Abstract—Air Traffic Managers increasingly need to consider environmental impacts when planning future operations or reviewing current procedures, particularly in relation to noise and emissions. In response to this need an environmentally aware Air Traffic Management (ATM) modelling tool has been designed and implemented in the context of the Environmentally Friendly Airport ATM Systems (EFAS) Project. This paper focuses specifically on the support environment provided by the ATM modelling tool and how it was used to inform the decision making process in an example case study examining the impact of various amounts of stacking on the environmental efficiency of Continuous Descent Approaches (CDAs).

It is found in a pessimistic scenario, (where no delay is absorbed ‘up-stream’), traffic arriving at a medium sized UK airport subjected to increasing traffic levels, (from 2004 out to 2030), experience exponentially growing stacks. In a 2015 timetable scenario, for example, stacks are found to generate approximately 11% more CO2 and 5% more NOx than top of descent CDAs alone. This finding underlines, from an environmental perspective, the need for the use of advanced ATM techniques such as Airborne Separation Assistance Systems (ASAS), Arrival Management tools (AMAN) and Collaborative Decision Making (CDM), to produce a set of efficient, de-conflicted, flight movements.

Keywords - Modelling, Stacking, Continuous Descent Approaches, Air Traffic Management, Environment, On demand delay.

I. INTRODUCTION

A. Background

NATS, the UK’s Air Navigation Service Provider, (ANSP), has forecasted that by 2015 its air traffic will have increased by 45%. Environmental impacts, if not addressed, will lead to unsustainable growth and constrain the development of airports. Consequently airport stakeholders need to make an informed exploration of the procedural and technological ATM options at their disposal to help the airport meet increasingly stringent environmental targets [1].

B. The challenge of developing Environmentally Friendly Airport ATM

It is the convergence of the air traffic network at its airports where some of the most intricate logic in ATM comes into play. This is true of how the traffic is managed and what metrics are used to measure its performance (principally the capacity it provides verses the emissions and noise it produces) [2].

One can develop hypotheses for reducing environmental impact but the testing and validation of these concepts is not always practical due to the cost, time and equipage issues involved. Therefore, when examining the impact of radical operational changes at a system wide level, (both for present and future scenarios), other methods are required to explore and rationalise the trade-offs involved. Computational models, (sometimes referred to as Synthetic Environments), are ideal for testing such hypotheses as they can realise the consequences of solutions without the cost of actual implementation. This helps to evaluate the properties or behavior of a potential solution, thereby allowing scenarios to be optimised to the requirements of the project. This process not only informs the planning and decision making process; it can also help to evolve the solution space itself.

II. THE EFAS PROJECT

The Environmentally Friendly Airport ATM Systems (EFAS) Project (see acknowledgments for details) identified a number of candidate ATM technologies and systems that were expected to reduce the environmental impact of the growth in air traffic. To assess the proposed operational improvements of these ‘solutions’ a modelling environment was developed.

The EFAS Model is a purpose built simulation environment designed to capture the environmental impact of an operational ATM system. It includes detailed information about aircraft movements, the noise they generate and the chemical emissions they produce. This environment is an integrated implementation of a bespoke trajectory model that utilises Eurocontrol’s BADA (Base of Aircraft Data) model 3.6 [3], the
FAA’s INM (Integrated Noise Model) 6.0 [4] and the QinetiQ Emission Model (the latter uses Boeing Fuel Flow Methodology and was previously used in [5]). Each ‘solution’ is assessed by modelling one or more scenarios. Each scenario represents a day of operations at a medium sized UK airport; it considers aircraft taxi, landing and take off (LTO) operations up to 20,000ft (although emissions calculations were capped at 10,000ft due to processing constraints). A scenario is defined by a number of configuration files, each describing an aspect of an ATM system. One such file is the arrivals timetable; one was created for each of the scenario years simulated (a busy day in 2004, 2010 and then out to 2030 in 5 year steps) by Cranfield University (see Fig. 1). Future aircraft types are mapped to existing types in BADA that had emissions and noise characteristics judged to be nearest. Linear reductions are applied to future aircraft type’s fuel burn and emissions to account for future aircraft type efficiencies.

![Figure 1. A number of scenario configuration files, with a preview of the arrival timetable configuration file.](image1)

Due to the processing power required to model a large number of scenarios, the EFAS Model is hosted at a QinetiQ data processing facility. As the facility is a shared resource, there were only a limited number of batch execution runs of the Model available to the EFAS project. Prior to a batch execution, each partner was invited to submit a collection of zip files to QinetiQ, with each file describing a model configuration designed to emulate a particular scenario.

Constructing scenarios is a complex and technical process, prone to error as it requires a high level of planning and forethought. As many of the configuration files are complex and dense, syntactical and semantic errors can be easily made. Without a tool to support the construction of scenarios any errors in configuration files will only be identified when the scenario is processed by the EFAS Model as they would result in execution failure. As use of the model is limited, such an execution failure is an undesirable waste of a limited resource.

Furthermore, as a large number of scenarios were planned for each batch execution (up to 100) transferring scenario zips between the EFAS consortium partners and the QinetiQ facility presented a technological and logistical challenge. This was further complicated due to the fact that once results were added to scenario zips the files became too large to email.

Therefore to overcome the problems discussed a scenario builder tool was developed to support the construction, submission and subsequent analysis of scenarios.

A. The EFAS Scenario Builder Tool

The Scenario Builder Tool enables the use of the EFAS Model using an access anywhere web-based interface. As the tool is web-based, it is platform independent, the user is not required to install any software and it could be securely accessed anywhere.

1) Scenario Construction

The user can create an unlimited number of scenarios using the tool. When first accessing the tool, the user is presented with a list of all existing scenarios and their current state, such as ‘Under construction’, ‘Ready for processing’ and ‘Results available’ (see Fig. 2).

![Figure 2. Scenario list filtered for batch run 3.](image2)

The tool allows a scenario to inherit all or part of its configuration from other scenarios built using the tool, encouraging reuse of configuration files between partners and ensuring maximum comparability between different scenario results. A number of default or ‘baseline’ scenarios were provided for each modelled day.

Configuration of a scenario is split into a number of functional sections, such as Airspace Design, Timetable & Aircraft, Airport & Weather, etc. For each individual configuration file the user can upload a custom version of the file, preview the file’s contents directly in the browser, use the default version of the file or inherit a version of the file from an existing scenario.

![Figure 3. Configuring a scenario.](image3)

1 Access to the tool required a username and password and all transmissions to and from the server were SSL encrypted.
Automated error checking validates a modelling scenario’s configuration for syntactic and semantic errors, ensuring that errors are caught at the development stage - before the modelling scenario is processed by the EFAS Model. Any errors are provided to the user in an easy to understand in-context manner, (see the red text in Fig. 3).

2) Job Submission

Once the construction of the scenario has been completed, the user can set the modelling scenario as ‘Ready to process’. The tool provides a facility to allow bulk download of all scenarios marked as ‘Ready to process’.

3) Result Delivery

When modelling results are available for one or more modelling scenarios, they can be uploaded to the Scenario Builder Tool. Results are then accessible through each modelling scenario’s ‘results’ tab (see the far right tab in Fig 3).

B. Scenario Assessment Lifecycle

The Scenario Assessment Lifecycle (Fig. 4) shows how the Scenario Builder Tool is used to analyse, assess and iteratively develop a solution in EFAS.

An example case study examining the impact of holding on Continuous Descent Approaches (CDA) that made full use of the Scenario Builder Tool is now illustrated.

III. EXAMPLE CASE STUDY: THE IMPACT OF AIRBORNE HOLDING ON CDA

A. The use of holding and path-stretching in ATM

Efficient airport ATM operations rely on the timely deployment of optimal aircraft operating principles during approach, landing, taxi, take off and departure. An efficient approach to landing is one that yields an effective loss of the aircraft’s potential energy as it descends without needing additional energy input, (e.g. to account for level segments or holding periods). This is achieved by managing its momentum from Top Of Descent (TOD), En-route or stack altitude such that the vertical and lateral speed of the aircraft as it is accepted onto the glide slope are optimised for the aircraft type to ensure a safe and efficient landing. In advancing aircraft operations towards this envisaged ‘optimal trajectory’ such concepts as Low Power/Low Drag (LPLD) and Continuous Descent Approaches have been conceived.

Application of LPLD principles seeks to minimise noise at the aircraft source by specifying the maintenance of a low thrust and low drag profile of the aircraft. The aircraft is maintained in the most aerodynamically ‘clean’ configuration for as long as operationally possible in the prevailing air traffic and meteorological environment. Ideally the aircraft minimises its air brake use and delays the deployment of both the flaps and landing gear until they are absolutely necessary for the safe energy management of the approach. By comparison a CDA minimises the periods of level flight while maintaining as close to thrust idle as possible. Unlike an LPLD approach a CDA specifies the nature of the vertical approach profile to be flown.

Due to safety considerations it is generally accepted that the aircraft must be established on the glide-slope in its final configuration for landing by 2000 ft Above Ground Level (AGL). After this point the aircraft is flown solely to capture the correct speed at touchdown.

However, busy airports operating at close to maximum capacity need to preserve flexibility in aircraft arrival times to accommodate wake vortex safety considerations and the permanently evolving nature of the Terminal Maneuvering Area (TMA) (e.g. meteorology, traffic etc). As such aircraft are not allowed to fly freely down their optimum descent path because the controller has to repeatedly intervene to appropriately space the traffic (e.g. by using ‘path-stretching’ techniques). Various projects around the world are attempting to find the correct balance between these two conflicting needs by utilising state-of-the-art technology [6][7][8].

The application of simple queuing theory to this problem dictates the necessity for airborne holding (currently stacks are used) from which the approach controller can select and vector into land in the optimum sequence. This method ensures that any slack in the system is immediately accounted for, however its use leads to inefficiency and environmental damage [9][10][11].
This case study aims to determine the impact of stacking upon the environmental efficiency of CDAs by exploring current and future scenarios where stacking is used; (a) to excess, (b) in moderation and (c) eliminated entirely in the EFAS model.

B. Scenario Building and Analysis

The scenario builder tool provided access to all of the parameters used as inputs into the simulation – as such it was used to modify the BADA configuration files to emulate the use of LPLD procedures as part of CDAs. Thus the scenario builder enabled maximum flexibility when constructing scenarios while still ensuring that the files submitted were fit for processing and offered maximum comparability with each other and their parent scenario.

Further, the scenario builder allowed the amount of delay introduced into the scenario to be varied by allowing the user to specify the maximum duration of delay that could be applied to any given flight. From this input the pre-processing feature of the tool produced a timetable that was modified to include this ‘on-demand’ delay. The revised timetable could then be reviewed online before submitting the scenario to the EFAS model. Users effectively controlled the amount of stacking within the scenarios by jointly manipulating this delay parameter with another controlling the threshold that determined when the delay held by a given aircraft required it to stack. The traffic handling logic dictated that the time spent by a given aircraft in the hold remained constant; the duration for which an aircraft was held for was exponentially related to the delay it possessed. In addition users effectively were able to control the amount of path-stretching activity within a scenario – it too being a function of the delay introduced.

1) Decision making

Initially the tool was used to build scenarios that compared the noise and emissions associated with stacking, path-stretching and TOD CDAs using LPLD settings (corresponding vertical profiles are shown in Fig. 5). Pre-processor parameters were manipulated firstly to reduce the total stacking duration in the baseline scenario (generated using relatively large airborne separation requirement assumptions) by approximately a half (a 54% reduction in duration was actually achieved) and secondly to eliminate it entirely.

2) Results

Reducing the amount of airborne delay in the EFAS model meant fewer aircraft flew the longer path-stretch routes on final approach - thereby concentrating the arrival noise contours over a smaller area, as shown in Fig. 6. If these path-stretch routes are to be used in combination with CDAs Standard Terminal Arrival Routes (STARs) with dynamic TOD points will need to be defined and used as part of routine operational procedures. The suitability of this mitigation technique will depend upon the geographical distribution of noise sensitive areas surrounding a given airport.

Figure 5. Vertical approach profiles (black reference line indicates the angle of a 3 degree approach).

As traffic levels increase in future years the time spent in the stack will grow exponentially (see Fig. 7). In reality it is unlikely that the two runway EFAS airport would operate with a total stacking duration longer than that used at major airports [12] as capacity is likely to have become saturated by this point. Consequently 2.0x10^5 seconds could be reasonably assumed as a maximum total stacking duration. Therefore the scenarios where the approach traffic stacks for a longer duration than this (i.e. 2025 & 2030 of the 100% stacking scenario and 2030 of the 54% stacking scenario, as shown in Fig. 7) represent a hypothetical case where;

- no delay is propagated upstream (e.g. through Eurocontrol Central Flow Management Unit imposed ground delays); and;
- traffic demand continues to grow as forecast beyond the capacity of the airport (in reality excessive stacking would reduce demand for slots at the airport).

Because random perturbations are not simulated in the EFAS model it is thought that we currently underestimate the amount of stacking likely to be already occurring in the earlier scenario years.

Figure 6. The final approach 57 Leaq noise contour in the 2030 scenario year. Blue contour is that generated with delay included in the model, red without. Screenshot taken from the ‘Route Builder’ visualisation tool built by David Atkins to support step 4 of the scenario assessment lifecycle.
Further, these results show that the amount of carbon dioxide generated during the approach is directly proportional to:

- the scenario year – reflecting the trade-off between increased traffic levels and the ‘cleaner’ aircraft types of future years (the rate of CO$_2$ emission production in the stack decreases by 91% from 54800 kg s$^{-1}$ in 2004 to 4460 kg s$^{-1}$ in 2030);
- the stacking duration (i.e. the length of time in mode); and;
- the number of aircraft entering the stack (i.e. the number of power-ups required to support level flight).

**TABLE I. INCREASE IN EMISSIONS DUE TO STACKING.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Full Stacking</th>
<th>54% reduction in stacking duration</th>
<th>No Stacking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Increase in Carbon Dioxide Emissions</td>
<td>% Increase in Nitrous Oxide Emissions</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>4.3</td>
<td>2.7</td>
<td>0.0</td>
</tr>
<tr>
<td>2015</td>
<td>11.1</td>
<td>7.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2030</td>
<td>30.9</td>
<td>20.9</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figures indicate the increase in emissions as a % of those generated solely by TOD CDAs.

Increased traffic levels will generate more emissions in the stack, (Ref. Table 1), without the introduction of new technologies and procedures. These will need to be capable of reducing excessive traffic demand at a particular airport (i.e. by managing peaks in traffic through flow management and strategic timetabling) and improving the logic used to handle the approaching traffic.

3) Implications for the ATM System

The results describe the need for an “environmentally friendly” ATM system to implement TOD CDA techniques at a system wide level. To meet this requirement advanced ATM is called for at both the strategic and tactical levels to create a set of efficient, de-conflicted, flight movements. Various ATM techniques that may be involved in the creation of such a set of movements are discussed in this section, primarily in the context of the airport and TMA environments. Further detailed investigation, modelling and validation of these concepts are required to establish their environmental performance.

A suite of tactical control tools will help to provide more certainty in the Required Time of Arrival (RTA) for the aircraft on approach, relative to each other. This could be deduced in a high traffic environment by the approach Air Traffic Control Officer (ATCO) utilising an Arrivals Manager (AMAN) software toolset. AMAN attempts to optimise the sequence of arrivals primarily by grouping aircraft of a similar weight together to minimise wake vortex separations. The longer the range of AMAN the more optimised the sequence becomes – principally through better planning and a more effective tailoring of the upper airspace arrival time. The end result of using the AMAN tool is the creation of a sequence (i.e. the attachment of a number to each inbound aircraft depending on their position in the queue to land). Once sequenced the controller then issues a set of clearances based on this information.

Secondly the short term assurance of adequate spacing between arriving aircraft can be maintained by tactical
Airborne Separation Assistance Systems (ASAS). This capability enables aircraft to maintain a relative spacing between each other in order to safely reduce the distances between arriving flights. It works by providing airborne surveillance assistance to the flight crew (thereby helping them to maintain the separation of their aircraft from others) and improving the situational awareness of the ATCO during the approach. This reduces the workloads of both Pilot and Controller while possibly allowing overall runway capacity to be improved. It is worth noting that various categories of ASAS application exist with varying degrees of responsibility placed on the flight crew (rather than the controller) to provide adequate spacing between their aircraft and the surrounding traffic. These concepts range from straightforward surveillance to operating high-density airspace without ground controllers. Most applications of airborne spacing in the descent are based on maintaining a fixed relative spacing in time, rather than in distance. Since the groundspeed reduces on the approach a fixed time spacing means that aircraft close up in distance as they descend.

ASAS is sufficiently flexible to allow its users to fly preferred pre-defined routes - such as those STARs that could facilitate CDAs or LPLD approaches. This particular functionality has been proven in the design of the CDA into UPS’s Hub in Louisville, Kentucky [13]. This places a requirement upon the aircraft’s ability to navigate along the STAR to within given navigational accuracies - such as those specified by Precision Radio Navigation (P-RNAV)\(^2\). A P-RNAV route is pre-programmed and controlled by, the Flight Management System (FMS) – the flight crew select the route upon receiving an appropriate clearance from Air Traffic Control. Strategic AMAN and tactical ASAS, underpinned by P-RNAV, provide different facets for the planning and accommodation of the arrivals sequence – their joint use provides optimal performance. The flexibility in the system is derived from the dynamic nature of the ASAS and AMAN systems which continually respond to the developing TMA situation in real time.

From a more strategic point of view stacking is essentially a manifestation of the inefficiency associated with the runway capacity bottleneck in the airport system. Effective ATM to overcome this challenge can be realised through flow management, ideally that made in a Collaborative Decision Making (CDM) – Network Operations Planning (NOP) environment supported by a System Wide Information Management (SWIM) infrastructure (as envisaged by the SESAR Concept of Operations [2]). Such a situation would allow detailed planning of flight operations both when drawing up timetables and imposing strategic control tactics, such as ground or En-route delays.

\(^2\) The ‘P-RNAV’ standard gives a lateral track keeping performance to within 1 NM (Nautical Mile) for 95% of the time. The Vertical Navigation ‘VNAV’ capability is optional for P-RNAV - the vertical profile may be flown either by pilots or automatic systems (the latter using approach specific information held in an on-board navigation database).

IV. CONCLUSIONS

This paper has shown how a web-based modelling support tool has supported the EFAS Project, reducing the risk of potential delays and ensuring that project partners utilise the EFAS ATM modelling tool to its maximum potential. In particular a case study has outlined how the tool was used to introduce different amounts of delay into scenarios exploring the impact of Stacking on TOD CDAs. The result of this modelling effort is the illustration of a function that describes how total stacking duration will grow exponentially with the increasing traffic levels of future years. The amount of CO\(_2\) generated in the stack is directly proportional to the stacking duration, the number of aircraft entering the stack and the scenario year. These findings highlight, from an environmental perspective, the importance of the technologies and procedures that will assist in minimising the amount of stacking in the air transport system of the future.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the EFAS Partners and the UK Government Technology Strategy Board in the production of this paper. The EFAS Project was launched in October 2005 and is due to run until early 2008, co-funded by the Technology Strategy Board (TSB) - a non-departmental public body sponsored by the UK Department for Innovation, Universities and Skills (DIUS). The Thales ATM-led consortium includes Helios Technology, Selex Sistemi Integrati, QinetiQ, NATS and BAE Systems from the private sector; Manchester Metropolitan University Centre for Air Transport and the Environment (CATE); and Loughborough University Systems Engineering Innovation Centre.

Particular thanks go to Professor Roy Kalawsky of Loughborough University for his support on the EFAS Project. Special mention must also go to Tomas Dyjas and Ben Stanley both of Helios for preparing Fig. 7 and for providing information on the role of ASAS & AMAN respectively.

REFERENCES

[2] “SESAR Definition Phase; Milestone 3”; SESAR Consortium for the SESAR Definition Phase Project co-funded by the European Commission and Eurocontrol, Doc. Ref. No. DLM-0612-001-02-00, Section 10.2.4 “Sustainability Assessment”, September 2007

