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Decision Support for Airport Surface Management and Control

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Continual increases in air traffic have threatened to produce gridlock in parts of the national aviation system (NAS). Efforts to improve NAS efficiency and throughput by incorporating decision support tools (DSTs) and other automation have been difficult because of NAS complexity and unpredictability. We describe some of the more important recent studies of airport surface management and offer suggestions for further improvement.

Objectives

Find ways to safely increase departure and arrival throughput at an airport, to reduce taxi times and to accommodate customer priorities and constraints. Design an airport departure management system that is resilient in the face of uncertainty about pushback times, taxi times, takeoff times and airspace constraints.

Background

Prior to airline deregulation and for a few years afterward, commercial air traffic in the U.S. National Airspace System (NAS) was relatively stable and the system itself operated reasonably well under the direction of highly experienced air traffic controllers and managers, even though the NAS was never funded well. All of this began to change as traffic increased in the face of lower prices. More aircraft were needed to accommodate ever-increasing numbers of passengers. Prior to September 11, 2001, traffic in the busiest terminal areas had become very heavy; arrival and to a lesser extent departure delays were rising toward intolerable levels, and the public and the U. S. Congress began to complain loudly about the inadequacy of the system. Older methods of air traffic and traffic flow management (TFM), the function which balances air traffic demand against available airspace capacity, were heavily taxed in the face of personnel shortages. The situation reached crisis levels during the summer of 2000, when traffic at the heaviest terminals became grossly overloaded and some of the most overloaded terminal areas, none designed for these traffic levels, approached gridlock.

A variety of flow control actions, such as weather avoidance routes, miles-in-trail flow restrictions, and ground delay programs were taken to ameliorate the en-route delays, but were only partially successful in handling the situations that arose. A major problem was, and is, the lack of predictability in both the en - route and terminal area systems. Since TFM decisions were typically made 30 minutes to several hours in advance of anticipated congestion, ATC and System Command Center traffic predictions were subject to significant uncertainty. The magnitude of the uncertainty was not known, presented or fully understood. As a result, TFM decisions were often overly conservative, and were often taken at inappropriate times based on the actual accuracy of prediction data" (1).

Maintaining a steady flow of traffic into the NAS from airports also requires predictions, on a shorter timeline, in order to make efficient use of airport and terminal area resources. "If a ramp administrator or controller pushes back several aircraft scheduled off the same runway and through the same departure gate, these aircraft are likely to end up adjacent in the departure queue. This could result in decreased runway throughput due to Air Traffic Control (ATC) departure spacing requirements", which depend on aircraft type and weight (2).

Terminal area and surface operations also present operators and managers with uncertainties.
Uncertainty about, among other things:

Both expected and unforeseen problems in preparing aircraft at gate (loading, fueling, late passengers, late crew transfer, mechanical problems, etc.)

Unavoidable problems during pushback (interfering aircraft or surface traffic, tug not available, flight documents late in arriving, etc.)

Unexpected problems during taxi-out (airport layout idiosyncrasies, need for deicing, congestion of taxiways, long runway queues, airspace congestion, blocked departure fixes, etc).

Unwanted problems at departure queues: (insufficient space to re-order departing aircraft, sequencing, ordering by weight classes, departure fixes, en-route issues, etc.)

Other problems before or at takeoff: (surface congestion due to arriving aircraft)

The need to accommodate airline and other operators' needs, priorities and preferences.

Issues

What is the net impact of this large number and variety of variables on our surface operations? What is the core problem, and how might we cope with it in real time?

The Cost of Surface Traffic Delays in Air Transport (3) In 2004, Departure/arrival delays of >15 minutes at 11 major European airports exceeded 15%.

Subsequent work by Eurocontrol showed that departure delays from London Heathrow Airport (LHR) were higher than at any other airport in Europe.

In summer 2004, British Airways' (BA) airborne holding just at LHR totaled 298,904 minutes. This is the equivalent of having three aircraft unavailable for the season.

BA's Air Traffic Flow Management arrival delays attributable to LHR amounted to 126,254 minutes, the equivalent of one permanently grounded aircraft.

On departure, aircraft ground movements delays at LHR amounted to 226,894 minutes (the equivalent of another "grounded" aircraft), mainly due to airfield congestion and layout problems.

Assuming approximately 100 passengers per LHR flight, total passenger delay minutes from airborne holding alone during summer 2004 amounted to 2,295 passenger delay hours per day—or 287 passengers holding for eight hours every day.

The Complexities of Surface Management Aids

Many investigators have attempted to get a handle on this very complex and challenging problem. Idris (4) modeled the movement of aircraft on the airport surface as a controlled queueing system and observed that aircraft queues are manifestations of flow constraints. "While runways, taxiways, ramps, gates, and air traffic control all contribute to departure delays, the largest queues and delays occur at the runways. Runway flow constraints are the result of the required minimum separation between departures, as well as downstream restrictions that propagate back to require additional inter-departure separation at the runway."

Atkins (5) noted that "These delays between consecutive departures may indicate an opportunity for automation to increase throughput." He proposed a new method for reconstructing the departure queues from available data. (This notion has motivated a good deal of research into Departure Management Systems.)

Pujet and colleagues (6) also observed that "in less than ideal weather, arrival and departure can be dramatically reduced … The reduced departure capacity can result in very long taxi-out times at peak hours, as the departing aircraft wait in a queue before being allowed to take off." They proposed and validated an input-output model of the current departure process … and used this model to estimate the feasibility and benefits of departure control mechanisms which aim at reducing departure queues in low visibility conditions. They observed that "in initial computer simulation tests, the heuristic departure slot allocation algorithm (they) described did not perform as well as the simple state-feedback gate holding control scheme" … in which aircraft are held at their gates whenever N becomes larger than a saturation value N_{sat} which typically corresponds to periods when the runway queue is not empty and thus when the runway is operating at maximum capacity (p. 13).

Departure Management

A number of authors have focused on pushback as a timed event at which delays can be minimized, reasoning that if departing aircraft can arrive at their departure queue at the exact time they are needed, queues, and thus delays, will be minimized. It should be noted that in the United States, push-back times have not been specified by Air Traffic Control, which takes over management of aircraft only at a specific location or "spot", where control is turned over to ATC by the operating air carrier. ATC has generally operated under a "first-come, first-served" heuristic which does not take account of aircraft weight, departure fix, or any of a number of other variables that can become important in expediting the departure process.

Carr (7) examined "best-case" errors in push-back forecasts under minimum uncertainty conditions (which had not been done previously) and tested several quantitative models for computing push-back forecasts against 3820 of 17,344 real-world ground operations over three months of Lufthansa flights through Frankfurt. The dataset contained detailed timing of all turn processes. He discussed important variables in the turn process in some detail (ch. 2).

Carr concluded that "Uncertainty in the airline turn process imposes limitations on pushback predictability, which in turn limits DST performance … The best-case standard deviation of forecast error for all of the forecast techniques was observed to be lower-bounded at roughly half (+/-5 min) of the average-case standard deviation derived in previous studies. Furthermore, this forecast error did not decrease until only a few minutes prior to pushback. … Due to these difficulties with delayed turns over a short horizon, it is necessary to build DSTs which *do not rely on predicted pushback times* for such turns." (p. 53)

It was observed that "current pushback forecast errors (on the order of +/-15 min.) cannot be reduced by a factor of more than 2 or 3. Furthermore, for each ground event, only 3 observations are necessary to achieve best-case performance: available time between actual on-blocks and scheduled off-blocks; the time until deboarding begins; and the time until boarding ends.

He observed further that "Any DST used in real-world operations must be robust to this 'noise floor'". "To support the development of robust DSTs, a unified framework called *ceno-scale modelling* is developed. This class of models encodes a wide range of observed delay mechanisms using *multi-resource synchronization* (MRS) feedback networks. A ceno-scale model instance is created for Newark International Airport, and the parameter sensitivity and model fidelity are tested against a detailed real-world dataset." (from author's abstract).

It is interesting to note that during his research at Newark, Carr observed "a fundamental control strategy" in place at Continental Airlines, a major user of that airport. This company, to assist ATC and minimize delays, "responded to severe downstream restrictions by pre-sequencing departing aircraft on the airport surface. This pre-sequencing strategy was conceptually simple: departing aircraft which needed to use the same downstream navigational departure fix were grouped together into separate queues. This allowed ATC to easily select aircraft to meet the availability of each fix. In contrast, the other airlines at EWR did not have the necessary space or infrastructure to pre-sequence or aggregate their departures. In that case, the departure at the head of a FIFO (first in, first out) buffer was often delayed waiting for its fix to become available, while several following aircraft in the same buffer which could have departed were unnecessarily delayed." (Carr, p. 91).

Strategies to Minimize Departure Delays

Anagnostakis and Clarke at the MIT ICAT (8) (2002) analyzed surface movements at several major airports and searched for strategies to mitigate departure delays. They introduced a "two-stage" optimization algorithm for solving the runway operations planning (ROP) problem to determine the optimal departure schedule. "The goal of runway operations planning is to generate a schedule of operations (arrivals, departures and crossings) that are as close to optimality as possible while taking into account uncertainties in pushback and taxi operations. Successful implementation of these optimal schedules will minimize departure inefficiencies related to such factors as wake vortices, downstream constraints, … workload limitations, and intersecting runways" (p. 2). They described and illustrated the two stages of their model using data from Boston's Logan Airport. The hypothesis motivating this study was that ROPs could be generated and used as a guide to create pushback plans (sequence and timing) in a way that enhances airport throughput and delay performance, even without managing aircraft taxi operations (from gates to runways) at a very detailed level (e.g., assigning intersection priorities) and without implementing sophisticated surface operations planning schemes (advanced taxi route planning).

This paper (9) is an excellent early (2000) discussion of a conceptual departure planning system. It outlines and illustrates the interaction between air carriers and ATC necessary to permit either manual or automated surface control of departing aircraft, and also the information required for mixing arrival and departure flows when this is necessary (p. 13-14).

As Anagnostakis et al. stated (in 9, abstract), "arrivals and departures are highly coupled processes, especially in terminal airspace, with complex interactions and sharing of the same airport resources between arrivals and departures in practically every important terminal area." Most of the alternative strategies for increasing departure throughput, as illustrated above, have focused on managing the pushback process, although this cannot be done efficiently without taking account of the gate resources needed for arriving aircraft, and the same taxi surface space must accommodate both departing and arriving aircraft for a period if their times overlap.

As shown by Carr, long-term prediction of ready-to-push time has been extremely difficult as well as imprecise. This has been a consistent message in many of these studies. What may be viable alternatives, given that some means of monitoring, directing and tracking departing aircraft is essential to minimize departure queues?

In 2000, Anagnostikos proposed (9) a "virtual queue manager" which "may be used to convert taxi delays to gate delays, which are less costly both for airlines and the environment" (p. 7, fig. 7). He also mentioned that the availability of CDM information has improved [the timeliness of] advanced cancellation notices appreciably. CDM is discussed below.

Resequencing of Departures before Takeoff

Jason Atkin and coworkers at the Faraday Centre and University of Nottingham did detailed studies of London Heathrow Airport. They noted that the unique shapes and locations of the departure holding areas at LHR required considerable planning by controllers to resequence departures. From Abstract: "At many airports the runway throughput is the bottleneck to the departure process and as such it is vital to schedule departures effectively and efficiently. For reasons of safety, separations need to be enforced between departing aircraft. … Departures from London Heathrow are subject to physical constraints that are not usually modeled in departure runway scheduling models. … We will show how these constraints have already been included in the model we present or can be included in future. … We propose a metaheuristic-based solution for determining good sequences of aircraft in order to aid the runway controller in this difficult and demanding task. Finally, some results are given to show the effectiveness of this system …" (10) Given the findings by many investigators that the most serious delays are at the runway waiting for takeoff, this approach, while airport-specific, would appear to be worth studying to ascertain its potential applicability to other airports where limited sequencing space is a problem.

The European Air Traffic Management organization, EUROCONTROL, has for over a decade been studying and developing ways to improve air traffic management. Though European ATC has been strictly aligned according to a "management by direction" paradigm (14), a number of papers from that area suggest rather strongly that this attitude is gradually changing. Some of the materials are from government and commercial organizations participating in developing and fielding advanced air traffic management systems; others are from some of the airports involved in bringing such management systems to fruition in day-to-day operations. It should be said that investigators in the United Kingdom, the U.S., the Netherlands and elsewhere have also been active in this area.

Integrated Departure Management Systems

The DLR Institute for Flight Guidance, in Braunschweig, Germany, working in cooperation with the DFS (the German Air Navigation Services provider) and various contractors, has worked very actively on aircraft management concepts for many years. The Institute has also worked in collaboration with the United States, Great Britain and Eurocontrol to develop automation that can help controllers with their very difficult tasks and to help relieve them of the ever-increasing volumes of traffic with which they are confronted in their work. A major figure in this work has been Deitmar Böhme, of that Institute. The following summary of the present status of the DLR work is based on a series of three presentations he and co-workers have made during 2003-2005.

Böhme's first paper (2003), *Optimal Runway Operations Planning* (ROP), (11), discusses the overall concept of ROP, the work then in progress, the building blocks of the planning algorithms, and the initial structure of a major planning module called DMAN, the departure planner. The initial operational concept for DMAN was developed by The Defence Evaluation and Research Agency in England. Eurocontrol had asked for a module that could provide planning of take-off operations and decisions for optimal runway allocations. DMAN was planned as a stand-alone demonstrator and pre-operational prototype and was tested by DLR alone and in combination with other service modules: A-SMGCS (an advanced Surface Movement Guidance and Control System), in the context of AATM (Airport Airside Traffic Management), and other tools under development. It was also scheduled for testing at Prague Airport, and at Frankfurt.

Dr. Böhme's second review paper, prepared with Eugène Tuinstra of the NLR, National Aerospace Laboratory of the Netherlands, *Tactical and Pre-Tactical Departure Planning* (12), was presented in 2005 at DLR. The purpose was to increase airport efficiency by implementation of decision support tools based on planning algorithms, some discussed in the earlier presentation. These DSTs by that time included:

AMAN, an arrival manager,
DMAN, the departure manager,
SMAN, a surface manager, and
GMAN, a stand and gate manager.

Collaborative Decision Making

A major purpose of these studies was to consider the Collaborative Decision Making (CDM) aspects, to involve all CDM partners, especially airlines and airports; to anticipate the future "airport situation", especially adverse conditions, to perform pre-departure planning to enhance network efficiency, to schedule operations depending on time, and finally to concentrate on departure management as a key process of Airport Traffic Management that needs to be supported urgently by tools. The paper discussed the optimization process: why, in particular, pre-tactical and tactical planning required decision support, then placed CDM and Departure Management in the larger context of ATC runway planning. It introduced a new tool, an Outbound Punctuality Sequencer (OPS), and showed certain features of its design. It pointed out that OPS minimized separation by optimizing the punctuality of *all* flights, thus increasing capacity; that OPS improved punctuality by CDM and preference functions, leading to enhanced predictability, and that the methods regulated queueing and taxi movements, leading to reduced controller workload. The paper went on to discuss the architecture of the Eurocontrol/DLR DMAN system and showed some of the planning constraints. It then presented some first results from real-time simulation trials of DMAN. As an instance, queue length with DMAN was decreased from approximately 7 aircraft to about 2 aircraft in a 70-minute simulation.

The authors concluded that in the Gate-to-Gate project, it was proved successfully that a considerable increase in efficiency of departure management could be achieved with both modules: RTS1: tactical DMAN, RTS2: pre-tactical DMAN. The modular TANDEM approach of a combined pre-tactical and tactical departure manager combines the desirable features of both approaches, i.e.:

the CDM capability of a pre-tactical planner (extended planning horizon; incorporation of pre-departure planning of airlines, airport and ATC), as well as

the tactical support of ATC to establish optimal departure schedules in a highly dynamic environment with many unforeseen events.

The modular TANDEM approach afforded a stepwise implementation of the modules.

The coordination principles allow:

A silent hand-over from pre-tactical to tactical (without additional communication effort), and

Variation of the strength of coupling due to the demands of the actual traffic situation.

The authors suggested that a quantitative estimation of benefits and evaluation of performance and quality measures need further investigations and extended real-time simulations.

The third presentation by Dr. Böhme, also in 2005, was titled *Airport CDM: The Contribution of the XMAN Approach* (13). (“XMAN” refers to the entire suite of tools comprising the Departure Planning Process: AMAN arrival manager, DMAN departure manager, TMAN turn-around manager, each fully developed and implemented, and SMAN, the surface manager, which is partly developed.) The author offers the following objectives: an increase in punctuality (target off-block time), an increase in predictability and an increase in efficiency in terms of airport resources and network capacity. The partners in this collaborative approach are airport operators, aircraft operators, ground handlers, the air navigation service provider (ANSP), the Central Flow Management Unit (CFMU), a part of ATC, and support services, all linked by CDM. The elements of the CDM-A (advanced) program include airport CDM information sharing, turn-around process, variable taxi time calculation, collaborative management of flight updates, a collaborative pre-departure sequence, and CDM in adverse conditions to anticipate delay situations and apply strategies to facilitate a quick return to normal operations.

The XMAN approach: automated use of tools to assist controllers in planning and tactical decision making, is a major tool in these processes. Böhme presents some general principles for planning of consecutive operations: backward propagation of target times, forward estimation of the first, or earliest, times of events and a warning that every planned target time must never be smaller than the corresponding predicted earliest time.

Finally, Böhme discusses the incorporation of aircraft priorities of the airline/airport and suggests how these priorities can be incorporated as preferences in the planning process.

He concludes that CDM and XMAN are not competitive, but mutually supporting concepts. He notes that XMAN planning tools can provide quantitative measures of accuracy (predictability, reliability) as on-time information. More reliable planning information will support both intra-airport CDM and inter-airport CDM through improved coordination among the participants in these processes.

Coordinated planning tools have the potential to provide techniques, with whose help airline/airport preferences can be taken into account without disadvantageous side-effects such as the need for additional communication, the risk of inconsistent constraints, the risk of a substantial loss of overall efficiency, or disturbances and complication of the management tasks of ATC.

The latest, but perhaps the most essential, project in the XMAN approach is called *collaborative decision making*, and its essence is to facilitate the transmission, storing and retrieval of data necessary to the departure (or arrival) processes. This very complex, dynamic, distributed system is information-bound. The output of the system is decisions, and the input necessary to arrive at consistently good decisions is information—about state, status, intentions, problems—all of the information that will permit the next person or facility handling a given aircraft to do so with full knowledge of those parts of the system which may impact that aircraft's ability to continue its progress.

Summary and Conclusions

Information and knowledge are the commodities that have been most lacking in aviation's past. The system has in a few years gone from one in which a good deal of experience and intuition was necessary for effective functioning to one in which our communications devices, databases and dynamic changes in system state and function can easily drown even a capable operator in data and information. Herein lies a major human factors opportunity, for we know how to assist our operators in the task of assimilating the information if we take maximum advantage of the capabilities of CDM and provide assistance to those who are designing the displays, decision aids, and human-machine interfaces that will be needed to take full advantage of this opportunity.

Dr. Böhme is not the only investigator in this field to have realized the critical need to make all of the players active participants in the production process. But the concept of a system of systems (XMAN) anchored by a sound, real-time medium for communication of all necessary information among participants, (A-CDM), is relatively new and very promising. Whether this concept will suffice to help us understand and solve the difficult problem of optimizing departures in this heavily loaded air transport system is not really foreseeable yet, but it seems clear that without this communications platform to link the parts of this complex of tasks, we are most unlikely to solve the problems that gave rise to this paper and to the large body of research in this field.

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