s12469-009-0011-z

[4] J.A.D. Atkin, E.K. Burke, J.S. Greenwood, "The TSAT Allocation System at London Heathrow: The Relationship Between Slot Compliance, Throughput and Equity", Public Transport, Volume 2, Number 3, 173-198, 2010. DOI: 10.1007/s12469-010-0029-2

[5] J.A.D. Atkin, E.K. Burke, J.S. Greenwood, "A comparison of two methods for reducing take-off delay at London Heathrow airport", Journal of Scheduling, Volume 14, Issue 5, 409-421, 2011. DOI: 10.1007/s10951-011-0228-y

[6] J.A.D. Atkin, Geert De Maere, Edmund K. Burke, J.S. Greenwood, "Addressing the Pushback Time Allocation Problem at Heathrow airport", Transportation Science, Volume 47, Number 4, 2013, DOI: 10.1287/trsc.1120.0446

[7] D. Karapetyan, J.A.D. Atkin, A.J. Parkes, J. Castro-Gutierrez, "Lessons from building an automated pre-departure sequencer for airports", Annals of Operations Research, Volume 252, Issue 2, 2017, DOI: 10.1007/s10479-015-1960-z

Grants:

[8] E.K.Burke: Hybrid Meta-heuristics for Air Traffic Control Scheduling. EPSRC GBP40,000, National Air Traffic Services Ltd GBP21,000. October 2003 to September 2006.

[9] E.K.Burke: Hybrid Metaheuristic Solutions for Runway Scheduling. NATS. [redacted text] January 2007 to March 2013.

[10] J.A.D. Atkin: TSAT Heathrow Tuning, NATS. [redacted text] December 2011 – ongoing.

[11] E.K.Burke: PLATFORM: Towards more general Optimisation/Search Systems, (GR/S70197/01). EPSRC GBP422,908. February 2004 to May 2009.
[12] E.K.Burke: SANDPIT: Integrating and Automating Airport Operations (EP/H004424/1). EPSRC GDP681,924, Manchester Airport plc GBP10,000, Zurich Airport GBP11,160. October 2009 to September 2013.
[13] U.Aickelin: The LANCS Initiative in Foundational Operational Research: Building Theory for Practice, (EP/F033214/1). EPSRC GBP1,988,920. November 2008 to November 2013.
[14] J.A.D. Atkin: Heathrow DMAN. NATS. [redacted text] From May 2016 - ongoing.

4. Details of the impact

Algorithms to predict TTOT and TSAT, developed at the University of Nottingham, have been fully implemented within sequencer systems at two international airports, London Heathrow, UK and Geneva, Switzerland. The adoption of the systems has improved operations at both airports and had environmental benefits because of reductions in fuel burn.

Airports are extremely complex and constrained environments, and therefore difficult to model, requiring bespoke solutions. London Heathrow is the busiest airport in Europe and the seventh busiest in the world based on passenger traffic. A standard sequencing system would not be suitable. [redacted text] Algorithms developed at the University of Nottingham were adopted by Heathrow in August 2013. These algorithms generate TTOTs and TSATs which then feed into Heathrow's Collaborative Decision Making (CDM) platform **[I]**. Final approval for live continuous use of the second system, at Geneva, was granted in 2016 **[H].** [redacted text].

Since implementation, Nottingham researchers have continued to work on developing and improving the Heathrow system. [redacted text].

Airport CDM (A-CDM) Compliance

Airport Collaborative Decision Making (A-CDM) is a globally recognised standard for airports that aims to improve the efficiency and resilience of operations by optimising the use of resources and improving the predictability of air traffic. A key requirement of A-CDM is for airports to provide TTOTs for aircraft soon enough and accurately enough to improve Air Traffic Flow and Capacity Management. A-CDM involves sharing information, predicting TTOTs, and determining pushback times for aircraft (TSATs), and then utilising this information to improve the efficiency of the airport, airline, and airspace. Implementation of the algorithms developed at the University of Nottingham has enabled both Heathrow and Geneva to obtain A-CDM compliance **[E, H]**. [redacted text]

The early benefits of A-CDM compliance for Heathrow and other airports (Geneva was not CDM compliant at the time of the evaluation, so was not included) were summarised in the 2016 Eurocontrol CDM report **[G]** that draws a direct link between the University of Nottingham research (the prediction of TTOTs and TSATs) and the benefits considered below. Importantly, the system is continuously being updated and improved, indicating that the 2016 assessment of benefit will be conservative. Although the situation has changed in 2020, with the reduction in air traffic because of the COVID-19 pandemic, the Heathrow system had been in operation for over 6 years by the start of 2020, and the Geneva system for over 3 years.

Given the complexity of the air transportation system, and the interactions between airports, airlines, and airspace, it can be hard to accurately measure the impact and importance of the benefits measured for Heathrow **[G]**. Eurocontrol attempted to quantify the potential economic benefit of A-CDM compliance for Heathrow and estimated the predicted financial saving to be EUR73.4M in the first year, then EUR65.8M/annum every year following **[F, p.54]**. [redacted text].

Improved punctuality

Departure punctuality for passengers was the single biggest component of the financial benefit of A-CDM predicted by Eurocontrol, assessed as contributing ~EUR40M/year of the ~EUR65M annual figure **[F, p.54]**. Before the implementation of A-CDM at Heathrow, punctuality was commonly below 50%. In 2019, in what was the busiest year on record, the airport achieved 78.5% departure punctuality.

Improved control and management of air traffic
Since embedding the University of Nottingham algorithms into their sequencing system, "*Take-off time accuracy* [at Heathrow] *has improved from an average of 8.7 minutes to 30 seconds per flight*" **[G, p.112]**. This is vital for enabling airspace improvements as Heathrow is a major contributor of air traffic into European airspace. TTOTs were not previously accurate enough in order to be able to plan for bottlenecks. The algorithms provide more accurate predictions of take-off times, leading to improved planning. In addition, at times of over-demand, airspace capacity is managed by applying take-off time timeslots (CTOTs) to aircraft on the ground. Meeting these is vital for efficient airspace sector planning and usage and the algorithms find sequences, which comply with CTOTs. "*CTOT compliance improved significantly throughout 2015 and is now consistently above 90% making LHR (London Heathrow) one of the airports with the best compliance in Europe*" **[G, p111]**. Eurocontrol quantified the predicted benefits to Air Traffic Control (ATC) of "*Fewer lost slots and over-deliveries*" to be EUR1.3M per year **[F, p.54]**.

Improved airport efficiency
"*The publication of the TSAT has helped partners to be aware of periods of delay and promotes a sense of equitability in resolving this situation*. *TSAT compliance requirements have continued to dissuade flights from early start-up requests and driven ATC attention to provide pushback authorisation within the TSAT window. The result of this has been a tightening of the start-up process and significantly improved awareness of both stand availability and asset / resource demand*" **[G, p.111]**. The validity of the generated TSATs is shown by the willingness and ability of airlines to adhere to them, with early start-up request behaviour "all but eliminated" **[G, p.18]** and "*improvement in TSAT adherence*" **[G, p.66]**. This ability to better utilise resources was key for the savings identified by Eurocontrol **[F]**.

Reduced fuel burn and decreased runway queuing time
One airline, British Airways (BA), used the TTOTs generated by the algorithm to implement single-engine taxiing, starting some engines later when known to be feasible. This was estimated to save them GBP2M in fuel each year, 16,000 tonnes of CO_2 emissions and 4,200 kg of SO_2 **[G, p.112]**. Extrapolating these figures for the 6 years that A-CDM has been in operation gives total savings to BA at Heathrow of > GBP12M, 96,000 tonnes of CO2 and 25,200 kg of SO2. Reducing emissions at Heathrow was a key initial driver for A-CDM: Heathrow have a commitment to a 10% reduction in the Airfield Carbon Footprint. "*The TSAT procedure has facilitated an optimised traffic mix at the runway which has resulted in record peak departure rates*" at Heathrow **[G, p.111]**.

TSAT/TTOT generation at Geneva has improved efficiency at the airport and had beneficial impact on the environment.

Improved recovery from disruption
When aircraft flow is disrupted it is important to get the backlog of aircraft off the ground as soon as possible, but optimal sequences can be difficult for humans to identify since there are many more options to consider. "*Since the implementation of A-CDM, LHR has also seen improved recovery rates from periods of disruptions and can now depart 60 aircraft an average of 20 minutes sooner than prior to implementation*" **[G, p.111]** "*This results in significant reductions to knock-on delay, flight cancellations and usage of the restricted noise and Night Jet Movement (NJM) quota*" **[G, p.21]**, also offering positive knock-on benefits for both passengers and those who live in close proximity to the airport, as well as the airlines operating from them.

5. Sources to corroborate the impact
[A] [redacted text]
[B] [redacted text]
[C] [redacted text]
[D] [redacted text]

[E] *Heathrow becomes 5th CDM Airport*, Eurocontrol press release. Available from http://www.eurocontrol.int/news/heathrow-becomes-5th-cdm-airport, accessed 2 December 2020 [PDF]

[F] *Airport CDM Cost Benefit Analysis*, Eurocontrol Report, 2005. Available from https://www.eurocontrol.int/publication/airport-cdm-cost-benefit-analysis-cba-report-2005, accessed 6 January 2021 [PDF]

[G] Eurocontrol, Airport *Collaborative Decision Making (A-CDM) Impact Assessment* (2016). Available at: https://www.eurocontrol.int/concept/airport-collaborative-decision-making, accessed 6 January 2021 [PDF]

[H] Geneva airport CDM web page. Available at https://www.gva.ch/en/desktopdefault.aspx/tabid-490/ , accessed 2 December 2020 [PDF]

[I] NATS web page explaining TSAT. Available at https://www.nats.aero/services/information/target-start-up-approval-time-tsat/, accessed 2 December 2020 [PDF]