Distributed Schemes for Integrated Arrival Departure and Surface Scheduling

Literature Review of Past and Current Approaches to Integrating Arrival Departure and Surface Scheduling

Author:

Husni Idris

NASA Technical Monitor:

Shannon Zelinsky

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Prepared For:

NASA Ames Research Center
Moffett Field, CA 94035-1000

Prepared By:

900 Technology Park Drive, Suite 201
Billerica, MA 01821

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Preface

This document is a literature review covering past and current approaches to integrating the scheduling of arrival, departure, and surface operations. This document was prepared by Engility Corporation, 900 Technology Park Drive, Suite 201, Billerica, MA, under NASA Research Announcement (NRA) Contract Number NNA14AB46C. It represents the deliverable "Report on the literature review/assessment of past analyses relevant to centralized and distributed integrated arrival departure and surface scheduling" for the NRA titled "Distributed Schemes for Integrating Arrival Departure and Surface Scheduling"

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Introduction

As the traffic congestion in the National Airspace System (NAS) increases, the interaction between the different traffic flows which compete for limited resources increases. This interaction is more pronounced at and around airports, where arrival and departure flows often intersect in the terminal airspace and on the airport surface. While the norm in managing these flows has been to segregate them procedurally, the increase in demand and congestion is necessitating more sharing of limited resources such as the runways and increasingly the airspace fixes and routes. Hence, there is an increased need for traffic management solutions that integrate these arrival, departure, and surface operations.

This research effort, entitled “Distributed Schemes for Arrival Departure and Surface Scheduling”, will attempt to identify solutions for integrating the scheduling of arrival, departure, and surface operations in one airport and in metroplex systems. As a first step, this document describes a literature review of past and current approaches to this problem and an analysis to highlight their advantages and disadvantages.

The document is divided into two main parts. The first part describes the issues related to the interaction between arrivals and departures in current operations and the current state of the art of addressing these issues. The second part presents an analysis of the approaches that were identified in the literature which propose to tackle some of the issues related to the interaction between arrivals and departures. While there are many approaches in the literature that focused on either arrivals or departures and on one component of the airport system such as the airspace or the runways, the in-depth literature review covered only the approaches that attempted to integrate between arrivals and departures at least to a certain extent. These approaches are briefly summarized, critiqued, and compared against a number of criteria to highlight their advantages and disadvantages.

Current state of the art for arrival-departure integration

In order to simplify the presentation, the description of the current state is organized in three sections corresponding to three components of the airport system: (1) terminal airspace, (2) runways, (3) airport surface including the taxiways and ramp. These subsystems are highlighted on a schematic of an airport system in Figure 1 showing the flow of arrivals and departures around an airport system. In each of the components, the issues related to the interaction between arrivals and departures in current operations are described, along with the current approaches to manage them, including some examples of NextGen plans.

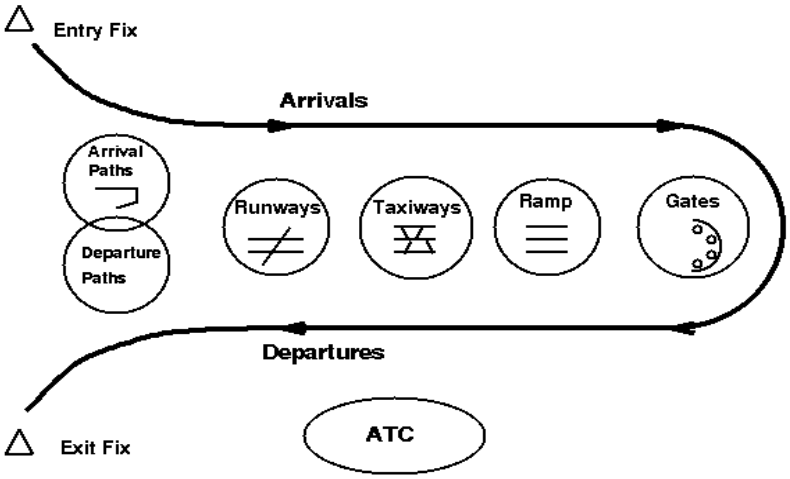

Figure 1. The airport system

The arrival-departure integration related issues in current operations were identified based on a limited number of resources, namely: issues described and tackled in the literature, recent and past site visits, and consultation with subject matter experts (SMEs). The issue identification is an ongoing exercise and will be continued in support of the selection of real world problems for analysis. The selection of real world problems will include additional SME feedback, and hence, will probably add to and refine the list of issues identified in this report. However, this list of issues will serve as a starting point and will be circulated to SMEs for feedback and for input about specific real world examples where the important issues manifest.

Terminal Airspace

The terminal airspace includes the airspace resources (fixes and routes) between the runways and the arrival and departure fixes. Historically, procedures ensured the segregation of arrival and departure flows in this environment. However, interactions are increasing with the increased traffic. Often, these interactions involve arrivals and departures of airports in close proximity in metroplex systems.

Arrival-departure related issues

The main issues that were identified form the site visits and from the literature include:

- Metering of arrival flows from the cruise and top of descent to match the runway acceptance rate.
- Merging multiple arrival streams into the approach paths.

- Merging the departure flows into the overhead stream.
- Merging departures from multiple airports into common fixes.
- Maintaining continuous descent and uninterrupted climb.
- Separating arrivals and departures at intersection points without leveling off.
- Lack of sufficient routes for arrivals and departures.
- Lack of sharing of resources (fixes and routes) between arrivals and departures.

Current approaches for mitigating arrival-departure interactions

The traffic management approaches in current operations have focused on either arrivals or departures in this environment and little on their interaction.

Time based metering (TBFM), using the traffic management advisor (TMA) and its extensions, has been deployed and used at most centers. It has limited capability to schedule departures into the arrival stream using the departure clearance capability. The FAA is currently extending TMA in a number of ways that integrate departures [1]:

(1) Information sharing will allow other NAS systems such as surface automation and users such as airlines to know the scheduled arrival and departure times. This will open many opportunities for collaborative and distributed schemes for metering and scheduling.
(2) The integrated arrival departure capability (IDAC) will be implemented in TBFM work package 2, which will automate the process of releasing departures into a gap in an overhead stream. This capability will be enabled by extending the time based metering further upstream from the airport, resulting in point is space metering. Tower controllers will be provided with a list of possible departure times to chose from and information about the congestion at the meter point.
(3) NASA's Precision Departure Release Capability (PDRC) will be integrated in work package 3. PDRC adds better takeoff time prediction based on surface trajectory modeling [2-3]. PDRC uses high fidelity trajectory predictions to calculate the takeoff times and the times at the metering point. It computes the takeoff time by dividing the trajectory between the merge point and the push back into two portions. The airborne part is calculated using TMA's trajectory prediction that models the ascent using the performance of the aircraft. The takeoff time is calculated using a surveillance system and air carrier data of push back. The ground segment of the trajectory is calculated by the Surface Management System (SMS). PDRC prioritizes flights based on the aircraft being airborne or on the ground, and where in the airborne or ground phase it is. It assigns release times in the form of a schedule presented to the tower controller.

Runway system

The runway system includes the multiple runways at an airport which may be crossing runways or closely spaced runways such that their flows need to be coordinated.

Arrival-departure related issues

The main issues that were identified form the site visits and from the literature include:

- Balancing of the runway usage between arrivals and departures to match the demand.
- Sequencing of arrivals and departures to maximize throughput and accommodate user concerns.
- Making sufficient gaps between arrivals to insert departures, both to maintain throughput and for departures with particular gap requirements.
- Change in runway assignment to accommodate runway balancing, flow of traffic, and specific flight concerns such as location of gate.
- Lack of accuracy in shooting gaps between arrivals or departures on closely spaced or crossing runways.
- Arrivals crossing of departure runways while taxiing leading to interruption in the departure flow and adding to the arrival taxi delays.
- Conforming to restrictions on the takeoff time.

Current approaches for mitigating arrival-departure interactions

There has been large improvement in the sharing of situation awareness between the Tower and the TRACON through the display of surface surveillance information (for example ASDE-X) to the TRACON and electronic flight information. However, this information has not been utilized explicitly in the automation of runway scheduling of arrivals and departures. The coordination of the runway use continues to be mostly manual. Traffic management coordinators use demand lists to make decisions about favoring arrivals or departures in the runway usage. For example, at ATL runway 28 is often shifted between arrivals or departures to match the demand. Controllers coordinate the gaps needed between arrivals to accommodate departures, which is dependent on the human performance. As pointed out in a site visit to ATL, when a runway is shared between arrivals and departure, a Tower controller may ask for 4 nautical mile gaps between arrivals while another may ask for five or six.

In the near future, NextGen will adopt technologies for runway arrival scheduling and for runway departure scheduling, without integration. For example, NASA's Terminal Area Precision Scheduling and Spacing (TAPSS) extends the TMA scheduling algorithms to the runway and provides decision support to the TRACON controllers, in the form of slot markers and speed advisories, to achieve the desired arrival schedule [4-5]. TAPSS arrival sequencing uses an extended TMA algorithm, which is based on first come first serve while satisfying the minimum separation requirements with an additional safety buffer. NASA's Spot and Runway Departure Advisor (SARDA) includes an algorithm for optimal runway departure sequencing which incorporates runway crossings but assumes that the arrival schedule is given [6-7]. SARDA's runway sequencing algorithm uses a mixed integer linear program (MILP) formulation. Both algorithms include runway assignment.

Taxiway/Ramp

The taxiway and ramp are discussed as one component for simplicity.

Arrival-departure related issues

The main issues that were identified form the site visits and from the literature include:

- Long departure queues leading to congestion on the surface with unnecessary fuel burn and emissions.
- Limited flexibility to sequence departures for optimal runway throughput.
- Delayed accommodation of restrictions until aircraft are in the queue, resulting in disruption of operations and excessive wait while passengers are on board.
- Excessive taxi between the assigned runway and the gate location.
- Blockage of taxi segments and ramp entry points with departures waiting to taxi.
- Blocking of pushback due to sharing of ramp space.
- Blockage of arrival gates by late departures occupying the gate.
- Lack of gate resources to accommodate metering of departures by holding at gates.
- High uncertainty in the turn around operations and lack of information sharing between users and service providers.

Current approaches for mitigating arrival-departure interaction

As in the runway system, the increased surveillance information (for example ASDE-X), while increased situation awareness, has not been used explicitly for optimizing taxi operations. NextGen includes in its vision decision support tools for taxi routing and taxi congestion management. Most of the research has focused on congestion management for departure operations. Congestion management through departure metering at the gate or ramp was operational at JFK with demonstrated benefits in terms of taxi time savings [8]. SARDA includes a component to compute spot and gate release times that meet the assigned runway time for each flight, while maintaining a small queue at the runway end. Collaborative departure queue management (CDQM) is another concept that assigns to each airline a number of slots in time windows, which they can use to introduce flights into the movement area. The slots are computed such that a small queue is maintained at the runway end, using a time delay indication of the queue [9]. The N-control strategy uses a queue length that is determined based on a runway throughput saturation model [10].

Detailed review of arrival-departure scheduling Approaches

Because the management of the traffic of an airport system has been performed to a large extent by segregating the arrival and departure flows procedurally, the literature has mainly focused on managing arrivals or managing departures, as was mentioned in some of the examples in the previous section. The attention to the integration between the two has emerged in recent research motivated by the increased interaction between arrivals and departures in operations, and hence the increased need to address their integration. The integration between arrivals and departures brings about different characteristics of the problem, which renders many of the approaches that have been developed for either problem non applicable without major changes. The recent integrated approaches deal mainly with such modifications and extensions to the earlier approaches to accommodate the integrated problem. Hence this detailed literature review did not cover the approaches that focused on either arrivals or departures without a certain level of integration.

There are also efforts that focused on the more strategic function of runway configuration management or the more tactical function of controlling aircraft trajectories and maneuvers for conflict detection and resolution and conformance to the schedule. These efforts are also not detailed in this review because they are considered out of the scope of the intended research. These efforts however, will be reviewed and consulted for interactions with the arrival, departure, and surface scheduling problem in this project.

Twenty approaches that addressed the integration of arrival, departure and surface scheduling have been identified in the literature. An approach may be represented by multiple papers that reported incremental changes to the same approach. They are summarized in Appendix A in a table format for each group of papers that constituted an approach. A key word (referring to one or more of the authors) is given in the top row along with the list of references. Each approach is critiqued on the following elements.

1. Problems Tackled: A description of the problems tackled in the paper, related to arrival-departure integration.
2. System: The system components that the work focused on such as taxiways, runways, or airspace and the degree of integration between these components and with other systems such as the en route phase of flight or strategic configuration change.
3. Flows: Although all the papers presented here had some aspect of integrating arrivals and departures, in some cases this level of integration is described if needed.

4. Algorithm: Description of the algorithmic approach to modeling the problem and searching for solutions.
5. Objectives: The objectives that were considered in the work, for example, reducing delay, reducing fuel burn, including user concerns such as airline schedules, passenger concerns, and controller workload.
6. Realism: The degree of simplification of the models used in the work. For example, using hypothetical or real-world problems, small scale or large scale networks, real data or fictitious data.
7. Uncertainty: Did the work use deterministic or stochastic modeling.
8. Dynamic: Describes if the work used static or dynamic planning.
9. Distributed: Was approach centralized or used distributed agents, and the nature of the agents.
10. Computation: Did the work deal with computational issues and how effectively. It is difficult to compare the computational load of different approaches because of the variation in problem size, and the software and hardware used. In general, if a typical problem was performed in seconds it was termed as good, if in minutes it was termed as fair and if in hours it was termed as low.
11. Maturity: Was the work mature, for example, was it tested in the lab or in the field and did it result in demonstrable feasibility and benefits. In this analysis the maturity is considered low for any work that was not applied in human in the loop (HITL) simulation, and medium if it was demonstrated in HITL simulation but needs refinement and high only if it was acceptable in the demonstrations.
12. Key results: Some of the work's conclusions if relevant.

Based on the detailed summaries in Appendix A, Table 1 provides a comparison of the approaches with respect to the criteria just outlined. In the first column of the table the keyword used in Appendix A for each approach is used. Following the table a discussion of the main observations under each criterion is given.

Table 1. Comparison of twenty approaches to arrival-departure-surface scheduling

Approach	Problem	System	Flow	Objective	Search	Distrb	Matrty	Uncrty	Dyn	Real	Cmptn
Xue	Scheduling & routing	Runway to fix	Arr/Dep	Delay & workload	GA	Central	Low	Buffers	Yes	Good	Good
Balakrishnan	Scheduling	Runway	Arr/Dep	Thruput	DP w/ CPS	Central	Low	Det	No	Fair	Fair
Zhao	Scheduling & routing	Gate to fix	Arr/Dep	Delay	MILP	Central	Low	Det	Yes	Fair	Fair
Capozzi	Scheduling & routing	Runway to fix / Metro	Arr/Dep	Delay	MILP	Central	Low	Det	No	Fair	Good
Wieland	Scheduling & routing	Gate to fix / Metro	Arr/Dep	Delay	MILP	Airport agents	Low	Det	Yes	Fair	N/A
Bertsimas	Scheduling & routing	Gate to fix	Arr/Dep	Delay	MILP	Central	Low	Det	No	Fair	Fair
Kim/Clarke	Scheduling & routing	Runway to fix	Arr/Dep	Delay & fuel burn	MILP	Central	Low	Det	Yes	Fair	N/A
Solveling / Clarke	Scheduling	Runway	Arr/Dep	Thruput, delay and schedule	MILP	Central	Low	SAA	Yes	Fair	Low
Durand	Scheduling & routing	Gate to Runway	Arr/Dep	Delay	Branch & bound and GA	Runway /surface agents	Low	Yes	Yes	Fair	Fair
Piera	Scheduling	Runway	Arr/Dep	Thruput	Petri Net	Sub-networks	Low	Det	Yes	Fair	N/A
Hwang	Scheduling	Runway	Arr/Dep	Thruput	Branch & bound	Central	Low	Det	No	Fair	Good

Saraf/Sawhill	Scheduling & routing	Gate to fix / Metro	Arr/Dep	Flight time, fuel	GA	Agent based	Low	Baysion Belief	Yes	Fair	Low
Yoo **&** Lee	Scheduling	Runway	Arr/Dep	Delay	FCFS	Central	Medium	Buffers	Yes	Good	Good
Bosson	Scheduling & routing	Runway to fix	Arr/Dep	Total/flight delay	MILP	Central	Low	SAA	No	Good	Fair
Montoya	Scheduling	Gate to runway	Arr/Dep	Delay or thruput	DP w/ & w/out CPS	Central	Low	Det	No	Fair	Good
Hancer - liogullari	Scheduling	Runway	Arr/Dep	Delay	SA	Central	Low	Det	No	Fair	Good
Clare	Sceduling & routing	Gate to runway	Arr/Dep	Delay & distance	MILP	Central	Low	Det	Yes	Fair	Good
Bianco	Scheduling	Runway to fix	Arr/Dep	Delay or thruput	Local search heuristic	Central	Low	Det	Yes	Fair	N/A
Chevalley	Scheduling & routing	Runway to fix	Arr/Dep	Delay & fuel	FCFS	Central	Med	Buffers	Yes	Good	Good
Diffenderfer	Scheduling	Runway	Arr/Dep	Delay	FCFS	Central	Medium	Buffers	Yes	Good	Good

Some abbreviations in Table 1:

Dep = Departure	CPS = Constrained Position Shift	SAA = Sampling average approximation
Arr = Arrival	Metro = Metroplex	N/A = not available
Det = Deterministic	SA = Simulated annealing	FCFS = First come first served
DP = Dynamic Programming	Distrb = Distributed	
MILP = Mixed Integer Linear Program	Matrty = Maturity	
GA = Genetic Algorithm	Uncrty = Uncertainty	
Dep = Departure	Dyn = Dynamic	
Arr = Arrival	Cmptn = Computation	

The following general observations are made for each of the criteria used to compare the approaches to integrating arrival, departure and surface scheduling.

Issues/problems tackled

Some of the issues that were tackled by the approaches identified include:

(1) Increasing the efficiency in using the airspace resources by allowing sharing resources with temporal separation in addition to spatial segregation [Xue, Bosson, Cappozzi, Chevalley]
(2) Providing multiple route options for arrivals and departures to increase flexibility and efficiency [Xue, Bosson]
(3) Providing more route options for departures to increase the flexibility in hitting gaps in an arrival stream or for coordinating departures into a common fix [Chevalley]
(4) Enabling the continuous descent and ascent at the shared resources by temporal separation [Xue, Bosson] and decision aid [Chevalley]
(5) Integrating the scheduling of the airspace fixes/routes with the scheduling of the runway [Bosson, Bianco, Zhao, Capozzi]
(6) Modifying the arrival schedule to close unnecessary gaps and to create gaps to accommodate departures, improving the utilization of the runway [Yoo/Lee, Deffenderfer].
(7) Optimizing the runway utilization
(8) Ensuring feasibility of the runway schedule based on taxi constraints [Wieland, Clare, Durand].
(9) Managing surface congestion (for example gate hold) in an integrated manner with runway sequencing [Durand, Bertsimas, Clare, Montoya]

Some effort [Chevalley, Deffenderfer, Yoo/Lee] focused more on a near-term concept for the scheduling of the arrivals and departures (using IDAC type system) which is coordinated between the TRACON and Tower TMC's in a HITL experiment. The other efforts focused on an optimization approach to the scheduling of arrivals and departures at the shared resources along with the selection of routes.

Some of the issues identified by Chevalley in dealing with uncertainty are noteworthy. In their first experiment, the controllers were allowed to vector a departure to meet the gap in the arrivals stream and continue climbing. This capability was removed in a follow on experiment in order to assess the effect of decision aids to meet the gap. The controllers lost the vectoring flexibility and were less able to meet the gaps. As a result, the team designed a flexible set of route options that added the flexibility to meet the gap and avoided the need for vectoring. The added flexibility was useful; however, a discrepancy with the nominal route and its scheduled time of arrival was introduced because of the path extension associated with the route options.

This issue points to the need to maintain flexibility in the nominal route itself and not only in the control maneuvers and to the need for consistency in the flexibility provided by the higher level scheduling and the lower level control.

Another issue was addressed by Kim et. al. is the gate assignment problem, where three metrics were optimized in a Tabu search: passenger transit time between gates, taxi delay between the gate and the spot, and gate schedule robustness [11]. Robustness was defined as the duration of gate conflicts, where an arrival finds a gate occupied by a departure. They showed significant reduction in passenger transit time, taxi delay, and waiting for gate conflicts (by arrivals). They did not consider interactions with the rest of the airport system. This paper is not detailed in Appendix A for comparison with the other approaches.

Integration between system components

Most approaches focused on integrating arrivals and departures at the runway as evident in Table 1. Some approaches attempted to integrate the scheduling of arrivals and departures at airspace resources with the scheduling at the runway [Bosson, Bianco, Capozzi], while some approaches extended the runway scheduling to the surface scheduling and metering [Durand, Clare, Montoya]. Some approaches also included the whole system from the airspace and including the surface network up to the gates [Zhao, Bertsimas]. Bertsimas attempted to integrate the scheduling of the runway, airspace and surface resources with the runway configuration management problem. Some of the scheduling and routing algorithms used the taxi routing as a feasibility test for the runway schedule [Weiland, Bertsimas, Clare].

One observation is that integration with the outside system was non-existent (except through departure restriction constraints on runway scheduling). Most efforts considered the system bounded by the gates and the TRACON entry and exit points and attempted to reduce the time of transitioning through it. There was no consideration, for example, of the turn around process where arrivals turn into departures, except in an isolated manner by [11] in a gate assignment problem or to model uncertainty [Saraf/Sawhill].

Algorithms

While the approaches used a variety of algorithms, one observation is the trend towards dividing the problem into stages for tractability [Solveling, Bosson, Bertsimas, Capozzi]. This was motivated mainly by computational tractability, but also justified from an operational point of view. For example, since the runway throughput depends on aircraft type, a common first stage is to determine an optimal aircraft type sequence and a second stage would assign flights to the sequence by matching their type.

Another observed trend is the use of genetic algorithms, seemingly as a favorite approach both from a computational perspective and due to its ability to combine well with other methods such as linear programming [Capozzi] and branch and bound [Durand].

Objectives

The main objectives that were observed in the approaches are:

1. Increasing utilization (minimizing makespan)
2. Reducing delay and time spent within the system
3. Reducing deviation from scheduled runway times. This is the extent of incorporating user concerns that was observed.
4. Minimizing fuel and emission cost.
5. Minimizing workload represented by controller interventions to maintain separation.

None of the approaches considered impacts outside of the airport system such as the impact on the aircraft remaining route and time of flight after exiting the airport system as a result of the actions taken within the system. Deviation from the schedule is one way to measure the overall impact on users.

Constraints

Most constraints were common among the approaches albeit were modeled with different levels of details and realism. Constraints included always the minimum separation requirements. The studies that conducted HITL simulations [Chevalley] went to a great length to produce separation requirements as practiced in the field. This exercise points out the importance of the realism of the simplifications that the scheduling optimization algorithms make. The optimization methods report benefits relative a FCFS strategy that applies the same separation constraints as the automation. Validating against actual performance is almost always avoided because of the difficulty to duplicate the real behavior or isolate out non-relevant effects from the real data. While this is justified, it is often the case that air traffic controllers would perform better than the automation unless the automation makes accurate assumptions about the constraints. It is evident that the research efforts have been increasing the fidelity in modeling the constraints by for example accounting for more aircraft classifications, equipage, and procedures.

The approaches varied in considering the time advance for arrivals or departures.

Some approaches [Balakrishnan, Capozzi] included fairness in terms of maximum position shifting, which was also motivated by computational tractability. An interesting observation is that many of the approaches did not consider this constraint without a clear justification.

Uncertainty modeling

Many of the approaches remained deterministic as evident from Table 1. Buffers were often used to mitigate uncertainty in deterministic approaches. As the integration scope of the problem was made larger [Zhao, Capozzi, Bertsimas], the approach tended to remain deterministic because of the increased complexity. Few of the efforts modeled uncertainty explicitly [Bosson, Solveling]. In these cases, stochastic models used scenarios generated from probability distributions and statistical sampling techniques among the sample scenarios (such as SAA) to keep the problem tractable.

Static versus dynamic approach

Most of the approaches presented a static problem formulation. Dynamic formulations focused on rolling time windows, which was also used to make the problem tractable with a shorter horizon.

Centralized versus distributed

Almost all the approaches were centralized and non collaborative with the users. Even when the problem was formulated as components or stages, there was no notion of distributing the components to agents when possible. One metroplex approach [Wieland] was distributed among airports but the airport problem remained centralized.

Realism of assumptions and application

Most approaches were applied to real world problems with real data and demonstrated realism in this respect. Except for the HITL experiment, most approaches lacked a concept of operation for how to apply the elements of the approach in actual operations. For example, when the problem is formulated into multiple phases or stages with different objectives, scopes, horizons, and interactions, there was no concept for how these phases would materialize in an operational context. No assumptions were made about the relative timing and flexibilities needed between the stages. The motivation for the formulations tended to be driven by making the problem tractable computationally rather than feasible operationally.

Computation performance

Most efforts addressed the computational load, which was a driving motivation for many simplifications. Computational tractability was accomplished and demonstrated in almost all efforts through a number of techniques:

1. Sampling average approximation to handle the large number of scenarios under uncertainty.
2. Multi threading and parallel processing.
3. Multi-stage formulation.
4. Windowing with short horizons.

5. Constrained position shifting.
6. Meta-heuristics search techniques and greedy algorithms

Maturity

The most mature approaches are the simple ideas of closing excess gaps and providing customized gaps in the arrival stream to accommodate departures, which were demonstrated in HITL simulations [Chevalley, Yoo/Lee, Deffenderfer]. Most other efforts are in a proof of concept stage, with application to a real world problem in a fast time simulation environment.

Appendix A: Summaries

This appendix includes the summary and notes about each approach in a table format. Each approach may be represented by multiple papers that reported incremental changes to the same approach. A key word (referring to one or more of the authors) is given in the top row along with the list of references.

Xue	M. Xue and S. Zelinski, "Optimal Integration of Departures and Arrivals in Terminal Airspace", *Journal of Guidance, Control, and Dynamics*, AIAA. Vol.37, No.1, pp.207-213, 2014. (first published in 2012 at ATIO) M. Xue and S. Zelinski, "Optimization of Integrated Departures and Arrivals Under Uncertainty", *AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* , August 12-14, 2013, Los Angeles, CA. M. Xue and S. Zelinski, "Dynamic Stochastic Scheduler for Integrated Arrivals and Departures", *33rd Digital Avionics Systems Conference (DASC)*, October 5-9, 2014, Colorado Springs, CO.
Problem	Increasing flexibility in the terminal airspace by providing multiple route options and allowing sharing of fixes and route segments rather than procedural segregation. Also reducing length of arrival and departure routes if shorter options are selected. Combined decisions for route selection, delay before entry (fix for arrivals or runway for departures), speed along route, and delay along route (for arrivals).
System	Shared waypoints and route segments in the terminal airspace between the runway and the entry/exit points.
Flows	Integrated arrivals and departures
Algorithm	Used non-dominated sorting genetic algorithms (NSGA) as the search engine. It allows multi-objective evaluation with pareto tradeoff.
Objectives	Considered two objectives, delay relative to unimpeded transit time and controller intervention (workload). Intervention was estimated by the resulting discrepancy relative to separation between aircraft, which was assumed to require controller intervention applying delay to reestablish separation.
Constraints	In the air a four nautical mile separation applied. On the runways, a minimum wake vortex separation requirements over four weight class categories. Speed limits and the route structure.
Uncertainty	Earlier versions were deterministic while later versions incorporated uncertainty explicitly. Uncertainty added to entry times using normal distributions. Compared several techniques to handle uncertainty including buffers for deterministic solutions, simulation to estimate average values of the objective function during iterations, and dynamic planning with varying the time window sizes.
Dynamic	Earlier version of the work was static and then improved into dynamic planning.
Distributed	Algorithmic approach is centralized.
Computation	Addressed computational issues by using parallelization on graphics processing units (GPU).
Realism	Applied the approach to real world problem in LAX. Used actual traffic schedule from one day of operation. Used high fidelity trajectory modeling (CTAS trajectory synthesizer) for estimating expected arrival times. The scale of the problem was small. Focusing on few interacting flows and one day of operation.
Maturity	Low maturity: Work is in prototyping mode with high fidelity simulation

	assessment.
Key Results	Identified tradeoff between delay savings and controller intervention (to regain separation) under different control strategies of full segregation versus sharing of routes. Sharing saves delay, particularly when coupled with shorter shared routes, but at expense of more adjustments to maintain separation.

Bosson	C. Bosson, M. Xue, and S. Zelinski, "GPU-based Parallelization for Schedule Optimization with Uncertainty", *AIAA Aviation and Aeronautics Forum and Exposition 2014*, June 16-20, 2014, Atlanta, Georgia. C. Bosson, M. Xue, and S. Zelinski, "Optimizing Integrated Terminal Airspace Operations Under Uncertainty", *33rd Digital Avionics Systems Conference (DASC)*, October 5-9, 2014, Colorado Springs, CO.
Problems	Increasing flexibility in the terminal airspace by providing multiple route options and allowing sharing of fixes and route segments rather than procedural segregation. Also reducing length of arrival and departure routes if shorter options are selected. Combined routing, sequencing and scheduling decisions.
System	Shared resources are waypoints and route segments in the terminal airspace between the runway and the entry/exit points.
Flows	Integrated arrivals and departures
Algorithm	Machine job-shop scheduling formulation and multi-stage stochastic programming: the first stage solves deterministically for the optimal runway sequence based on aircraft weight class; the second stage solves the routing and scheduling problem by assigning flights to the slots in the sequence of stage one, while minimizing the impact of flight time uncertainty; the second stage uses multiple perturbed scenarios and an average sampling approximation technique; finally a third stage adjusts the computed schedules to maximize on-time performance of the flights to the runway, several scenarios from the second stage are used in the third stage. A mixed integer linear program is solved in the iterations.
Objectives	Considered three objectives: minimize the sum of exit times (overall delay), minimize flight specific delay (difference between the start and the release to start processing as soon as possible), and minimize earliness or tardiness relative to the schedule at exit points. Uncertainty leads to interventions by controllers to adjust speed to maintain separation, which is also evaluated.
Constraints	In the air a four nautical mile separation applied. On the runways, a minimum wake vortex separation requirements over four weight class categories. Speed limits and the route structure.
Uncertainty	Uncertainty was added to the release times and due dates (ETA) using normal distributions. Used sample average approximation to determine expected value of cost function.
Dynamic	Static problem.
Distributed	Algorithmic approach is centralized
Computation	Addressed computational issues by using multithreading on graphics processing units. Computation time was shown to tradeoff with robustness, which increases with increasing the number of scenarios. Computation time ranged between 2.5 and 32 minutes for 10 to 1000 scenarios. 100 scenarios recommended as a good compromise with about 10 minute computation time.
Realism	Applied the approach to real world problem in LAX. Used actual traffic schedule from one day of operation. The scale of the problem was small. Focusing on few

	interacting flows and one day of operation.
Maturity	Low maturity: Work is in prototyping mode.
Key Results	Identified impact of speeding up arrivals. Sharing incurred less delay and controller intervention than segregation unless early arrival releases were forbidden.

Zhao	H. Chen, Y. J. Zhao, and C. Provan, 2011, Multiple-Point Integrated Scheduling of Terminal Area Traffic, Journal of Aircraft, Vol. 48, No. 5, pp. 1646-1657 Heming Chen and Yiyuan J. Zhao. "Sequential Dynamic Strategies for Real-Time Scheduling of Terminal Traffic", Journal of Aircraft, Vol. 49, No. 1 (2012), pp. 237-249.
Problems	The approach addresses scheduling and route selection to increase throughput (minimize total flight delay) at multiple points including fixes, runways and gates of a single airport. Runway assignment is abstracted as part of route selection: runways are part of the routes available. Once a route is selected the runway is by default. Fixes and gates are terminal points at which delay is measured. Routes may have common segments. For example a runway can be used for arrivals and departures. The sequence may change from one common segment to another.
System	The system is from arrival fixes to gates and from gates to departure fixes. Single airport with multiple runways. Fixes and gates are terminal points at which delay is measured.
Flows	Integrated scheduling and route selection for arrivals and departures between gates and fixes, passing through runways.
Algorithm	Multi-point scheduling using mixed integer linear program. Used Gurobi Optimization. Compared optimized route and schedule, optimized schedule with pre-assigned routes, and FCFS with pre-assigned routes. FCFS is based on ETA to the first scheduling point.
Objectives	Minimized overall flight delay, defined as the difference between the scheduled and estimated arrival times of a flight. A weighted sum of gate delay and fix delay is used.
Constraints	Time separations are imposed at all points (derived from distance separation requirements). Speed limitations imposed as limits on transit times. Sequence is maintained along a segment but can change from one common segment to another. No time advance is considered.
Uncertainty	Scheduling at multiple points is stated as mechanism to mitigate uncertainty through more flexible structure! Otherwise the problem presented is deterministic.
Dynamic	Static planning extended to dynamic planning.
Distributed	Algorithmic approach is centralized
Computation	Different algorithms compared in terms of computation time. For a simple one hour, 60 flights, 7 routes problem, routing and scheduling took multiple hours.
Realism	Applied the approach to a real world problem in JFK and used actual traffic schedule. Used a directed graph for the route structure which is a simplification given that some taxi segments can be used both ways. The scale of the problem is small. The network of nodes and links reduced to a small set of 2 runways and 7 total routes where a route is fix-runway-terminal. No provision is given to runway reassignment after joining a route (which contains a runway). All three arrival routes go to one terminal. Four departure routes start at same terminal and assigned to one runway. Five scheduling points per route.

	Considered a mix of weight classes and different traffic levels. One hour problem with 10-60 aircraft. Separation criteria were simplified, using the same separation requirement at all airborne points as the runway and a nominal speed for all aircraft to turn distance to time: 50 seconds, increased to 65 and 85 for wake turbulence, and 30-second separation at taxi scheduling points.
Maturity	Low maturity: Work is in prototyping mode with a static algorithm implementation and no dynamic simulation.
Key Results	Demonstrated tradeoff between delay savings and computational time using FCFS, versus scheduling on fixed routes, versus routing and scheduling.

Wieland	Frederick Wieland, Ankit Tyagi, Vivek Kumar, William Krueger, METROSIM: A Metroplex-Wide Route Planning and Airport Scheduling Tool (AIAA 2014-2162) 14th AIAA Aviation Technology, Integration, and Operations Conference, Atlanta, GA. 2014.
Problems	The approach attempts to solve a full metroplex problem by interconnecting independent airport planners through a centralized metroplex planner. Each independent airport planner optimizes its own operations, resulting in a runway assignment and schedule. The metroplex planner can override the separate airport schedules based on applying airspace constraints that represent interactions between the airports. The combined outcome is a coordinated runway schedule and conflict free trajectories for all airports' flights.
System	The system is a metroplex of airports that extends from the gates of each airport to an airspace boundary defined by a diameter that encompasses their surrounding airspace.
Flows	Arrival, departure and surface flows of all the airports in the metroplex.
Algorithm	The airport planner uses a mixed integer linear program in Matlab for the runway schedule generation and for the surface algorithm that tests the feasibility of the schedule (or minimizes taxi time). The metroplex planner is a conflict resolution algorithm that uses a kinematic trajectory generator and a merging a spacing logic.
Objectives	The metroplex planner which is the central and overriding authority attempts to minimize the distance (or time) flown within the system. If airport planners provided desired runway schedules, the metroplex planner tries to honor these schedules if they are feasible. The airport planner objective is to minimize arrival and departure delays (it also states maximizing throughput). It is possible to configure the airport planner to also minimize taxi time.
Constraints	The airport planners maintain minimum separation requirements at the runways and taxiways in addition to operational constraints such as no passing along the same path segments and transit time limits. The algorithms assume a given route structure that is derived based on historical data for the airspace and using shortest path for the surface. The centralized planner ensures conflict free trajectories.
Uncertainty	The formulations presented are deterministic.
Dynamic	Planning is dynamic repeated every 15 minutes with 5 minute sub-cycles.
Distributed	Algorithmic approach is distributed in terms of airport agents.
Computation	The distribution of the problem over independent airport planners is motivated partially by the computation efficiency for real time application. Computation load is not discussed due to the early stage of the concept.
Realism	The algorithms were applied to two airports LGA and JFK using actual data over one hour. Feasibility was demonstrated in terms of converging to a beneficial solution using a 15 minute horizon. However, the simulation was not validated against the actual data because only a subset of the actual traffic was used in the simulation.

Maturity	Low maturity: Work is in prototyping mode.
Key Results	Demonstrated converging to a beneficial solution using a 15 minute horizon.

Bertsimas	D. Bertsimas, Air Traffic Flow Management at Airports: A Unified Optimization Approach, Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013) Chicago, IL, 2013.
Problems	The approach attempts to integrate the runway configuration, runway and gate assignment, runway sequencing, gate holding, fix holding, and routing in a single airport problem including surface and terminal airspace. The goal is to optimize the operations more globally through an integrated approach.
System	The system is a single airport from the gates to the boundary fixes of the terminal airspace.
Flows	Arrival, departure and surface flows between the arrival/departure fixes and the gates.
Algorithm	The algorithm follows a two phase approach. In phase one, the runway configuration and runway sequencing problem is solved optimally since the runway is assumed to be the bottleneck. Phase one assumes infinite capacity other than of the runways and hence that flights can travel unimpeded along the shortest paths and remain at gates and holding areas as long as needed. In phase two, the taxiway, gate, and airspace capacity constraints are enforced, solving the gate holding and routing problem. Phase two attempts to meet the phase one solution (runway assignment and sequence) and assumes flexible flight deadlines (if not feasible it relaxes them). The algorithm applies a discrete time representation with intervals of 20 seconds, short enough to represent separations and use Gurobi to solve the discrete program.
Objectives	The objective is to minimize the travel time between the entry points (gates for departures and fixes for arrivals) and the exit points (gates for arrivals and fixes for departures. Gate holds and delays prior to entry are maximized. Different weights are assigned to airborne and ground time. A penalty is imposed on runway configuration change.
Constraints	Constraints in phase one (see algorithm description) include: minimum separations between aircraft types on runways including closely spaced and crossing runways; compatibility between a runway and a flight which is time and configuration dependent; runway occupancy times; and earliest times of arrival at the runway. Constraints in phase two include: route network compatibility; route segment capacities; runway assignment and sequence as computed from phase one; runway usage compatibility which is configuration and time dependent (runway may not be available due to weather).
Uncertainty	The formulations presented are deterministic.
Dynamic	Static problem presented.
Distributed	Centralized.
Computation	Solved a problem of about 150 flights in about 10 minutes (200 to 1400 sec), with less than 1% from optimality (measure by the phase two solution reaching the phase one optimal solution).
Realism	Applied the method to one day at BOS and one day at DFW. Some simplifications may reduce realism: In practice the separations between aircraft

	and runway occupancies in visual conditions may need a resolution higher than 20 seconds (the discrete time resolution).
Maturity	Low maturity: Work is in prototyping mode with static implementation.
Key Results	Demonstrated feasibility showing that the phase one was feasible and phase two was able to approach its solution. Showed reduction in travel time through the system relative to historical times and significant gate holding as a result (which was not compared to real data).

Kim/Clarke	Bosung Kim, and John-Paul Clarke, Modeling and Optimization of Terminal Area Utilization by Assigning Arrival and Departure Fixes (AIAA 2013-5256) AIAA Guidance, Navigation, and Control (GNC) Conference, Boston, MA 2013
Problems	Balancing the traffic load over arrival and departure fixes often non-balanced at major airports and in bad weather conditions. The balancing is achieved through fix assignment and scheduling, in conjunction with runway scheduling, to account for fix and runway capacity constraints. The scheduling both at the fixes and the runway is based on rate balancing rather than explicit flight sequencing. Absorbing delay upstream of the arrival fixes in the cruise segment is motivated by saving on fuel burn and emissions.
System	The system is a single airport from the runways to the arrival and departure fixes and including the initial STAR fixes.
Flows	Arrival and departure flows between the arrival/departure fixes and the runways.
Algorithm	The algorithm is a mixed integer linear program.
Objectives	The objective includes three components: upstream delay (ground delay before the runway for departures and airborne holding delay in cruise for arrivals), outside TRACON impact for arrivals only (in terms of fuel burn due to the path length difference by assigning the flight to a different arrival fix), and inside TRACON impact for arrivals only (in terms of fuel burn in the transition time inside the TRACON).
Constraints	Flow rate constraints imposed at the fixes and the runways.
Uncertainty	The formulation presented is deterministic.
Dynamic	Thirty minute rolling window was used in the example; however the fix assignment was not changed dynamically, only the schedule.
Distributed	Centralized.
Computation	N/A.
Realism	Applied the model to load balancing between the fixes at ATL. The approach justifies a delay over a longer path if the overall fuel burn is reduced. The assumption that fuel is the main driver of the decision is not always true. The fuel burn for departures during climb is ignored because it would dominate the performance since the fuel burn is highest in climb. An assumption is made that arrivals are assigned to the runway that is closest to the arrival fix, which may not be true all the time. The runway capacity constraints are rate constraints inferred from capacity tradeoff curves between arrivals and departures, rather than explicit separation constraints.
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Demonstrated benefits in terms of queuing and fuel savings (12% and 4% respectively) by assigning flights to a fix that required longer cruise segments but shorter downwind segments.

Solveling / Clarke	Gustaf Solveling, Senay Solak, John-Paul Clarke, Ellis Johnson. Runway Operations Optimization in the Presence of Uncertainties. Journal of Guidance, Control, and Dynamics, 34(5), 2011.
Problems	Optimizing the runway throughput under uncertainty.
System	The system is a single airport runway system.
Flows	Arrival and departure flows at the runways.
Algorithm	A two-stage planning algorithm is used. The first stage is a sequence optimizer and used a two-stage stochastic program to determine an optimal sequence of aircraft types. Multiple scenarios are considered through sampling from the distributions of the demand. For each scenario a deterministic assignment problem is solved to assign flights to the sequence slots and Bender's decomposition is used to link the different scenarios. The second planner is an assignment optimizer which uses a MILP to assign flights to the optimal sequence of the first stage.
Objectives	The sequence optimizer has two stages: the first stage maximizes runway utilization by minimizing the last time of using the runway. The second stage minimizes a flight cost function which is the deviation of the assigned time from an estimated schedule time (representing FCFS). The assignment optimizer maximizes runway utilization and minimizes deviation from the schedule for each flight, which captures passenger and crew concerns.
Constraints	The sequence optimizer satisfies the minimum separation requirements between aircraft types. Separation requirements are maintained with the last flight preceding the data set. The number of aircraft types given time slots is equal to the number in the demand data set. The assignment optimizer satisfies the sequence computed by the sequence optimizer by assigning flights to each runway slot of the same type. It also satisfies earliest time constraints (scheduled time for departures and earliest time of arrival given distance and allowed speed increase). Separation requirements constraints are extended to accommodate the triangular inequality that results from multiple runway and arrival-departure interactions.
Uncertainty	The sequence optimizer of the first planning stage is a stochastic program. Its outcome is a set of scenarios for flight landing and takeoff times. Distributions of pushback delay, taxi out delays, and arrival delays were generated from historical data and used in sampling scenarios. Sampling average approximation (SAA) is used to mitigate the large number of possible scenarios. The assignment optimizer is a deterministic MIP assuming the uncertainty has been removed.
Dynamic	A rolling window scheme was used: One hour horizon used for the sequence optimizer. The horizon is shifted such that the first half of the sequence positions included in the first iteration is frozen and the second half is not for the next iteration. For flight scheduling, a freeze horizon of 30 minutes is used and flights in the next 15 minutes are assigned to the slots frozen in the

	previous sequence optimizer iteration.
Distributed	Algorithm approach is centralized.
Computation	Run time ranged from 30 to 200 minutes for 93 flights.
Realism	Applied the model to actual data from DTW. The second stage is performed after the uncertainties have been realized (aircraft already pushed back or taxied to some extent, and arrivals are close enough to assume the accuracy of landing is high). The sequence in the first stage is imposed on the second stage (assuming there are no uncertainties to require sequence adjustments) which reduces the flexibility of the second (deterministic) stage. Reliance on probability distributions that need to be derived based on historical data and discretized to a reasonable level to maintain computational tractability.
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Showed benefits in terms of improved runway utilization and reduced flight delays and deviations from the schedule relative to FCFS sequencing and to deterministic modeling. The benefits were shown only under significantly high demand values.

Hancerliogullari	Gulsah Hancerliogullari, Ghaith Rabadi, Ameer H. Al-Salem, Mohamed Kharbeche, Greedy algorithms and metaheuristics for a multiple runway combined arrival-departure aircraft sequencing problem. Journal of Air Transport management, 32, 9-48, 2013.
Problems	Optimizing the runway throughput.
System	The system is a single airport runway system, with multiple identical runways
Flows	Arrival and departure flows at the runways.
Algorithm	Optimal solutions found through MILP. Several greedy and meta-heuristic approaches were proposed to speed up the MILP: the adapted apparent tardiness cost with separation and ready times (AATCSR) is a greedy algorithm that applies a priority index for each flight and flights are assigned according to it, the index reflects the urgency for a flight by exponentially increasing the priority as they approach their ready, target, and deadline times and if their separation time is short. Fast priority index (FPI) also assigns priorities in a similar manner but linearly which makes the search faster. Simulated annealing search associated with the two priority schemes above. Meta-heuristic for randomized priority search (Meta-RaPS) associated with the priority schemes above.
Objectives	Minimized a weighted tardiness sum over flights (delay from a target landing or takeoff time).
Constraints	The constraints include: minimum separation requirements, limits on tardiness relative to target times, bounds on the number of aircraft assigned to each runway for runway load balancing, time window restrictions.
Uncertainty	Algorithm is deterministic.
Dynamic	A static problem is presented.
Distributed	Algorithm approach is centralized.
Computation	For a problem of 25 aircraft, the MIP ran in few minutes (4-2600 seconds) while the greedy algorithms ran in less than a 1000th of a second, and found a solution less than 2% from optimal. With SA, some exact optimal solutions were found and generally near optimal with about 0.5%, with an increase in computation time to 0.5 second.
Realism	Algorithm was applied to fictitious data. The assumption of using identical multiple runways is limiting. The problem size used is small with only 25 aircraft.
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Showed that the use of greedy algorithms was effective at finding near optimal solutions with AATCSR being the best. Showed that the meta-heuristics also improved the greedy algorithms with SA being superior.

Clare	Gillian L. Clare, and Arthur G. Richards. Optimization of Taxiway Routing and Runway Scheduling, IEEE Transactions on Intelligent Transportation Systems, Vol. 12 , No. 4 . 2011.
Problems	Optimization of runway scheduling and taxi routing.
System	The system is a single airport with runways and taxiways up to the gates, which are approximated by the entry/exit of the ramp.
Flows	Arrival and departure flows. Arrival landings are fixed. Only departures are scheduled at the runway. On the taxiways arrivals and departures are scheduled and routed.
Algorithm	A receding horizon (RH) approach is applied with a near-term planning horizon, a far-term approximation horizon, and a short execution horizon. The problem is formulated as a mixed integer linear program. The MILP iterates with a conflict detection algorithm. If conflicts are detected then constraints are added for these conflicts only and the iteration continues until a solution is found with no conflicts.
Objectives	Minimized a weighted sum of total taxi time, total taxi distance and the longest taxi time over active flights.
Constraints	The constraints include: the taxi network connectivity. Minimum separation requirements and speed limits. The arcs of the network are made too short in order to disallow overtaking. Separation between conflicted aircraft are added if found by the conflict detection algorithm. The route and schedule selected ensure that the remaining plan to the runway is consistent with the shortest path plan.
Uncertainty	Algorithm is deterministic.
Dynamic	Dynamic with receding horizon.
Distributed	Algorithm approach is centralized.
Computation	For a problem of 125 aircraft, the MIP ran in 120 seconds in Matlab Simulink and CPLEX. The impacts of iterating with conflict detection and of the RH were isolated and shown to be significant.
Realism	Applied the simulation to few hours of at Heathrow airport. Some simplification were made: No consideration of taxiway crossing of runways or of mixed mode runways. Gates are aggregated by one node and no blockage was modeled between arrivals and departures at entry to and exit from (respectively) the gates. Currently planning considers active aircraft (past pushback time and landing time) with future research extension anticipated to projected flights. Some constraints such as not to revisit a node on the taxiways may be too limiting.
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Showed substantial benefits over FCFS in terms of earlier takeoff times, reduced taxi delay and increased gate holding.

Montoya	Justin Montoya, Zachary Wood, Sivakumar Rathinam. Runway Scheduling Using Generalized Dynamic Programming. AIAA Guidance, Navigation, and Control Conference, Portland, OR. 2011.
Problems	Optimization of runway scheduling. Although the surface is considered, only a single path is assumed to the runway. Therefore the routing problem is not considered.
System	The system is a single airport extending from the gates to the runway. Multiple queues are considered, including aircraft waiting at the gate, waiting at to depart at the runway, and waiting to cross the runway.
Flows	Arrival and departure flows. The arrivals are crossing the departure runway rather than landing on the runway. However, the approach is applicable to landings and departures since the triangular inequality is violated by the required separations.
Algorithm	Dynamic programming with and without position shift constraints.
Objectives	A pareto tradeoff between throughput and delay.
Constraints	The constraints include: Minimum separation requirements considering divergent headings and RNAV equipage. Miles in trail restrictions. Runway crossing times. Maximum position shifts.
Uncertainty	Algorithm is deterministic.
Dynamic	Static problem presented.
Distributed	Algorithm approach is centralized.
Computation	For a problem of 10 to 30 aircraft in 15 minutes, the optimal version took up to 2 minutes while the heuristics with maximum position shift took up to 2.5 seconds.
Realism	Applied the approach to a DRW problem. Considered divergent heading separations with RNAV equipage, this adds to the realism. Some unrealistic simplifications made: Single taxiway path. Separation between runway crossings from different crossing queues. Uniform runway crossing times (runway crossings take different times if the crossing is the first one or following another crossing).
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Showed substantial benefits over FCFS in terms throughput increase (8%) and delay savings (40%-70%). The heuristics were within 5% from the optimal solution with significant computation speed up.

Bianco	Lucio Bianco, Paolo Dell'Olmo, and Stefano Giordani. Scheduling models for air traffic control in terminal areas. Journal of Scheduling June 2006, Volume 9, Issue 3, pp 223-253.
Problems	Optimization of runway scheduling with transferring delay to holding outside the entry fixes and before departing.
System	The system includes the runway and the terminal airspace with a given route structure.
Flows	Arrival and departure flows.
Algorithm	The problem is modeled as a no-wait job-shop problem. Applies a local search heuristic called the cheapest search heuristic. Every time a new aircraft is introduced with an ETA, it is added to the end of the already established sequence and the cheapest local search is applied to improve on this insertion locally. The search for insertion is among feasible neighborhood sequences given constrained position shift (CPS), relative position shift (RPS) constraints and no overtaking constraints.
Objectives	Maximizing throughput and minimizing average and maximum delay, applied separately and compared.
Constraints	The constraints include: minimum separation requirements, occupancy times on runways and along airspace segments, earliest arrival times, maximum position shifts (to prevent extreme delays) and relative position shift (to limit workload).
Uncertainty	Algorithm is deterministic.
Dynamic	Dynamic.
Distributed	Algorithm approach is centralized.
Computation	Fast real time heuristic is used and demonstrated with no reporting of computation speed.
Realism	Aircraft wait in holding patterns before the entry fix and on the ground before the runway and then follow a prescribed path with no delay. All the delay is incurred in the holding patterns or on the ground with no delay in between.
Maturity	Low maturity: Work is in prototyping for proof of concept.
Key Results	Showed substantial benefits over FCFS in terms average delay savings (about 40%) and throughput increase (about 30%) relative to FCFS under high volume for a two hour scenario.

Chevalley	Eric Chevalley, Bonny Parke , Paul Lee, Faisal Omar, Hyo-sang Yoo, Joshua Kraut, Daphne Rein-Weston, Nancy Bienert, Kari Gonter, Everett Palmer. Decision Support Tools for Climbing Departure Aircraft Through Arrival Airspace. 33nd IEEE/AIAA Digital Avionics Systems Conference (DASC), 2014 Daphne Rein-Weston, Richard Jacoby, Eric Chevalley, Albert Globus, Hyo-sang Yoo, Bonny Parke , Paul Lee, Faisal Omar, Joshua Kraut, Nancy Bienert, Abhay Borade, Conrad Gabriel, Kari Gonter, Everett Palmer. Development of a Route Crossing Tool for Shared Airspace Environments. 33nd IEEE/AIAA Digital Avionics Systems Conference (DASC), 2014 Eric Chevalley, Bonny Parke , Paul Lee, Faisal Omar, Hwasoo Lee, Nancy Bienert, Joshua Kraut, Everett Palmer. Scheduling and separating departures crossing arrival flows in shared airspace. 32nd IEEE/AIAA Digital Avionics Systems Conference (DASC), 2013
Problems	Scheduling arrivals and departures at shared airspace merge points and at runways, for one or more airports. Providing multiple route options for departures to intersect an arrival stream, mitigating high uncertainty in the takeoff and climb phases through added flexibility.
System	Shared fixes in the airspace and the runways.
Flows	Integrated arrivals and departures
Algorithm	Nominal travel times used to compute release times corresponding to gaps in the arrival stream. Buffers are provided to ensure sufficient separation. Release times are coordinated between tower and terminal TMC in HITL experiment.
Objectives	Increased efficiency and throughput by sharing of airspace resources. Enabling continuous climb through sharing of resources and multiple route options. Increasing flexibility by providing multiple route options.
Constraints	Separation requirements at merge points and runways. Departures released in available slots to meet gaps in the arrival stream at the merge points.
Uncertainty	Introduced errors in the release times in the HITL experiments. Buffers were added to the separation requirements to mitigate uncertainty. Multiple route options are provided to increase the adaptability to mitigate the uncertainty.
Dynamic	Dynamic implementation supporting a HITL experiment.
Distributed	HITL experiment involved functions distributed to Tower and TRACON TMCs who coordinated release time. Decision support was provided to controllers to accomplish the scheduled merging.
Computation	Real time implementation in HITL experiment
Realism	Real time implementation ensured realistic environment. Separation rules were carefully designed to reflect controller behavior, for example, using the divergence procedure which enables violating the required separation if the aircraft are diverging with more than fifteen degrees.
Maturity	Medium maturity: Concepts demonstrated in HITL simulation; however, feedback from the HITL experiments is used to refine the concepts.

Key Results	Identified successful merging with substantial benefits in term of delay savings.

Piera	Miquel A. Piera and Olatunde T. Baruwa. A Discrete Event System to Optimize Runway Occupancy. Unpublished author communication.
Problems	Automating and optimizing the arrival-departure sequence.
System	Single runway, covering final approach to exit. The issue addressed in automating and optimizing the arrival-departure sequence.
Flows	Integrated arrivals and departures
Algorithm	Approach is simulation through Colored Petri Nets (CPN). Used CPN Tools software from Aarhus Denmark for building the model and CPN simulator from autonomous university of Barcelona for simulation. The net is used to transform the scheduling problem to a state search problem in a tree representing the problem state. The coverability tree is checked to restrict the search if certain conditions are encountered: dead end (no state transition enabled) and repetition (state was encountered before). This helps reduce the search space to an acceptable computational time.
Objectives	Maximize the runway throughput.
Constraints	Constraints include: Arrivals are favored over departures. Separation requirements are maintained with heavy, medium, and light categories. Applied runway occupancy times and final approach times.
Uncertainty	Deterministic.
Dynamic	A simulation approach is used to select a strategy by searching the state space. The simulation of the state space represents evolution in time. So the approach may be termed as dynamic, although it was exercised for dynamic replanning.
Distributed	Petri Nets could potentially represent distributed systems. Approach used subnets for arrivals and departures which competed for the runway.
Computation	The state coverability tree is checked to restrict the search if certain conditions are encountered: dead end (no firing enabled) and repetition (state encountered before). This helps reduce the search space to an acceptable computational time. Additional heuristics were used to prune the tree and stop exploring paths that are deemed non-productive.
Realism	Applied the approach to a single runway problem that is limited in scope. The decision making process of separating operations based on separation requirements and runway occupancy is quite detailed.
Maturity	Low maturity: Work is in prototyping mode using Petri Net tools.
Key Results	Strategies of all arrivals, all departures, and mixed arrivals and departures were simulated and compared under different aircraft type mixes. Showed that mixed operations performed better than segregated operations in terms of the number of operations per hour, under infinite demand.

Diffenderfer	Paul Diffenderfer, Zheng Tao, and Gaea Payton. Automated Integration of Arrival/Departure Schedules. Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), Chicago, IL.
Problems	Attempting to increase throughput by providing information to the approach controller about the departure queue and advisory about the exact spacing between successive arrivals that would allow one or more departures in between. Used slot markers as targets to hit on the final approach. Slot markers can be refreshed based on a selected aircraft.
System	Runway.
Flows	Arrival and departure flows over a limited horizon (only the final approach)
Algorithm	Simple heuristic used for the automation to compute the spacing needed between two arrivals to fit the departure that will be waiting to depart during the landing. The time spacing needed to fit the departure behind the arrival is converted into a spacing distance based on the arrival's current speed along the final approach. It is then displayed as a slot marker on the final approach to be associated with the next landing. The calculation is then repeated for the following scheduled departure and subsequent slot markers are generated relative to the preceding slot marker's expected landing time.
Objectives	Throughput by closing unnecessary arrival gaps and opening gaps for departures. Performed a HITL to assess workload.
Constraints	Minimum separation requirements. In baseline 4 nautical miles between arrivals. The tool used only IFR separation assumptions: departures are separated by 90 seconds and the next arrival should be 1.75 nm out of the threshold when a departure takes off.
Uncertainty	The slot markers can be adjusted if it becomes difficult to associate flights with them.
Dynamic	Dynamic. The slot markers can be adjusted if it becomes difficult to associate flights with them.
Distributed	Centralized. Focusing on final approach controller.
Computation	The heuristic algorithm performs simple calculations where computational load was not an issue. The algorithm was applied in real-time HITL experiment.
Realism	The concept is realistic and was implemented in a HITL simulation to obtain feedback on its feasibility. Controller responses were positive mostly, with a slight increase in workload but with successful use of the slot markers.
Maturity	High maturity: the concept was tested in HITL experiment with good overall feedback.
Key Results	The concept was tested in HITL experiment, which showed that the workload was increased with the tool, the controllers were successful 90% of the time in associating flights with slot markers, and throughput was increased for departures and in some cases for arrivals as well.

Yoo & Lee	Hyo-sang Yoo, Paul Lee, and Everett Palmer. Improving Departure Throughput by Dynamically Adjusting Inter-Arrival Spacing. 33nd IEEE/AIAA Digital Avionics Systems Conference (DASC), 2014
Problems	Attempting to increase throughput by adjusting the arrival schedule to provide spacing between successive arrivals that would allow one or more departures in between. Used slot markers to meet the schedule.
System	Runway.
Flows	Arrival and departure flows between runways and fixes.
Algorithm	Compared different strategies: Only delay of arrivals, delay and advance, and no slack capacity by advancing arrivals even if gap is not used by a departure. In HITL TSS generated natural spacing for one departure. A traffic management coordinator (TMC) position adjusted arrivals on a timeline to provide for two or three departures. The TMC can click on timeline and a calculated spacing for 2 or 3 departures is provided based on the separation rules.
Objectives	Throughput by closing unnecessary arrival gaps and opening gaps for departures. Performed a HITL to assess feasibility and workload.
Constraints	Minimum separation requirements. In analysis, used separation deduced from video analysis. In HITL, used VFR separation assumptions for LGA: departures are separated by 45 seconds and the next arrival should be 2 nautical miles out of the threshold when a departure takes off. Arrivals natural spacing at about 75 seconds naturally allows one departure in between. Used 120 for two departures and 135 for three departures.
Uncertainty	Deterministic analysis. Real time application in HITL experiment.
Dynamic	In analysis control strategies applied in static manner. In HITL experiment environment is dynamic.
Distributed	Centralized. Focusing on final approach controller.
Computation	The heuristic algorithm performs simple calculations where computational load was not an issue. The algorithm was applied in real-time HITL experiment.
Realism	The concept is realistic and was implemented in a HITL simulation of LGA to obtain feedback on its feasibility.
Maturity	High maturity: the concept was tested in HITL experiment with good overall feedback.
Key Results	The concept was tested in HITL experiment, no results reported yet. The analysis shows substantial increase in throughput (10-60 % for departures).

Hwang	Chandrasekar Sureshkumar and Inseok Hwang, Optimal Arrival and Departure Sequencing on a Runway System (AIAA 2013-4883) AIAA Guidance, Navigation, and Control (GNC) Conference, Boston, MA.
Problems	Optimizing sequence and runway assignment of arrivals and departures at the runway. It can be applied to any runway system.
System	Runway.
Flows	Arrivals and departures on a runway system.
Algorithm	Branch and bound algorithm, using mathematically proven bounds on the optimal value to limit the search for computation efficiency. The bounds are based on finding the sequence with the minimum summation of the minimum separation requirements.
Objectives	Minimized the makespan of operations on all runways.
Constraints	Separation requirements between operations. Handled all runway configurations (single, CSPR, V, and X) by simplifying them into a separation matrix between arrivals and departures. Maximum position shifting and other constraints such as precedence can be included.
Uncertainty	Deterministic formulation.
Dynamic	Static in three minute windows, with no replanning.
Distributed	Centralized.
Computation	Computation time much smaller than traditional branch and bound approaches and is fraction of a second for the 8 aircraft problem posed. The algorithm was applied to 3 minute time windows of real traffic, with maximum of 13 operations, which makes the computational load manageable, few seconds for the entire day.
Realism	Applied the approach to real world problem in ATL using 24 hour of traffic in 3 minute windows with 1008 arrivals and 985 departures. The sequence was changed within 3 minute windows which was justified based on Balakrishnan finding that advances of time more than 3 minutes can be outweighed by costs to the airline due to speed up fuel burn. The 3 minutes had maximum of 13 operations which also made the computation time manageable. Paper uses an elaborate grouping of aircraft based on wingspan and approach speed into four categories with average approach speeds: B-III or less (110 knots), B-III – C-III (130), C-III – D-IV (153), and >D-IV (166). Assumed IFR separation rules and used the speed to convert distance to time. For arrival-departure and departure-arrival used 45 seconds irrespective of type and runway. Equal loading on the runway was used. It is possible that no runway assignment was exercised by the algorithm since each runway system had one arrival and one departure runways at ATL. Separation between last aircraft in one 3 minute window and first one in the next is ignored and probably violated.
Maturity	Low maturity: Work is in prototyping mode with static implementation in Matlab with 8 arrivals and 8 departures and a one day of operations.

Key Results	Demonstrated reduction in the makespan of about one minute in the 3 minute windows and 7 hours in the day.

Balakrishnan	H. Balakrishnan and B. Chandran, Algorithms for Scheduling Runway Operations under Constrained Position Shifting. Operations Research, Vol. 58, No. 6, November-December 2010. B. Chandran and H. Balakrishnan, A Dynamic Programming Algorithm for Robust Runway Scheduling. Proceedings of the American Control Conference, New York, NY, July 2007.
Problems	Optimized sequence and schedule of arrivals and departures. Traded off fairness with efficiency by imposing a maximum position shift relative to FCFS.
System	Runway.
Flows	Arrivals and departures on a single runway.
Algorithm	Dynamic programming algorithm, which is rendered computationally feasible with the maximum position shift. Dynamic program originally formulated with no notion of time and each stage represents the addition of an aircraft to the sequence length, with the separation requirements satisfying the triangular inequality. This is feasible for arrivals-only and departures-only problems. The formulation is extended by a discrete time dimension to enable representing aircraft-dependent costs, which enables schedule optimization. The formulation is further extended by augmenting the state space to represent violations of the triangular inequality. This enables scheduling arrivals and departures on the same runway. A version is presented in which departures do not require time window constraints and inserted between arrivals while correcting for the triangular inequality (when two arrivals are separated by one departure). This reduces the complexity.
Objectives	Minimized the makespan of operations. Additional objectives possible by augmenting the dynamic program search tree. For example, generic aircraft-dependent cost functions can be used by augmenting the search tree using discrete time.
Constraints	Constraints are separation requirements, time-window constraints, and precedence constraints. In addition the algorithm applies a maximum position shift constraint relative to the FCFS position. Approach applies as long as the separation requirements satisfy the quadrilateral inequality.
Uncertainty	Initial versions of the approach were deterministic. A paper incorporated robustness to uncertainty into the approach for arrival scheduling and assessed the tradeoff between reliability (probability of violating the separation requirements) and throughput.
Dynamic	Static with no replanning.
Distributed	Centralized.
Computation	Run time is under a minute for a 50 aircraft problem.
Realism	Applied the approach to real world problem in DEN. Presentation of the algorithm is theoretical, but the computation issues are addressed such that it may be applied to a real-time situation.
Maturity	Low maturity: work was demonstrated through an example programmed in C.

Key Results	Benefits reported relative to FCFS in terms of increased throughput and reduced delay.

Capozzi	Brian Capozzi, Stephen Atkins, Seongim Choi. Towards Optimal Routing and Scheduling of Metroplex Operations. 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Hilton Head, SC. 2009 Brian Capozzi and Stephen Atkins. A Hybrid Optimization Approach to Air Traffic Management for Metroplex Operations. 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2010
Problems	The approach addresses scheduling and route selection at multiple points including fixes and runways. Addressed metroplex environment where the runways may belong to different airports in close proximity. Focused on segregation versus sharing of resources resulting in spatial versus temporal resolution of conflicts at scheduling points. The route structure is predetermined with possible sharing among flights from different airports. Runway assignment is abstracted as part of route selection: The assignment of the routes results in runway assignment.
System	The system is from arrival fixes to runway and from runways to departure fixes.
Flows	Arrivals and departures.
Algorithm	The basic formulation was a multi-point scheduling scheme using mixed integer linear program. The first paper presented low computational performance. In the second paper, the same problem is solved using a genetic algorithm to solve the discrete variables (route assignment and sequencing) and a linear program to solve the continuous variable (scheduling). The linear program computed the fitness function of the genetic algorithm mutations. This resulted in drastic computational improvements.
Objectives	Minimized overall flight delay within the system, defined as the difference between the scheduled and expected times of a flight at the final scheduling points. Fixes and runways are terminal points at which delay is measured. Total delay (within and outside the system) was also measured (but not optimized) and was reduced in some of the scenarios. Delay outside the system resulted from scheduled entry times that were later than the demanded times.
Constraints	Constraints include: separation requirements at the scheduling points, time window requirements, transit time limits with lower limits representing aircraft higher speed on a direct path and upper limits representing lower speed and path control, no passing on shared route segments, and limits on the amount of delay relative to FCFS.
Uncertainty	The formulation of the MILP is deterministic with increased buffers around the separation requirements to mitigate uncertainty. For example, larger buffers were used for the separation requirements between two aircraft that depart from different airports since they were not coordinated at takeoff.
Dynamic	Static with no replanning.
Distributed	Centralized.
Computation	Heuristics to speed up the algorithm included no-passing, schedule window size, and natural ordering which refers to limiting the delay relative to FCFS. The

	window size, for example, was selected to keep the computation time below one minute, which in some cases depleted the savings relative to no window limit. The MILP solved fifty aircraft in about one minute in the first paper and 8 aircraft problem in several minutes in the second paper. The genetic algorithm and linear program approach solved the eight aircraft problem in 4 seconds, and solved a 128 aircraft problem in 22 seconds with 10% optimality and in 120 seconds with 5% optimality.
Realism	Applied the approach to simplified problems abstracted form real situations. Used fictitious traffic with predesigned characteristics to highlight specific behavior. Considered a mix of weight classes and different traffic levels. Separation criteria simplified: for example using 3 nautical miles on the runway and 4 nautical miles at the fixes. For one example, used wake vortex separation requirements by weight class.
Maturity	Low maturity: Work is in prototyping mode with static algorithm implementation.
Key Results	Showed benefits of sharing resources versus procedural segregation in simplified problems.

Saraf/Sawhill	Aditya Saraf, Kris Ramamoorthy, Steven Stroiny, Bruce Sawhill, and Jim Herriot. Robust Integrated Arrival-Departure-Surface Scheduling Based on Bayesian Netwroks. 33nd IEEE/AIAA Digital Avionics Systems Conference (DASC), 2014
Problems	The approach integrates the scheduling and routing problems by solving 4D trajectories, hence possibly extending to the control problem. The tool is termed a spacing and scheduling decision support tool. For each scheduling problem a set of given spatial trajectories is used, and optimization is performed in the time domain by delaying flights. The alternate sets of trajectories however offer solutions that are spatially conflict free. Scheduling occurs by resolving conflicts at critical points such as the runways, gates and fixes, in a multi-point scheduling approach. The main issues addressed are handling uncertainty by explicitly modeling it and generating solutions that are best statistically over all the predicted possible scenarios. The work modeled the pre-pushback processes. In the application of the approach presented in the paper, however, only departures were used and the pre-pushback process was used to introduce uncertainty rather than connect an arrival to a departure.
System	The system is the metroplex between the terminal entry and exit points to the gates.
Flows	The approach is a generic 4D trajectory optimization that can integrate arrivals and departures, across the terminal and surface. The application only included departures, and specifically, scheduling the gate pushback time.
Algorithm	The algorithm in the concept design is a genetic algorithm; however, because of implementation issues, the algorithm used in the application is ration by schedule. Baysian belief networks (BBN) are used for modeling the uncertainties and are trained using simulation data. Matlab Bayes Net toolbox was used.
Objectives	The tool can optimize for fuel burn, flight time, variable cost index (VCI), required time of arrival, and more.
Constraints	Constraints include aircraft performance limits, separation requirements.
Uncertainty	Uncertainty is a major component of the approach. It is explicitly modeled using Baysian belief networks, which reduce the complexity of the probability distributions needed by identifying cause-effect interactions between the variables. Randomness is added at key points such as runways, gates, and fixes. A large number of scenario trajectories are generated. Each scenario is deterministic and optimized. Then a solution is selected as the best statistically among the scenarios. The optimal actions in each scenario are assessed based on their occurrence rate and the best actions statistically are applied.
Dynamic	Dynamic planning is part of the concept and SOSS is used as a simulation platform to be driven by the dynamic decisions of the tool.
Distributed	The optimization used “cooperative agents” which are described as computation agents that are assigned the task of finding an optimal path. It is not clear I these agents can be associated with aircraft, controllers, or users. In

	this sense the algorithm seems to be centralized and non collaborative, but the architecture may be extendible to support distributed schemes.
Computation	The approach is computationally expensive as thousands of scenarios are generated and explored with a high level of details to represent 4D trajectories. BBN are used to reduce the probability distributions needed and simplifications on the trajectory representation are mentioned as needed to reduce computational load. The example presented is simple both in terms of scope (only departures and only gate release time) and in terms of the algorithms used (ration by schedule) such that computation issues were not addressed. The approach seems to be far term in this sense, and the authors mention that it builds on the high computing power that is possible today.
Realism	The simplified problem dealing only with departures and with the gate release time was applied to a real case using JFK. It is not clear if the full problem is realistic when the simplifications are removed. It may become computationally infeasible. However, the architecture is amenable to simplifications. The analysis used simulation rather than actual data to validate the results.
Maturity	Low maturity: Work is in prototyping mode and was applied to a simple problem involving only departures and using simulation data rather than actual data for validation. The departure metering problem at JFK was used for a proof of concept experiment. The source of uncertainty was the pre-pushback process.
Key Results	Proof of concept experiment showed that delays on the order of one minute per flight are saved when aircraft were pushed using information about the uncertainty of the pushback process. This was contrasted with using the scheduled pushback time as the basis of the release decision.

Durant	Raphael Deau, Jean_baptiste Gotteland, and Nicolas Durand. Airport Surface Management and Runways Scheduling. Eighth USA?Europe Air Traffic Management Research and Development Seminar (ATM2009), Napa valley, CA.
Problems	Optimizing the runway sequences and resolving surface conflicts such as to best fit the optimized runway sequence. Also aircraft were metered at the gate and released based on their assigned takeoff time minus a taxi out time.
System	Runway, surface and gates.
Flows	Integrated arrivals and departures first by planning departures into a given arrival sequence. Then integrated the runway sequence into the surface movement by resolving surface conflicts and runway separation conflicts to minimize a cost function. The arrivals were allowed to move +/- 30 seconds to resolve conflicts. Also aircraft were metered at the gate and released based on their assigned takeoff time minus a taxi out time.
Algorithm	For the runway sequencing optimization a branch and bound algorithm is used. For the surface conflict resolution a clustering technique identifies clusters of conflicts and solves them individually. Decision variables included: the path of the flight, holding the flight at certain positions, and moving the landing time slightly. Then used two techniques: sequential resolution using branch and bound and a genetic algorithm to find the optimal solution. In the sequential algorithm the order of the conflict resolutions was based on the runway slot time. After landing the priority of the landed flights is decreased to favor the departing flights. The genetic algorithm was used to generate the prioritization of the order by which conflicts are resolved then the branch and bound algorithm was applied to the GA generated order. Applied a strategic off-block control to keep aircraft at the gate and then to pushback at their assigned runway takeoff time minus an unimpeded taxi time. This is no mention of controlling a departure queue length.
Objectives	A cost function (penalization) is defined for each flight: high cost of violating the required flow management time slot, otherwise linear in delay for non restricted departures. Arrivals are not penalized in the runway optimization because they are not re-sequenced. For the integration into surface movement, the arrival ground delay (after landing) was penalized such that higher priority is given to the departing flights. Arrivals are moved +/- 30 seconds to resolve surface conflicts.
Constraints	Constraints include: Separation requirements and flow management time slot restrictions (allowed to be violated but with high penality). For the integration into the surface movement used separations between aircraft on the surface of 60 meters and used runway wake turbulence separations in addition to clearing the runways. Arrivals are moved +/- 30 seconds to resolve surface conflicts.
Uncertainty	Used uncertainty in the taxi operations using distribution of taxi speed.
Dynamic	Approach attempts to synchronize the AMAN/DMAN horizon of 30 minutes with

	SMAN conflict resolution horizon of 5 minutes. The DMAN predicts and schedules over 30 minutes, then the SMAN solves conflicts for 5 minutes, then the DMAN updates and reschedules based on the new SMAN decisions, with an update rate.
Distributed	The approach integrated different components of AMAN/DMAN and SMAN.
Computation	The runway sequencing problem is solved on successive time windows of length 10 – 60 minutes. This windowing strategy reduces the computation needs. The branch and bound search algorithm is simplified by disallowing swapping arrivals, swapping equivalent departures (where there is no impact on delay) and swapping independent departures that do not overlap in time.
Realism	Applied the approach to one day at Roissy Charles De Gaulle with heavy traffic and a configuration with one arrival runway, one departure runway and a mixed operation runway, and arrivals have to cross the departure runway.
Maturity	Low maturity: Work is in prototyping mode with demonstration using a simulation of one day at CDG.
Key Results	Showed that open-loop simulation of departures with taxi conflict results in larger delay than a FCFS runway schedule that assumes no taxi delays. Then an optimized runway schedule saved time relative to the FCFS schedule. Showed delay savings when integrating the runway schedules with the surface movement planning, where using GA ordering performed better than sequential resolution, which was in turn better than FCFS. The prioritization based on the genetic algorithm reduced particularly the delays of arrival aircraft after landing, because it did not need to prioritize departures over arrivals, which was done in the sequential approach.

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