This presentation covers fundamental requirements and considerations for developing schedulers in airport operations. We first introduce performance and functional requirements for airport surface schedulers. Among various optimization problems in airport operations, we focus on airport surface scheduling problem, including runway and taxiway operations. We then describe a basic methodology for airport surface scheduling such as node-link network model and scheduling algorithms previously developed. Next, we explain how to design a mathematical formulation in more details, which consists of objectives, decision variables, and constraints. Lastly, we review other considerations, including optimization tools, computational performance, and performance metrics for evaluation.
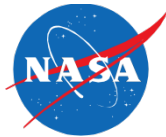
Scheduler Design Criteria: Requirements and Considerations

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Outline

- Requirements for scheduler development
- Problem scope
  - Optimization problems in airport operations
  - Assumptions and problem-solving approaches
- Methodology for airport surface scheduling
  - Node-link network model
  - Scheduling algorithms
- Problem Formulation
  - Objectives and decision variables
  - Constraints
- Other considerations
  - Optimization tools
  - Computational performance
  - Performance metrics for evaluation

General Requirements

- General requirements for software development
  - External interface requirements
  - Functional requirements
  - Performance requirements
  - Design constraints
    - Standards compliance
  - Logical database requirement
  - Software system attributes
    - Reliability, Availability, Security, Maintainability, Portability
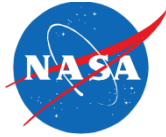 - Other requirements
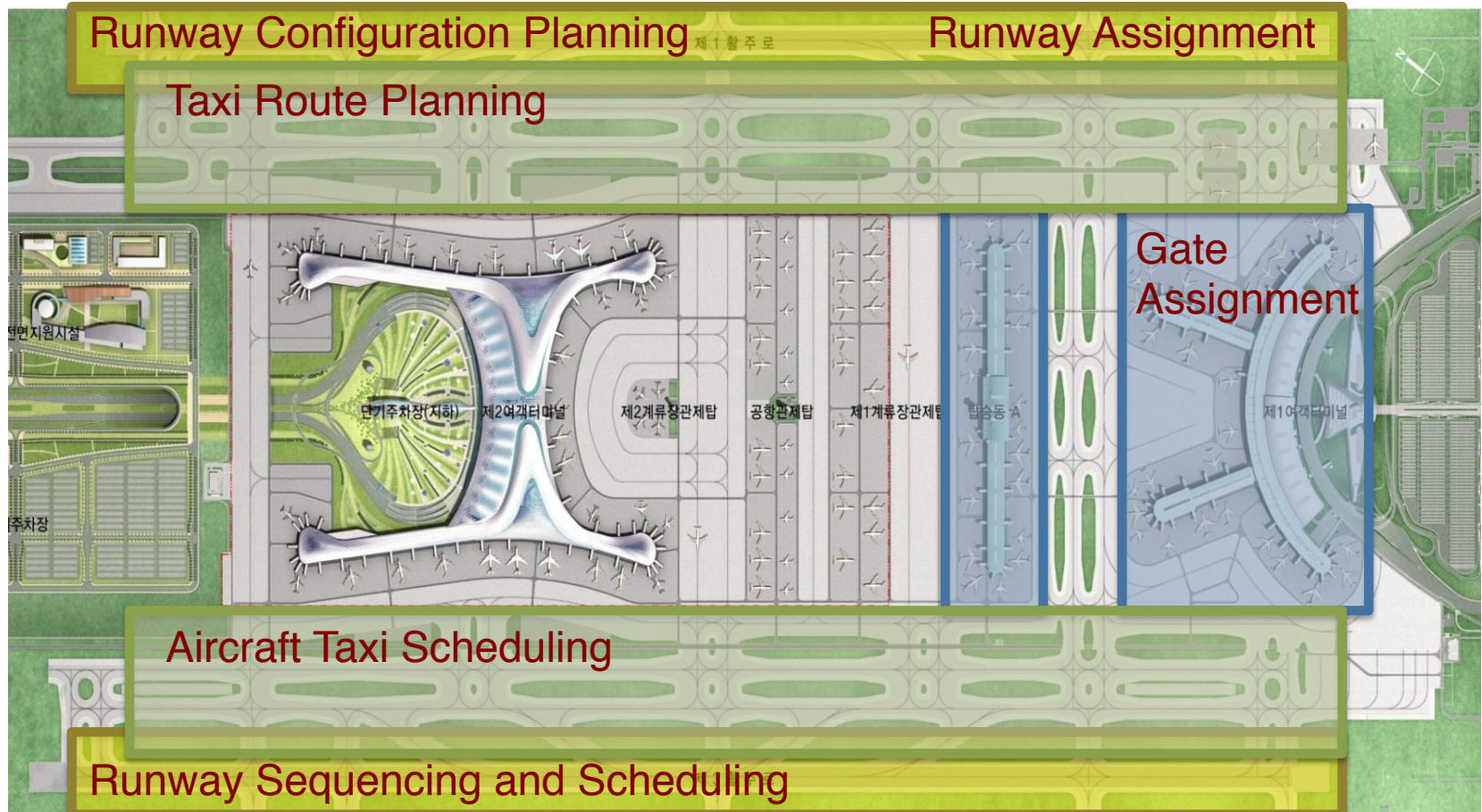
Requirements for Scheduler Development

- Performance requirements for schedulers in airport operations
  - Efficiency: Reduce flight delays and operational costs
  - Throughput: Increase airport capacity
  - Safety: Guarantee safe operations
  - Fairness: Consider fairness between airlines
  - Workload: Mitigate user (controller) workload
  - Predictability: Provide better estimates for target movement times
  - Robustness: Be robust against uncertainties
  - Environmental effect: Reduce fuel burn and gas emissions

- Functional requirements for schedulers in airport operations
  - Feasibility: Provide a feasible solution in real operations
  - Computational Tractability: Calculate a solution in a short time
  - User Interface: Easy to enter input data and use schedule output
  - Flexibility: Update a schedule easily to reflect dynamic situations
  - Expandability: Accommodate other objectives and conditions and connect with other decision support tools

Problem Scope

- What problem do you want to solve?

Runway Configuration Planning   Runway Assignment

Taxi Route Planning

Gate Assignment

Aircraft Taxi Scheduling

Runway Sequencing and Scheduling

Optimization Problems in Airport Operations

- Runway Configuration Planning [1]
  - To determine the best runway configuration under the given traffic demand, weather condition, and environmental constraints

- Runway Sequencing and Scheduling [2-9]
  - To provide the optimal sequence and schedule for runway use, including takeoff, landing, and crossing, given operational constraints and available time window

- Taxiway Scheduling [10-20]
  - To provide the optimal sequence and schedule of taxiing aircraft at significant control points on taxiways, given operational constraints and available time window

- Runway Assignment [21]
  - To determine the optimal runway for each flight between multiple runways for runway balancing, given runway use times, flight information, and airline preference

- Gate Assignment [22, 23]
  - To assign flights to the best gates for passenger transit and aircraft operations, given turnaround times and gate operational constraints

- Taxi Route Planning [10, 24]
  - To find the optimal taxi routes of aircraft on airport surface, given gates and runways
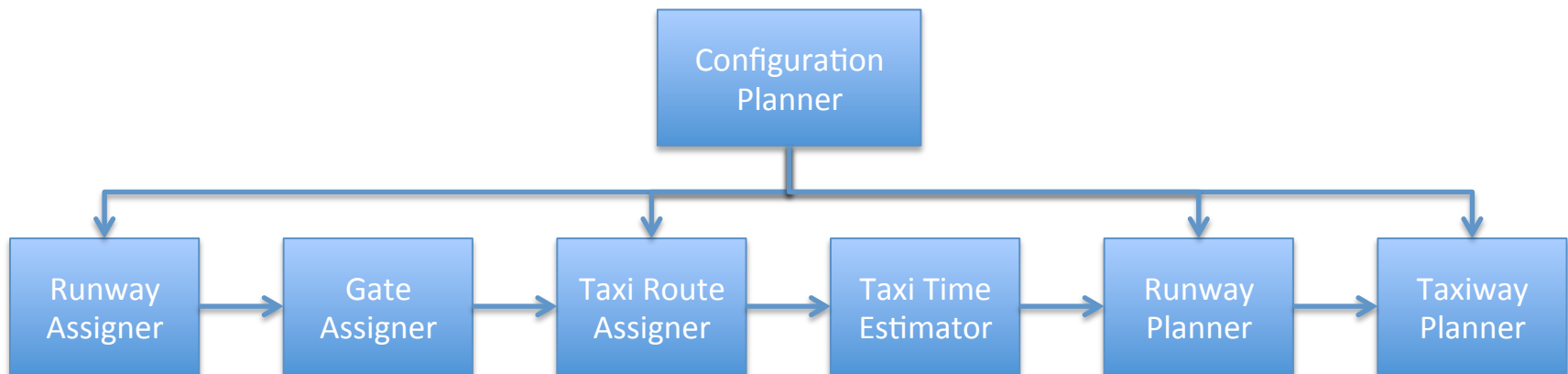
Assumptions

- Runway Configuration Planning
  - Traffic demand and weather forecasts are given and reliable.
- Runway Sequencing and Scheduling
  - Airlines agree to adjust the runway order within a limited range.
  - Earliest possible takeoff/landing times are given.
- Taxiway Scheduling
  - Given gate and runway, aircraft taxi routes are predefined.
- Runway Assignment
  - Assigned runways can be changed within the given time frame.
  - Estimated takeoff/landing times are given.
- Gate Assignment
  - Assigned gates can be changed within the given time frame.
  - Scheduled gate-in/out times are given.
- Taxi Route Planning
  - Given gate and runway, multiple taxi route options are available.

Solving Multiple Problems

- ## Integrated Approach [10, 14, 15]
  - All-in-one method that considers all constraints simultaneously
  - Takes longer time to find the optimal solution and sometimes fails to find a feasible solution
  - Needs a tradeoff between multiple objectives

- ## Sequential Approach [12, 16, 25]
  - Connects several modules separately developed for each purpose
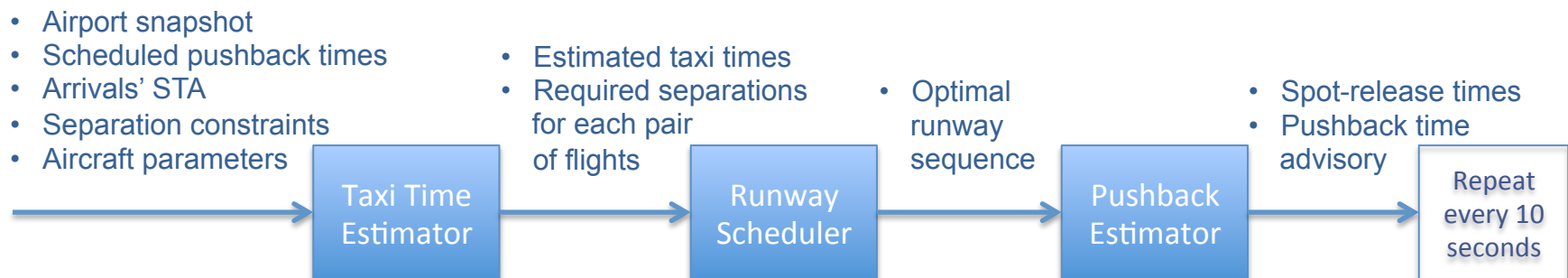 - May find the sub-optimal solution with given values from prior phases

Airport Surface Scheduling

- Optimizing runway and taxiway schedules
  - Shift the waiting times in the departure queues to gates to mitigate surface congestion and reduce taxi delays and fuel burn

- Assumptions
  - Gate, runway, and taxi route are already assigned.
  - Scheduled pushback times and estimated landing times are given.

- Expected output
  - Optimal pushback times (or spot release times) for departures
  - Optimal takeoff sequence and times for departures
  - Optimal runway crossing times for taxiing aircraft (e.g., arrival crossing departure runway)
  - Estimated gate arrival times (or ramp area entering times) for arrivals

Spot and Runway Departure Advisor (SARDA)

- SARDA solution
  - Better coordination through sufficient data exchange
  - Intelligent departure metering that shifts taxi delay to the gate
- Case studies
  - SARDA-DFW (2010, 2012): Tower controller decision support tool for Dallas/Fort Worth airport (DFW) [26, 27]
  - SARDA-CDM (2012): Collaborative Decision Making (CDM) [28]
  - SARDA-CLT (2015): Ramp controller's decision support tool for Charlotte airport (CLT) [29]

- Airport snapshot
- Scheduled pushback times
- Arrivals' STA
- Separation constraints
- Aircraft parameters

- Estimated taxi times
- Required separations for each pair of flights

- Optimal runway sequence

- Spot-release times
- Pushback time advisory

| Taxi Time Estimator | → | Runway Scheduler | → | Pushback Estimator | → | Repeat every 10 seconds |

Node-Link Network

- Airport surface can be modeled using a node-link network.
- Nodes
  - Represent significant control points on airport surface & terminal area
    - Gates, holding points, hardstands, spots, taxiway intersections, runway thresholds, runway exits, and runway crossings
    - Departure fixes and arrival fixes
- Links
  - Connect nodes and represent taxiways, runways, taxi routes, and air routes [13-15, 19]
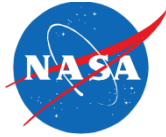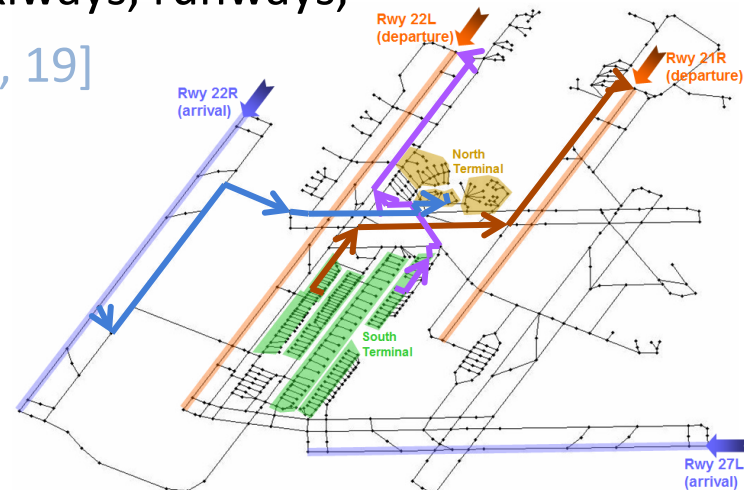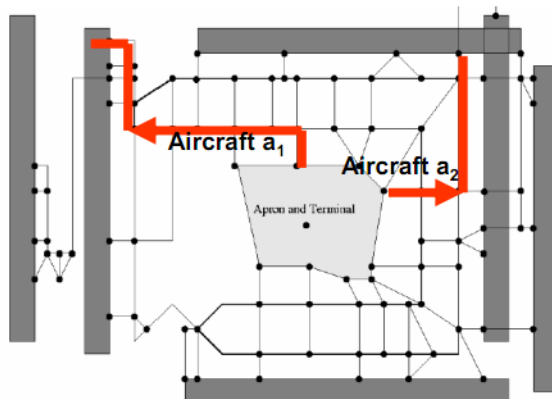
Scheduling Algorithms

- First-Come, First-Served (FCFS) discipline
  - Baseline to represent current operations
- Heuristic algorithms [5, 11, 18, 22, 23]
  - A practical method, not guaranteed to be optimal, but satisfactory
  - Search algorithms like Genetic algorithm, Tabu Search
- Dynamic programming [3, 4, 6-9]
  - Examines the previously solved sub-problems and combines their solutions to find the best solution
- Linear programming [12-17, 19, 20, 24, 30-32]
  - A mathematical formulation of a linear objective function, subject to linear equality/inequality constraints
  - Mixed Integer Linear Programming (MILP) models, Integer Programming (IP) models

Objectives

- Candidates for optimization goals
  - Maximize runway throughput
    - Equivalent to minimize makespan in a given flight group
  - Minimize aircraft travel times or delays
  - Minimize the maximum delay in a given flight group
  - Minimize fuel consumptions
  - Minimize aircraft operating cost
  - Minimize unfairness between airlines
  - Minimize controller workload
    - Minimize the number of interventions from controllers
  - Maximize schedule robustness under uncertain conditions [3, 8, 23]
    - Minimize the total expected safety violation
- Multiple objectives can be defined.

Decision Variables

- Controllable values in the optimization problem

- Continuous variables

  - Runway use times

  - Passage times at control points on airport surface

  - Example: $t_{i,u} \geq 0, \forall i \in \mathcal{D} \cup \mathcal{A}, u \in \mathcal{N}$

    - Time when aircraft *i* enters node *u*

- Binary variables

  - Runway sequence (takeoff, landing, crossing)

  - Sequence at taxiway intersections

  - Example: $z_{ij}^u \in \{0, 1\}, \forall i, j \in \mathcal{D} \cup \mathcal{A}, i \neq j, u \in \mathcal{I}$

    - The binary variable will be one, if aircraft *i* enters node *u* earlier than aircraft *j*; otherwise, it equals to zero.

Constraints

- Safety constraints
  - Runway separation requirements due to wake turbulence
  - Minimum spacing distance between taxiing aircraft
- Time constraints
  - Earliest/Latest possible pushback times for departures
    - Earliest Off Block Time (EOBT), Maximum gate-holding
  - Earliest/Latest possible runway arrival times for departures
  - Estimated landing times for arrivals
  - Traffic Management Initiatives (TMIs) such as EDCT, CFR, MIT, and MINIT
  - Frozen flights: existing flights on taxiways, already optimized in previous runs
- Operational constraints
  - Aircraft taxi speed range
  - No overtaking allowed on straight taxiways [13, 31]
  - Airlines request (e.g., critical flights, airlines preference)
  - Runway slots (e.g., limit in takeoffs per hour to the same departure fix)

Separations

- Over runways
  - Wake-vortex separation criteria, depending on weight classes
    - Departure-departure
    - Arrival-arrival
  - Separation between arrivals and departures for mixed use runway
    - Departure-arrival
    - Arrival-departure
  - Separation between arrivals and departures for runway crossings
  - Separation between arrivals and departures for converging runway operations
- In terminal airspace
  - Area Navigation (RNAV) separation
  - Separation between departures from parallel runways going to same fix
  - Separation between departures going to same constraint fix (MIT)

MILP Model Example

- Mathematical formulation [15]

Runway Delay   **Taxi-out Time**   **Taxi-in Time**

$$\text{minimize} \sum_{i\in\mathcal{D},r\in\mathcal{R}} \alpha_r(t_{i,r} - \text{EarliestOffT}_{i,r}) + \alpha_d\left(\sum_{i\in\mathcal{D},r\in\mathcal{R}} t_{i,r} - \sum_{i\in\mathcal{D},g\in\mathcal{G}} t_{i,g}\right) + \alpha_a\left(\sum_{i\in\mathcal{A},g\in\mathcal{G}} t_{i,g} - \sum_{i\in\mathcal{A},r\in\mathcal{R}} t_{i,r}\right)$$

$$\text{subject to } z_{ij}^u + z_{ji}^u = 1, \forall i,j \in \mathcal{D}\cup\mathcal{A}, i\neq j, u\in\mathcal{I} \qquad \textbf{: Sequencing constraint}$$

$$t_{i,v} \geq t_{i,u} + \text{MinTaxiT}_{uv}, \forall i\in\mathcal{D}\cup\mathcal{A}, (u,v)\in\mathcal{E} \qquad \textbf{: Max taxi speed}$$

$$z_{ij}^u = z_{ij}^v, \forall i,j\in\mathcal{D}\cup\mathcal{A}, i\neq j, u,v\in\mathcal{I}, (u,v)\in\mathcal{E} \qquad \textbf{: Overtaking avoidance}$$

$$z_{ij}^u + z_{ji}^v = 1, \forall i,j\in\mathcal{D}\cup\mathcal{A}, i\neq j, u,v\in\mathcal{I}, (u,v)\in\mathcal{E} \qquad \textbf{: Head-on conflict avoidance}$$

$$t_{j,u} - t_{i,u} - (t_{i,v}-t_{i,u})\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -(1-z_{ij}^u)M, \forall i,j\in\mathcal{D}\cup\mathcal{A}, i\neq j, u\in\mathcal{I}, (u,v)\in\mathcal{E} \qquad \textbf{: Min separation on taxiway (1)}$$

$$t_{j,v} - t_{i,v} - (t_{j,v}-t_{j,u})\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -(1-z_{ij}^v)M, \forall i,j\in\mathcal{D}\cup\mathcal{A}, i\neq j, v\in\mathcal{I}, (u,v)\in\mathcal{E} \qquad \textbf{: Min separation on taxiway (2)}$$

$$t_{j,r} - t_{i,r} - \text{Rsep}_{ij} \geq -(1-z_{ij}^r)M, \forall i,j\in\mathcal{D}, i\neq j, r\in\mathcal{R} \qquad \textbf{: Min separation on runway}$$

$$t_{i,r} \leq \text{EarliestOffT}_{i,r} + \text{MaxRunwayDelay}_{i,r}, \forall i\in\mathcal{D}, r\in\mathcal{R} \qquad \textbf{: Takeoff time window}$$

$$t_{i,g} \geq \text{OutT}_{i,g}, \forall i\in\mathcal{D}, g\in\mathcal{G} \qquad \textbf{: Earliest possible pushback time}$$

$$t_{i,g} \leq \text{OutT}_{i,g} + \text{MaxGateHold}_{i,g}, \forall i\in\mathcal{D}, g\in\mathcal{G} \qquad \textbf{: Latest possible pushback time}$$

$$t_{i,r} = \text{OnT}_{i,r}, \forall i\in\mathcal{A}, r\in\mathcal{R} \qquad \textbf{: Landing time}$$

$$t_{i,u} = \text{FrozenT}_{i,u}, \forall i\in\mathcal{D}'\cup\mathcal{A}', u\in\mathcal{N} \qquad \textbf{: Existing flights on taxiway}$$

$$z_{ij}^u \in \{0,1\}, \forall i,j\in\mathcal{D}\cup\mathcal{A}, i\neq j, u\in\mathcal{I} \qquad \textbf{: Sequencing variable}$$

$$t_{i,u} \geq 0, \forall i\in\mathcal{D}\cup\mathcal{A}, u\in\mathcal{N} \qquad \textbf{: Continuous time variable}$$

Optimization Tools

- Optimization Solvers
  - ILOG (Commercial): IBM ILOG CPLEX Optimization Studio
    - http://www-01.ibm.com/software/info/ilog/
  - Gurobi (Commercial): Gurobi Optimizer 6.5
    - http://www.gurobi.com
  - Xpress (Commercial): FICO Xpress Optimization Suite
    - http://www.fico.com/en/products/fico-xpress-optimization-suite
  - MOSEK (Commercial)
    - https://www.mosek.com
  - YALMIP: free optimization toolbox for MATLAB
    - http://users.isy.liu.se/johanl/yalmip/pmwiki.php?n=Main.Download
- Programming languages for optimization
  - AMPL: A Modeling Language for Mathematical Programming [33]
    - http://ampl.com
  - Python, R, C, Java, MATLAB, …

Computational Performance

- Runtime
  - Includes pre-processing time to prepare input data, post-processing time to summarize the optimization output, and computation time spent to find the optimal solution
  - Important for real-time implementation
  - Depends on the problem size, hardware computing power, and algorithm's complexity
- How to improve computational performance
  - Reduce the number of flights in the given schedule by adjusting optimization time window
  - Simplified node-link model [32]
  - Relaxed constraints (e.g., constant separation, allowed violation) [32]
  - Larger discrete time unit (e.g., 5sec to 10sec) [13]
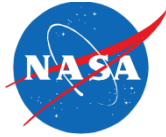- Tradeoff between runtime and optimization accuracy/benefits

Other Considerations

- Optimization time window
  - Planning horizon and overlap
  - Range of frozen flights
  - Discrete time unit
  - Minimum gate-holding time

- Gate conflicts [15, 22]
  - Gate conflicts can happen when gate holding is applied: A departure is still held at a gate when an arrival reaches the gate.
  - Options to resolve gate conflicts
    - Arrivals wait for gate
    - Departures pushback early
    - Gate reassignment for arrival
- Real-time implementation
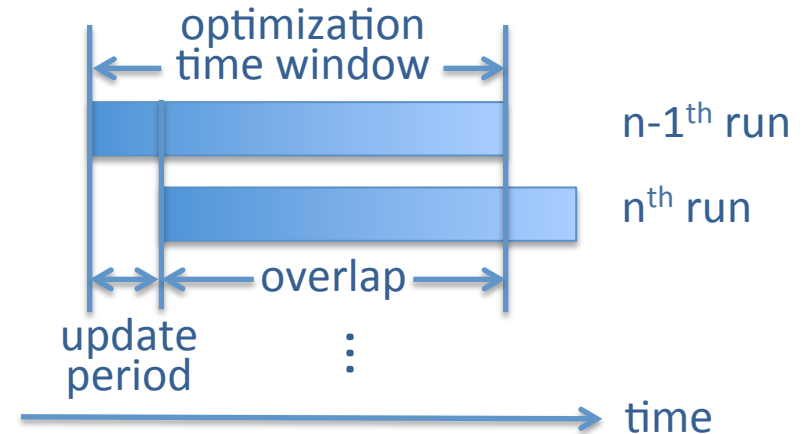
Performance Metrics

- Analyze schedule output from the optimization and measure the benefits and shortfalls
- Efficiency
  - Pushback delay at gate
  - Taxi-out time and delay for departures
  - Taxi-in time and delay for arrivals
  - Number of taxi stops and duration
  - Takeoff queue length and wait time
  - Fuel burn and gas emissions (CO_2, CO, HC, NOx) during taxi
- Throughput
  - Runway throughput for each runway (aircraft/hour or 15min)
  - Traffic Management Initiatives (TMIs) compliance
- Predictability
  - Takeoff time predictability

Summary

- Define the scope for a scheduling problem
- Make proper assumptions
- Investigate the constraints
- Determine the objective
- Choose the problem-solving approach
- Express the optimization problem in mathematical formulation, if possible
- Solve the problem using a proper optimization solver
- Consider the computational performance
- Evaluate the output from the scheduler using pre-defined performance metrics
- Improve the scheduler
  - Faster runtime, extended functions, multiple objectives, more constraints, …

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