NOVEL, MULTIDISCIPLINARY GLOBAL OPTIMIZATION UNDER UNCERTAINTY

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NASA LEARN Project Final Briefing
01/15/2015
PRESENTATION OUTLINE

- Introduction: The Metroplex Problem and Its Challenges
- Overview of the Project: Our Solution for Addressing the Challenges
- Project Technical Approach
- Results to Date
- Significance of Our Innovation
- Next Steps: Plans for Phase II Research Work
THE METROPLEX PROBLEM

- Two or more busy airports in close proximity
- Shared entry/exit points to the terminal airspace
- Inter-dependent, crossing arrival and departure flows
- Several traffic control facilities involved

SIGNIFICANCE TO THE NATIONAL AIRSPACE SYSTEM

- FAA’s Future Airport Capacity Task team report(1)
  - Eight metropolitan areas would require additional capacity by 2025, even after taking FAA’s planned improvements into consideration

- RTCA NextGen Mid-Term Implementation Task Force 5(2)
  - “Relieve congestion and tarmac delays at major metropolitan airports, inefficiencies at satellite airports, and surrounding airspace”

- Key Aeronautics Challenges (National Aeronautics R&D Plan(3))
  - Increasing airport approach, surface and departure capacity, and
  - Developing capability to perform four-dimensional trajectory (4DT)-based planning

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THE CHALLENGES TO AN OPTIMIZED, DE-CONFLICTED 4DT SOLUTION

- Complex interactions and network impacts
  - Requires integrated planning across airport surface and terminal airspace

- Uncertain future traffic behavior
  - Requires planning under the possibility of multiple different futures

- Competing and nonlinear objectives
  - Requires optimization-algorithms capable of handling complex objective functions
OUR LEARN PROJECT—OVERVIEW

Objectives:

- Develop 4DT-based traffic management tool called **PROCAST** by combining cutting-edge technologies from two diverse fields
  - Predictive technology/Data Science: Bayesian Belief Networks (BBNs)
  - Optimization technology: NGA’s Continuous Re-planning Engine (NACRE)

- Perform proof-of-concept demonstration by conducting simulation experiments using a test problem—New York metroplex traffic scheduling
  - In Phase I, we focus on a single-airport, arrival-departure-surface scheduling problem
  - Selected John F. Kennedy International Airport (JFK) as the focus site

- Enhance NASA simulation platform to enable terminal airspace traffic simulation and pre-pushback process modeling

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**PROCAST**—Probabilistic Robust Optimization of Complex Aeronautics Systems Technology
**WHAT IS THE INNOVATION?**

**BBNs:** Incorporate current state and past “learning” (historical data-mining and SME-defined causal relationship models) for generating realistic futures.

**Genetic Algorithms:** 4DT optimization over multiple flight domains; flexible objective functions; incremental “learning” over each successive planning iteration for fast computation.

**Current State**

**Metroplex Traffic**

**Flight Release Times**

**Select Statistically-Best Flight Release Times To Handle All Futures**

**Generate Possible Futures**

**1000s of Possible Futures**

**How to compute realistic futures?**

*Can we optimize over entire gate-to-terminal airspace boundary domain fast?*

**Optimize Every Future Scenario**

**Flight Release Times for Every Possible Future**
PHASE I TECHNICAL APPROACH

- Enables planning under uncertainty
- Can work with partial information
- Accounts for interaction and network effects

**NASA’s SOSS**

**Airport Surface Traffic Simulation Platform**

**Current State**

**PROCAST**

- Select Statistically-Best Flight Release To Handle All Futures
- Flight Release Times for Every Possible Future

**Bayesian Belief Network**

- 1000s of Possible Futures
- Optimize Every Future Scenario

**GA Trajectory Optimizer**

- Fast 4DT optimization covering surface and terminal airspace
- Flexible objective function definition

**Enables planning under uncertainty**
**Can work with partial information**
**Accounts for interaction and network effects**
PROCAST ELEMENTS

- Bayesian Belief Networks
  - Estimating pushback readiness times and transit times on airport surface

- NACRE Genetic Algorithm for optimizing 4D trajectories

- SOSS simulation platform enhancements
  - Added modeling of terminal airspace traffic
  - Added pre-pushback process uncertainty models

- Simulation-based benefits assessment of PROCAST
  - Modeled current-day operations at JFK as a comparison baseline
  - Compared simulation performance using realistic traffic scenarios

- Concept of operations for PROCAST DST
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WHAT ARE BAYESIAN BELIEF NETWORKS (BBNs)?

- BBN is a directed, acyclic graph
  - Nodes: Variables of interest
  - Arcs: Statistical or causal dependencies

- BBNs decompose complex joint probability distributions into smaller factors using conditional independence

- Subject matter experts design the graph structure using insights about the processes

- Machine learning is used to “learn” the parameters

- BBNs provide fast inference for
  - Prediction (from causes to effects)
  - Diagnosis (from effects to causes)
  - Explaining away (tie-break between two or more causes)

*A Simple BBN Example*
1. Analyze Historical Traffic Data and Identify Key Influencing Factors

2. Use Subject Matter Expertise To Model Causal Relationships in a Graph

3. Train the Graph Parameters Using Recorded or Simulated Historical Traffic Data
GENERATING REALISTIC FUTURE SCENARIOS USING BBNs

Random Process model of pre-pushback subtasks
(de-boarding, fuelling, boarding)

Current State of Pre-pushback Processes

Predict Pushback Readiness Times for All Departure Flights Currently at Their Gates

Current State of Surface Traffic

Predict Factors Influencing Taxi Time of Subject Flight

Predict Probability Distribution For Runway Departure Time for the Subject Flight

Sample from the Probability Distribution to Generate Multiple Possible Futures
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THE PROBLEM ADDRESSED BY NACRE

- The most valuable resource of an airport are its runways

- To sequence runways, consider
  - Wake vortex separation (weight class of aircraft)
  - Interleaving of arrivals
  - Departure fix
  - Frequent updates to arrival/departure information (PROCAST)

- How NACRE works
  - First optimize runway usage (arrivals and departures)
  - Then organize surface traffic planning around runway usage
  - Avoid using tarmac for aircraft storage
SEARCH SPACE SIZE-RUNWAY SEQUENCING

Number of Aircraft to be sequenced vs. Number of Different Sequences

- All possible permutations
- 2-place permutations
- 1-place permutations

Too Hard!

OK!
NACRE GA encodes runway sequencing
- Position shifts encoded as elements in a genome
- Quality of solutions evaluated
  - By throughput
  - By sum of squares of delays (to prevent any one aircraft from getting all the pain)

A genetic algorithm (GA) encodes partial solutions, like a genome.
- GAs work well when partial solutions are well – correlated to complete solutions. In the runway sequencing problem, reorderings in different parts of the sequence contribute mostly additively to fitness.
HOW MANY SMALL SEARCHES COVER LARGE SPACES

Original sequence

One permutation away

One permutation away

One permutation away

Net movement

20132020
AN INNOVATIVE APPROACH TO OPTIMIZING SURFACE MOVEMENTS

- Surface dynamics driven ultimately by optimized runway schedule
- Start with runway schedule, calculate taxi dynamics backwards in time to meet schedule
- Deconflict by “rigid time translation”
  - Leave gate earlier by time T sufficient for deconfliction
  - Wait at runway queue for the same time T
  - Runway queue acts as shock absorber
  - Minimize number of aircraft in motion on airport surface

**Node 1**
- Initial Trajectory (with conflict)
  - $t_1$

**Node 2**
- Initial Trajectory (with conflict)
  - $t_2$

**Node 3**
- Initial Trajectory (with conflict)
  - $t_3$

**Node 1**
- Modified Trajectory (w/o conflict)
  - $t_1-T$

**Node 2**
- Modified Trajectory (w/o conflict)
  - $t_2-T$

**Node 3**
- Modified Trajectory (w/o conflict)
  - $t_3-T$
NACRE SEQUENCER/OPTIMIZER
SUMMARY OF FUTURE DIRECTIONS

- Optimize on additional criteria:
  - Economically (based on A/C cost model, number of pax, etc.)
  - Airline Network integration (priority of flight depends on context, such as having to meet connecting flights or not)
  - History of delays (spread delays around fairly by airline, aircraft, etc.

- Use “hot start” capability of GA for bigger/harder problems
  - For sufficiently rapid replanning cycles, much of old solution is still valid
  - GAs strong point is incorporation of “partial solutions”

- Scale the GA to bigger/harder problems
  - Preserve speed so as to keep using BBN capability in real-time
  - Parallelizable on inexpensive hardware (GPU card, for instance)
  - Metroplex ground/TRACON problem
PROCAST ELEMENTS

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  - Added modeling of terminal airspace traffic
  - Added pre-pushback process uncertainty models

- Simulation-based benefits assessment of PROCAST
  - Modeled current-day operations at JFK as a comparison baseline
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- Concept of operations for PROCAST DST
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SIMULATION-BASED BENEFITS ASSESSMENT

SIMULATION TRAFFIC SCENARIO

- Selected one of the most commonly used runway configurations for simulation

- Derived realistic traffic scenarios from recorded surface surveillance (ASDE-X) data and airline schedules (OAG)

- Selected three 2-hour busy-traffic time-periods from 2013 for simulation
  - Scenario #1: November 24, 2013; 7 to 9 PM Local time; 82 departures, 63 arrivals

- Simulation Parameters
  - Planning Horizon: 45 minutes
  - Planning Frequency: Once every 5 minutes
SIMULATION-BASED BENEFITS ASSESSMENT

Compared simulated JFK surface and terminal operations as controlled by PROCAST against simulated current-day baseline operations.

<table>
<thead>
<tr>
<th>Scheduling method for Departures</th>
<th>Baseline Operations</th>
<th>PROCAST Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Simple, deterministic departures-only planning similar to current-day Departure Management Tools</td>
<td>• Combined arrival-departure planning</td>
</tr>
<tr>
<td></td>
<td>• Uses nominal pushback readiness time estimates</td>
<td>• Assumes periodic updates of pre-pushback process state</td>
</tr>
<tr>
<td></td>
<td>Deterministic arrivals-only planning based on current-day Traffic Management Advisor (TMA) scheduling algorithms</td>
<td>• BBNs generate multiple futures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Including estimates of pushback readiness times and times of arrival at key nodes in the surface-terminal network</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• GA optimizes arrival and departure operations over each future</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Statistical assessment selects best flight release times</td>
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### Two Other Variants of Procast

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<th>BBNs-only Operations</th>
<th>NACRE-only Operations</th>
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<td></td>
<td>• Assumes periodic updates of pre-pushback process state</td>
<td>• Combined arrival-departure planning</td>
</tr>
<tr>
<td></td>
<td>• BBNs generate multiple futures</td>
<td>• Only one future scenario is generated using nominal estimates of pushback readiness times, as in baseline operations</td>
</tr>
<tr>
<td></td>
<td>• Departures-only planning similar to baseline for each future scenario</td>
<td>• GA optimizes arrival and departure operations over only one future scenario</td>
</tr>
<tr>
<td></td>
<td>• Statistical assessment selects best flight release times</td>
<td></td>
</tr>
</tbody>
</table>

| Scheduling method for Arrivals   | Arrivals-only planning similar to baseline for each future scenario | |
|----------------------------------|--------------------------|
DELAY DISTRIBUTION FOR DEPARTURES

November 24, 2013, 7-9 PM Local Time Traffic Scenario (82 Departures)
DEPARTURE BENEFITS OVER MULTIPLE TRAFFIC SCENARIOS

<table>
<thead>
<tr>
<th>Traffic Scenario</th>
<th>BBNs-only Savings</th>
<th>NACRE-only Savings</th>
<th>PROCAST Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 24, 7-9 PM (82 departures, 63 arrivals)</td>
<td>+ 8%</td>
<td>- 6%</td>
<td>+16%</td>
</tr>
<tr>
<td>November 27, 8-10 PM (72 departures, 60 arrivals)</td>
<td>+ 12%</td>
<td>+ 0.2%</td>
<td>+24%</td>
</tr>
<tr>
<td>October 27, 11 AM-1 PM (62 departures, 90 arrivals)</td>
<td>+ 8%</td>
<td>+ 5%</td>
<td>+17%</td>
</tr>
</tbody>
</table>
Assuming similar conditions prevail for 100 days per year:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Delay</td>
<td>2,400 hours</td>
</tr>
<tr>
<td>Total Delay in Metroplex</td>
<td>3,000 hours</td>
</tr>
<tr>
<td>Fuel</td>
<td>155,000 gallons</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>$322,000</td>
</tr>
<tr>
<td>Operating Costs</td>
<td>$5 million</td>
</tr>
<tr>
<td>CO$_2$ Emissions</td>
<td>9.8 metric tons</td>
</tr>
<tr>
<td>Passenger Time</td>
<td>14,000 person-days</td>
</tr>
<tr>
<td>Passenger Time @ $30/hr</td>
<td>$10 million</td>
</tr>
<tr>
<td>Passenger Time NAS-wide</td>
<td>$15 million</td>
</tr>
</tbody>
</table>

Fuel burn rate = 8 kg / min taxiing, 40 kg / min airborne, cost = $993.60 / metric ton

Operating costs = $27 / min at gate, $41 / min taxiing, $78 / min airborne

1 minute savings in NYC = 1.5 minute savings NAS-wide*

Assumptions:

PROCAST ELEMENTS

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PROCAST CONCEPT OF OPERATION

- ATCSCC
- TRACON
- Center

**TRACON Delays or Path Stretches**

- Metroplex Coordination Center
  - TMI Mods
  - En Route Delays

**Departure Reroutes**

- Tower Airport A
- Tower Airport B
- Tower Airport C

**Runway Departure Times, Taxi Merge Sequences**

- Gate Release Times

- Ramp Airport A
- Ramp Airport B
- Ramp Airport C
SUMMARY AND KEY LESSONS LEARNED

- PROCAST showed significant benefits in proof-of-concept simulation experiments
  - 3000 hours of delays saved, $322K annual savings in fuel cost, $5 million savings in operating cost, $15 million in passenger time savings

- Predictive component by itself (BBNs-only) showed benefit
  - Speed of computation limited our ability to assess scheduling over a large number of possible futures

- Optimization-only component (NACRE-only) did not show benefit
  - Apparently sensitive to uncertainty in gate pushback readiness times
SIGNIFICANCE OF PROCAST

- Helps NASA address key aeronautics technical challenges

- Provides optimization tools and predictive capabilities that can be utilized in multiple existing NASA programs
  - Predictive and optimization support for IADS traffic scheduling algorithms
  - Coordinating surface planning with gaps in overhead en-route traffic streams
  - Predicting Traffic Management Initiatives (TMIs)
  - Evaluating candidate TMIs for Traffic Flow Management decision support

- Provides a platform for enhancing and validating NASA’s airport surface simulation tool SOSS

- Applicable to any problem with three features: (i) Complex interactions/network effects, (ii) Uncertainty, and (iii) Competing objectives
  - ATM safety assessment
  - Passenger-focused air traffic management
  - Non-ATM areas such as road transportation
# NEXT STEPS

<table>
<thead>
<tr>
<th>Phase I Findings</th>
<th>Next Steps (Phase II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single airport showed benefits; coordination across metroplex airports may be even more beneficial</td>
<td>Extend algorithms to a New York metroplex-wide scope including JFK, EWR, LGA, TEB</td>
</tr>
<tr>
<td>Current optimization capability does not fully address delay equity among airlines and airline economic objective optimization</td>
<td>Incorporate equity considerations and airline economic considerations (e.g., based on aircraft cost model, AOC data, number of pax, etc.)</td>
</tr>
<tr>
<td>Current optimization does not fully integrate runway sequence planning with ramp/taxiway CD&amp;R</td>
<td>Enhance optimization algorithms; explore existing NASA algorithms</td>
</tr>
<tr>
<td>Computation time limited ability to assess optimization over large number of possible futures</td>
<td>Explore the iteration space; assess computation acceleration, e.g., leverage parallelization</td>
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<tr>
<td>Current modeling in SOSS limited to a single airport</td>
<td>Modeling traffic on multiple metroplex airport surfaces and in terminal airspace</td>
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</table>
| Discussions with NASA IADS, ATD-2, and New York TBO research activity planners and researchers  
  - NASA AFH branch seminar  
  - Multiple meetings throughout the year | • Definite interest in New York metroplex traffic management DSTs—analyze test cases  
• Enhanced SOSS will benefit IADS research  
• Potential to benefit NASA Traffic Flow Management/Machine Learning research |
PUBLICATIONS

Papers

- Digital Avionics Systems Conference 2014: “Robust, Integrated Arrival-Departure-Surface Scheduling Based On Bayesian Networks”

Presentations

- NASA AFH Branch Seminar—1/6/2015
- Presentations to NASA SOSS simulation group—multiple
- NASA Open House Poster presentation—October 2014
- Presentation to FAA/JPDO representative, Sherry Boerner—July 2014
- Presentation to NASA SARDA research group—June 2014
ACKNOWLEDGEMENTS

Thanks to…

- NARI—for the support of this project and for fostering collaboration with NASA and LEARN researchers
- Robert Windhorst, Yoon Jung—for letting us use SOSS
- Zhifan Zhu and Sergei Gridnev—for SOSS software support
- NASA SARDA, ATD-2, IADS, and New York TBO researchers—for positive feedback throughout the project
- Kristin Rozier, Johann Schumann—for pointers on Bayesian Belief Network software
- Kris Ramamoorthy and Katy Griffin (ex-Saab employees)—for your technical contributions
QUESTIONS?
(SIMULATION PLAYBACK VIDEO)

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