Gate Optimization: Schedule Planning and Day of Operations

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Agenda

- Airline Overview
- Basic Model
- Implementation
- Added Objectives
- Planning Models
- Operational Models
- Key Results
- Future Work

Airline Snapshot

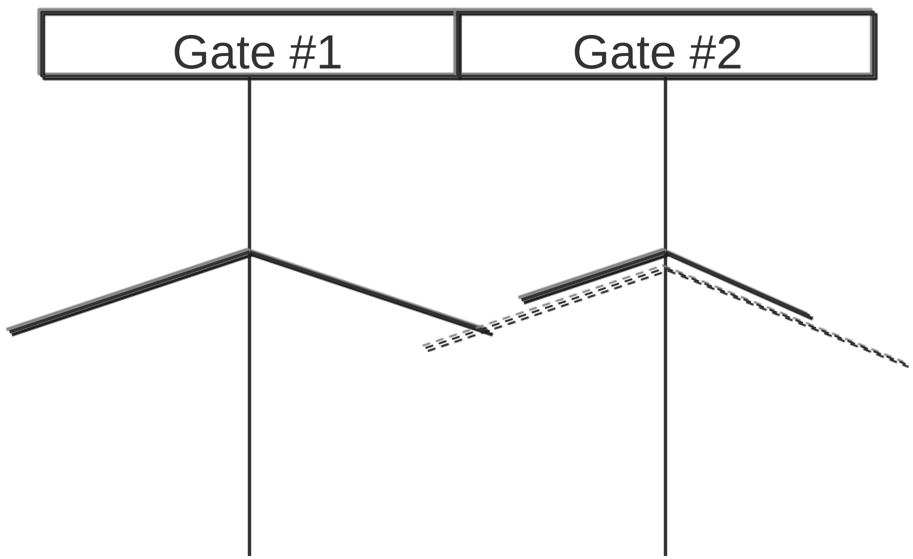
- One of the largest US Network Carrier
- Over 450 aircrafts, 3000 flights daily
- Over 25 different fleet types
- Over 1,200 flights, 75 gates at a key hub
- Around 50,000 connecting passengers
- Unlike Europe or Asia, arriving flights at all US airports have to be **mandatorily** assigned a gate; FAA does not allow remote bay parking

Basic Problem

- Given a set of flight arrivals and departures at a major hub airport, what is the ****best**** assignment of these incoming flights to airport gates so that all flights are gated?
- Gating constraints such as adjacent gate, LIFO gates, gate rest time, towing, push back time and PS gates are applicable

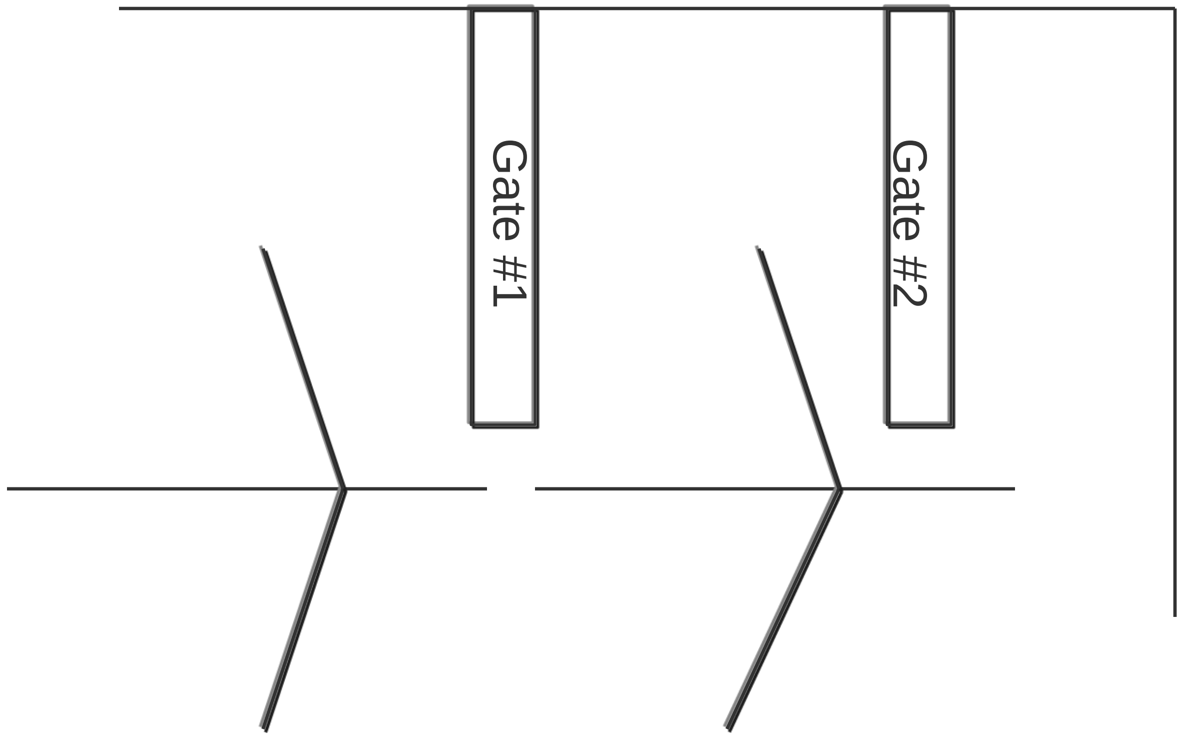
Terminology

- Adjacent Gates: Two physically adjacent gates such that when one gate has a wide bodied aircraft parked on it, the other gate cannot accommodate another wide body



Terminology

- LIFO: Last-In First-Out Gates – These gates are one behind the other making it physically impossible for the aircraft in the inner gate to leave before the aircraft at outer gate departs



Terminology

- Market: An origin-destination pair
- Turns: A pair of incoming and outgoing flights with the same aircraft or equipment
- Gate Rest: Idle time between a flight departure and next flight arrival to the gate. Longer gate rest helps pad any minor schedule delays, though at the cost of schedule feasibility
- PS Gates: Premium Service gates or a set of gates that get assigned to premium markets – typically where VIPs travel
- Towing: At times, a turn occupies gate for a long time because of the long gap between an incoming flight arrival time and outgoing flight departure time. Aircraft in such cases is towed away to a remote bay so that subsequent arrivals can be gated. Aircraft is brought back to the gate closer to its departure time.

Mathematical Model

- Maximize: Gain of assigning a favorable gate *k* to turn *i* – Cost of Towing – Cost of violating gate rest – Cost of not assigning a gate to a turn
- Subject to:
  - Cover constraint: Each turn is either assigned a gate or not
  - Overlap: Two overlapping flights cannot be assigned the same gate
  - Adjacent/LIFO Gates: For the set of such gates, two turn variables (extracted from equipment list) that cannot be flagged “assigned”
  - Towing: Towing turns broken up as two turns and corresponding towing penalty flag raised

Implementation

- Implementation of this basic gate assignment model in OPL
- Three step approach for solution:
  - The first step is data extraction, which extracts the relevant data from the schedule and outputs them in a data structure that can be read and used by the data selection model
  - The second step is data selection, which selects a set of turns for gate assignment. The selection is based on when and where the turn takes place.
  - At the end of the data selection process, the data selection model will call the optimization model to generate a gate assignment solution.
- Separating the entire process into several steps makes future enhancement and maintenance of the code easier

Additional Objectives

- Schedule Planning
  - **Maximize Connection Revenues**
    - This gating objective identifies connections at risk for a hub station and gates the turns involved such that connection revenue is maximized
  - **Minimize Number of Work Zones**
    - Flights must be gated in as few zones as possible so that employees' non-productive time (walking between zones) is minimized
  - **Maximize Robustness**
    - Flights must be gated based on the past pattern of flight delays to provide adequate gate rest between a departing flight and the next arriving flight
- Day of Operations
  - **Minimize Disruptions**
    - Deviation from the planned gating must be minimal
    - Variation in the number of departures and arrivals within a zone with respect to the planned schedule must be minimized
  - **Maintain Feasibility**
    - Retime flights so that the schedule remains operationally feasible

Users should have flexibility to choose one or more objectives simultaneously

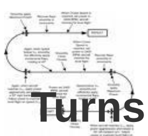
Assumptions


- Connection revenue is realized only if the passenger is able to deplane, walk between the gates and board before the connecting flight departs
- Deplaning time, walking time and boarding times are provided as point estimate inputs
- Connection revenue is provided as point estimate inputs
- Work shifts are 4 or 8 hour duration
- For schedule robustness, gate rest accounts for minimum gate rest and average delay of the turns

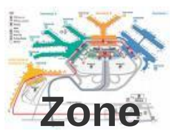
Inputs, Model & Output

Inputs

Flight Schedule



Turns Data



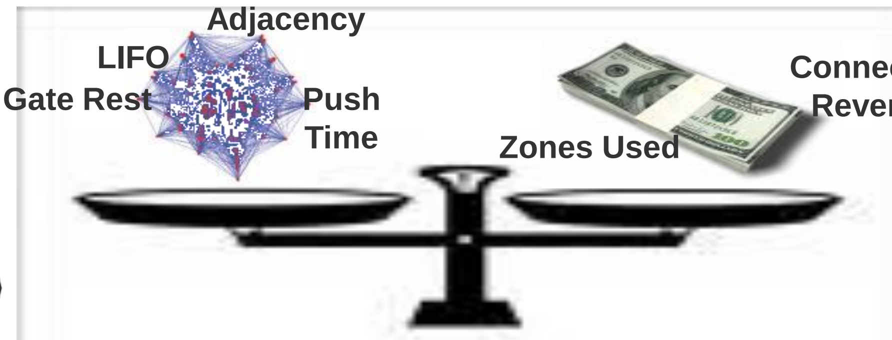
Zone Information

Gates Data

GateIdFrom	GateIdTo	WalkingTime
B1	B1	0
B1	B10	5
B1	B11	5
B1	B12	6
B1	[illegible]	6
B1	[illegible]	7
B1	B16	7

Walking Times

Methodology



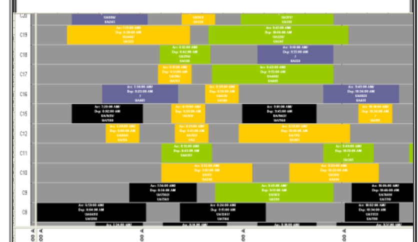
- Gate Adjacency
- Gate Rest
- Last In First Out Gates
- Push Back Time
- Towing
- PS Gates

Optimization algorithm

Outputs

TurnID	GateName
3757	C10
3758	C10
33	B5
34	B9
39	B8
3759	B10
3760	B10

Gate Assignments



Maximize Connection Revenue

Maximize

$$\sum_{(i,j)\in CNX}\sum_{k\in GATES}\sum_{l\in GATES} REVENUE_{ij} x_{ijkl} - \sum_{i\in TURNS} UNASSIGN\_PENALITY_i y_i \quad (1)$$

Subject to

$$\sum_k x_{ijkl} \le \sum_k z_{ik} \quad \forall \quad (i,j)\in CNX \quad \wedge \quad i,j \in TURNS \quad \wedge \quad l \in \text{GATES} \quad (2)$$

$$\sum_l x_{ijkl} \le \sum_l z_{jl} \quad \forall \quad (i,j)\in CNX \quad \wedge \quad i,j \in \text{TURNS} \quad \wedge \quad k,\in \text{GATES} \quad (3)$$

$$z_{ik} + z_{jl} - 1 \le x_{ijkl} \quad \forall \quad (i,j)\in CNX \quad \wedge \quad i,j \in \text{TURNS} \quad \wedge \quad k,l \in \text{GATES}$$

$$\wedge\ Arrival(i) + Walk(k,l) \le Departure(j) \quad (4)$$

$$x_{ijkl} = 0 \quad \forall \quad (i,j)\in CNX \quad \wedge \quad i,j \in \text{TURNS} \quad \wedge \quad k,l \in \text{GATES}$$

$$\wedge\ Arrival(i) + Walk(k,l) > Departure(j) \quad (5)$$

$$x_{ijkl} \in \{0,1\} \quad \forall \quad (i,j)\in CNX \quad \wedge \quad i,j \in \text{TURNS} \quad \wedge \quad k,l \in \text{GATES} \quad (6)$$

Minimize Number of Work Zones

Objective:

$$-ZONE\_PENALTY \sum_{L \in ZONE} \sum_{(s,e) \in INTERVAL} m_{Ls,e}$$

Constraint:

$$\sum_{k \in L} \sum_{i \in Turn(s,e)} y_{ik} \le Big\_M \times m_{Ls,e} \quad \forall\ L \in ZONE\ and\ s \le d_i\ and\ e \ge a_i\ and\ (s,e) \in INTERVAL$$

Bound:

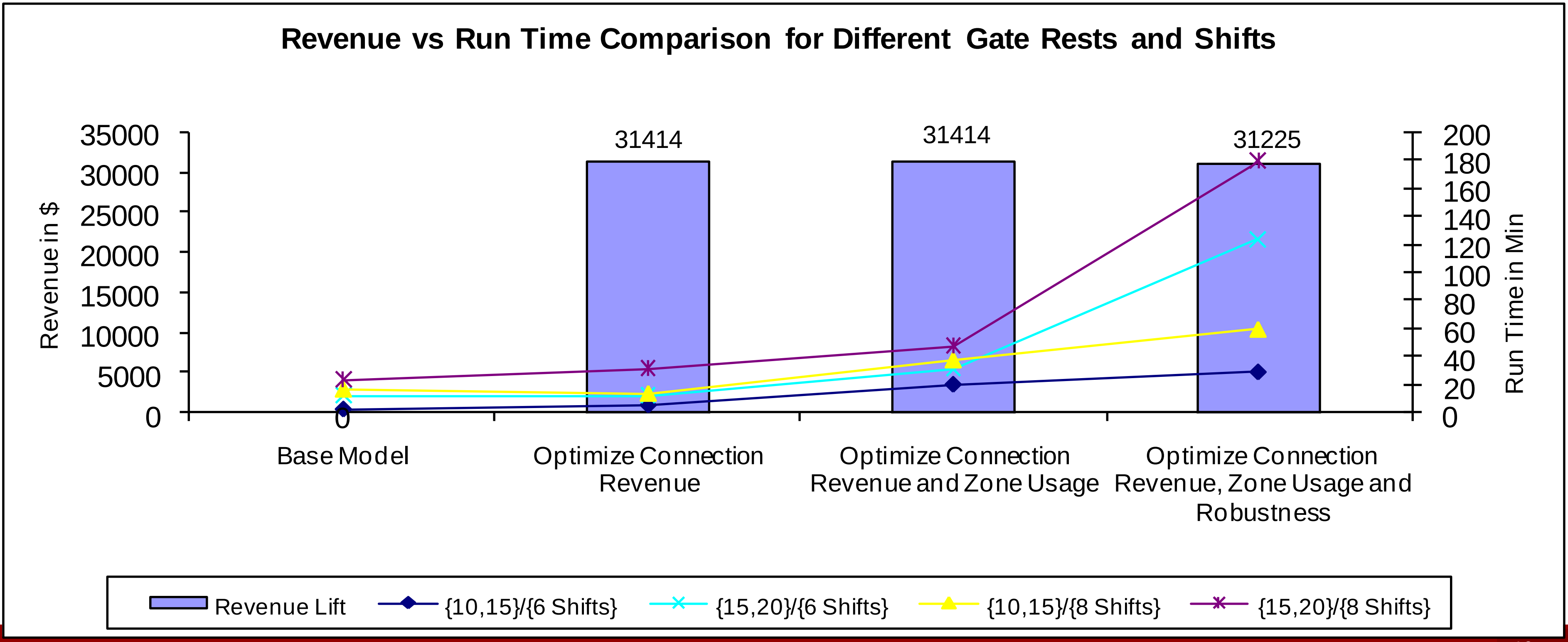
$$0 \le m_{Lse} \le 1 \qquad \forall\ L \in ZONE\ and\ s \le d_i\ and\ e \ge a_i\ and\ (s,e) \in INTERVAL$$

Maximize Robustness

- Issues to be considered
  - When delaying a flight under consideration, it could impact several other flights due to adjacency, LIFO and push time considerations
  - Hard coding of delay could result in several infeasibilities
  - Could gate rest be a consideration in the objective?
- Current structure of gate rest violation breakup into gate rest violation acceptable and gate rest violation excess is retained
- Suggested gate rest is computed by adding minimum gate rest to max of departure and arrival flight delay
- Min gate rest as per the existing model

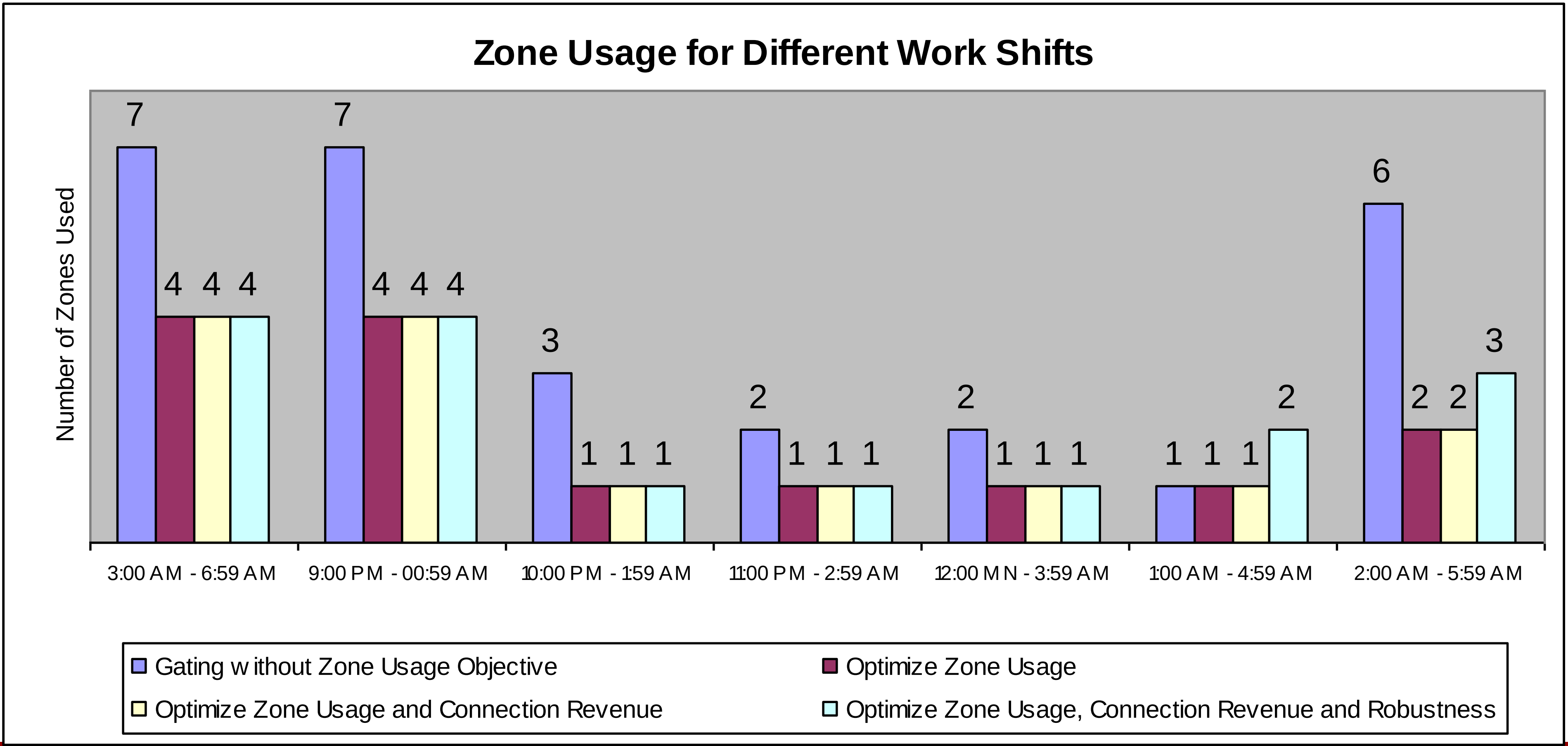
Results: Maximize Connection Revenues (Schedule Planning)

- Lift in revenue observed for this objective when evaluated separately as well as in conjunction with other objectives
- Run time increases as
  - number of objectives increase
  - minimum gate rest increases
  - number of manpower shifts under consideration increases
- In the table below, {x,y}/{z shifts} indicate x and y minutes of minimum gate rest for UAX and Mainline and z shifts



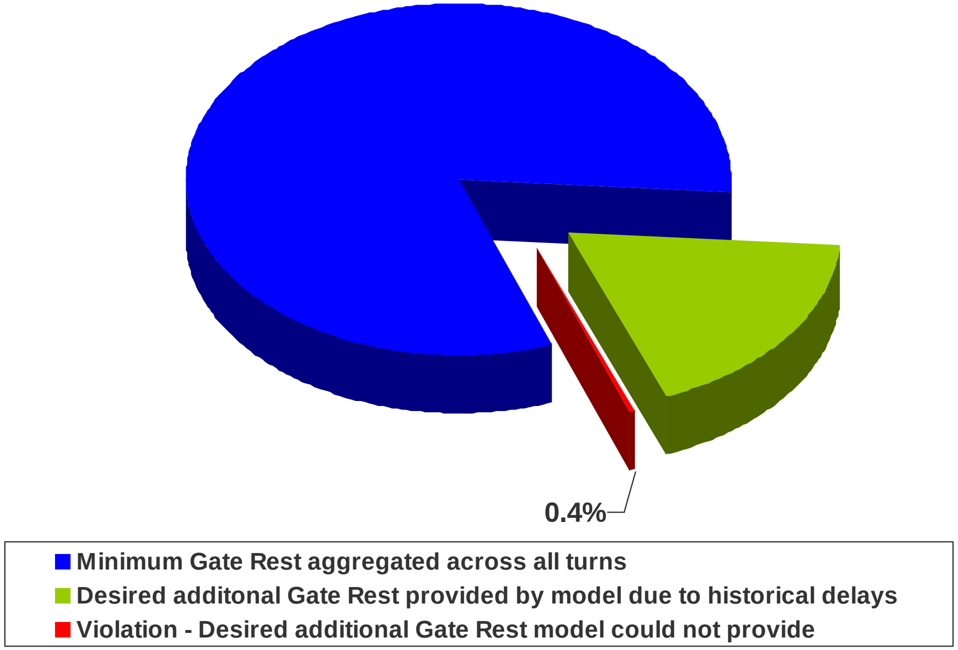
Results: Minimize Zone Usage (Schedule Planning)

- Reduction in zone usage observed for this objective when evaluated separately as well as in conjunction with other objectives except in rare cases where objectives conflict strongly
- Run time increases with the complexity of objectives and increasing minimum gate rest as discussed before



Results: Optimize Gate Rest Time (Schedule Planning)

- Desired gate rest is obtained based on historical pattern of delays; violation is only 0.4% when evaluated separately as well as with other objectives
- Run time increases with the complexity of objectives and increasing gate rest



Objective	% Violation
Gating without Robustness Objective	1.5%
Gating with Robustness Objective	0.4%
Gating with Optimizing Robustness and Connection Revenue	0.4%
Gating with Optimizing Robustness, Zone Usage and Connection Revenue	0.4%

Gate Reassignment: Operations Model

Parameters

$\text{planned\_gate}_{ij} = 1$ if turn i is assigned gate j in planning phase; 0 otherwise $\forall i \in T \wedge j \in G$

$\text{status}_i = 0$ if the turn i should not be regated, 1 otherwise $\forall i \in T \wedge j \in G$

P_REASSIGN = penalty for reassignment

Decision variables

$y_{ij} = 1$ if turn i is assigned (in new operations run) to gate j $\forall i \in T \wedge j \in G$

$x_i^1 = 1$ if turn i is reassigned (assigned a different gate from planned) $\forall i \in T$

$x_i = 1$ if turn i is unassigned in this model, 0 otherwise $\forall i \in T$

Gate Reassignment: Operations Model

Objective function

$$-\text{P\_REASSIGN}\sum_{i\in T} x_i^1$$

Constraints

$$y_{ij} + x_i^1 = 1 - x_i \forall i \in T \wedge j \in G \wedge \text{planned\_gate}_{ij} = 1 \wedge \text{status}_i = 1$$

$$y_{ij} = \text{planned\_gate}_{ij} \forall i \in T \wedge j \in G \wedge \text{status}_i = 0$$

$$x_i^1 = 0 \forall i \in T \wedge \text{status}_i = 0$$

Zone Reassignment: Operations Model

Parameters

$\text{start}_k = \text{start of time period k} \; \forall k \in \text{SHIFT\_PERIOD}$

$\text{end}_k = \text{end of time period k} \; \forall k \in \text{SHIFT\_PERIOD}$

$\text{arrival}_i = \text{arrival time of turn i} \; \forall i \in T$

$\text{departure}_i = \text{departure time of turn i} \; \forall i \in T$

$\text{P\_ZONE} = \text{penalty for planned gating difference}$

Decision variables

$z_{kt}^1 = \text{unrestricted integer} \; \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$

$u_{kt}^1 = \text{positive integer} \; \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$

$v_{kt}^1 = \text{positive integer} \; \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$

Zone Reassignment: Operations Model

Objective function

$$-\text{P\_ZONE} \sum_{k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}} u_{kt}^{1} + v_{kt}^{1}$$

Constraints

$$\sum_{i \in T \wedge j \in G \wedge j \in \text{gate}\ k\ \wedge \text{arrival}\ i\ < \text{end}\ t\ \wedge \text{departure}\ i\ \geq \text{start}\ t} \text{planned\_gate}_{ij} - y_{ij} = z_{kt}^{1} \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$$

$$z_{kt}^{1} + u_{kt}^{1} \geq 0 \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$$

$$z_{kt}^{1} \leq v_{kt}^{1} \forall k \in \text{ZONE} \wedge t \in \text{SHIFT\_PERIOD}$$

Flight Retiming: Operations Model

Objective function

$$\text{P\_SOMETHING} * \sum_{i \in T} pa_i + pd_i$$

Constraints for overlap

$$1............a_i \le d_j + M * \; 1 - ad_{ij} \; + \text{Min\_Gate\_Rest} \; \forall i \in T \wedge j \in T$$

$$2............a_i \ge d_j - M * ad_{ij} + \text{Min\_Gate\_Rest} \; \forall i \in T \wedge j \in T$$

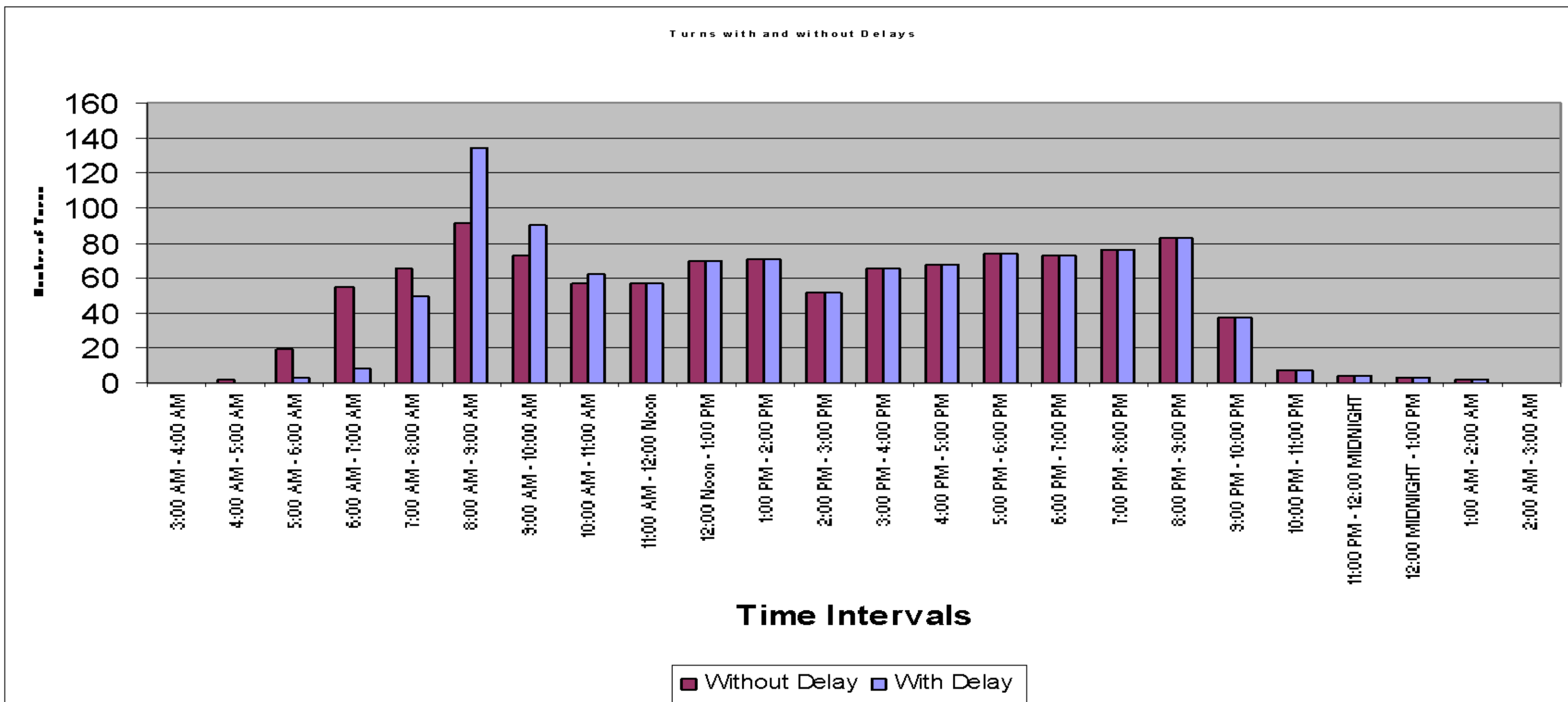
$$3............d_i + \text{Min\_Gate\_Rest} \ge a_j - M * \; 1 - ad_{ij}^1 \; \forall i \in T \wedge j \in T$$

$$4............d_i + \text{Min\_Gate\_Rest} \le a_j + M * ad_{ij}^1 \forall i \in T \wedge j \in T$$

ad_{ij}	ad_{ij}^1	Meaning
1	1	Turn i and Turn j overlap (adding minimum gate rest) and cannot be gated in same gate
1	0	Turn i departs before Turn j leaving sufficient gate rest so these two turns can be gated in same gate
0	1	Turn j departs before Turn i leaving sufficient gate rest so these two turns can be gated in same gate
0	0	Impossible case

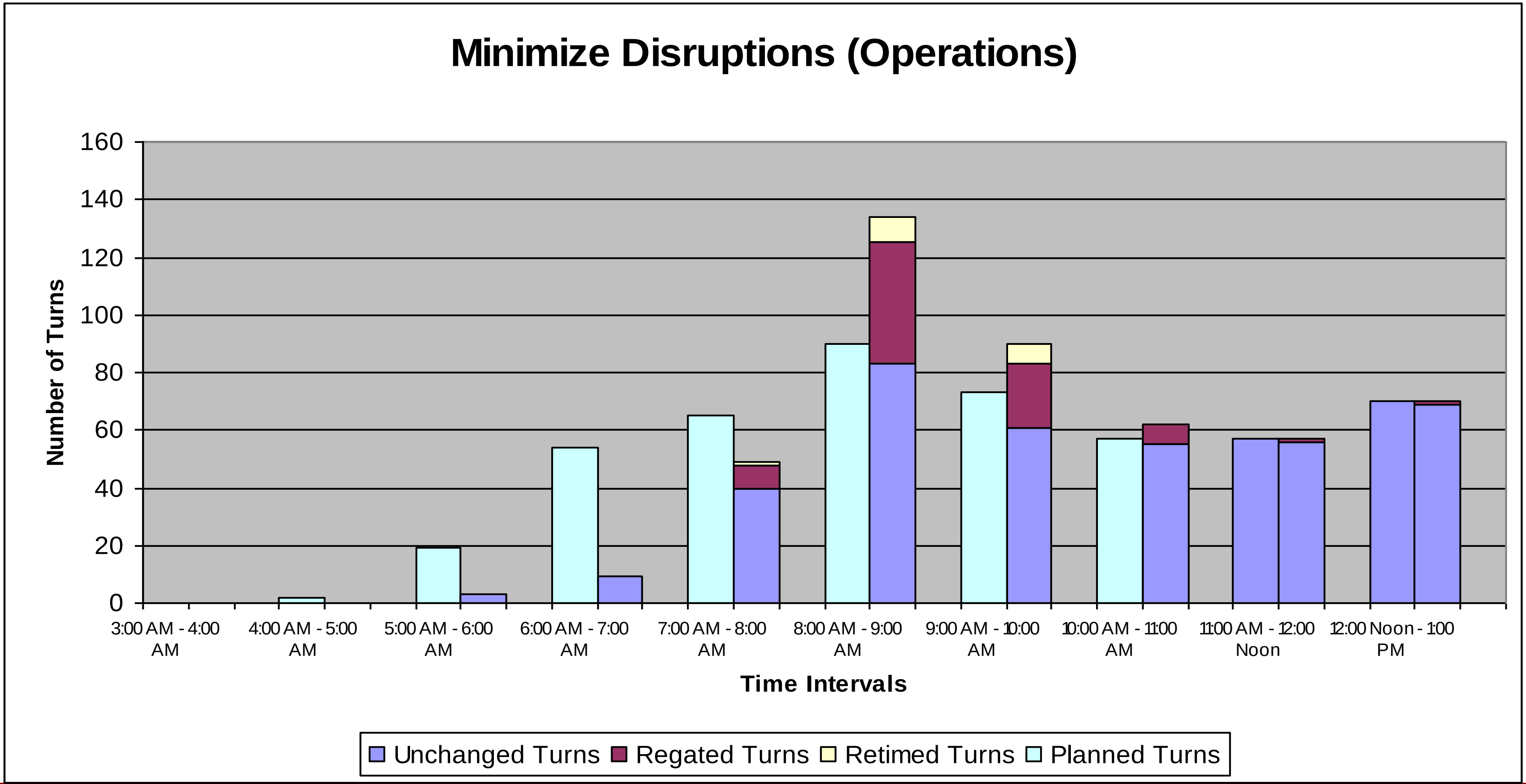
Data Set Creation: Operations Model

- Generated exponential (0.5 hrs) delays for all turns that arrive before 8:00 AM at ORD for Dataset #2
- A 50% spurt in the number of flights between 8:00 – 9:00 AM
- Tried to generate more data sets with 1 and 2 hour delays, but could not manage high skew level during the peak periods as in this case
- We generate two scenarios in the following manner:
  - Case#1: Penalties consistent for both delayed and non-delayed turns
  - Case#2: Double penalization for disturbing a non-delayed turn



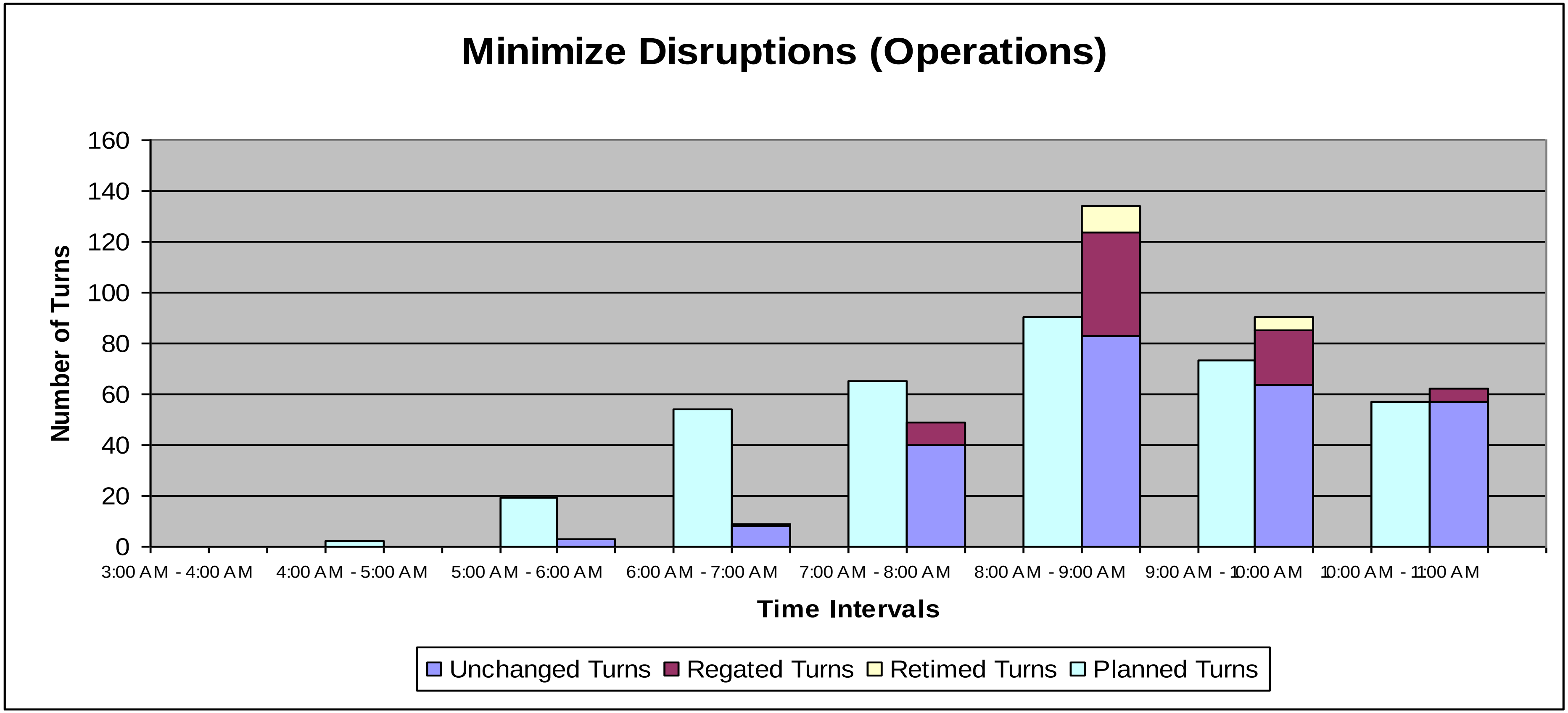
Results: Operations Model (Case#1)

- Minimize Disruptions
  - Schedule normalizes after 1:00 PM
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



Results: Operations Model (Case#2)

- Minimize Disruptions
  - Schedule normalizes after 11:00 AM
  - Our model able to gate 80% of these additional turns without retiming
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



Contributions and Future Work

- Problem formulation for all 5 objectives is original contribution. Problems in literature seldom useful
- Run time was a major challenge almost always
  - In some cases, pre-processing helped
  - In some other cases, problem relaxation helped
  - In some other cases, changes to formulation worked
- Identify ways to reduce long run times associated with incremental gate rest
- Better and more elegant approaches, such as column or row generation, must be tried for flight retiming model

Thank You!

Math Model: Operations Problem (Retiming)

Parameters

$\text{actual\_arrival}_i = \textit{actual arrival time of turn } i \; \forall i \in T$

$\text{actual\_departure}_i = \textit{actual departure time of turn } i \; \forall i \in T$

$\text{equipment}_i = \textit{equipment of turn } i \; \forall i \in T$

$\text{Min\_Gate\_Rest} = \textit{minimim gate rest}$

P_SOMETHING = *Penalty for every unit time retiming (delay) of a flight*

Decision Variables

$a_i = \textit{non negative integer arrival time of turn } i \; \forall i \in T$

$d_i = \textit{non negative integer departure time of turn } i \; \forall i \in T$

$ad_{ij} = \textit{boolean}$

$ad_{ij}^1 = \textit{boolean}$

$ad_{ij}^2 = \textit{boolean}$

$ad_{ij}^3 = \textit{boolean}$

$pa_i = \textit{non negative integer indicating extend of arrival time change in positive direction}$

$pd_i = \textit{non negative integer indicating extend of departure time change in positive direction}$

Math Model: Operations Problem (Retiming)

Objective function

$$\text{P\_SOMETHING} * \sum_{i \in T} pa_i + pd_i$$

Constraints for overlap

$$1............a_i \leq d_j + M * \; 1 - ad_{ij} \; + \text{Min\_Gate\_Rest} \forall i \in T \wedge j \in T$$

$$2............a_i \geq d_j - M * ad_{ij} + \text{Min\_Gate\_Rest} \forall i \in T \wedge j \in T$$

$$3............d_i + \text{Min\_Gate\_Rest} \geq a_j - M * \; 1 - ad_{ij}^1 \; \forall i \in T \wedge j \in T$$

$$4............d_i + \text{Min\_Gate\_Rest} \leq a_j + M * ad_{ij}^1 \forall i \in T \wedge j \in T$$

Constraints for adjacent gate restriction

$$5............a_i \leq d_j + M * \; 1 - ad_{ij}^2 \; \forall i \in T \wedge j \in T$$

$$6............a_i \geq d_j + M * ad_{ij}^2 \forall i \in T \wedge j \in T$$

$$7............d_i \geq a_j + M * \; 1 - ad_{ij}^3 \; \forall i \in T \wedge j \in T$$

$$8............d_i \leq a_j + M * ad_{ij}^3 \forall i \in T \wedge j \in T$$

Math Model: Operations Problem (Retiming)

Auxiliary constraints

$$9............a_i = \text{actual\_arrival}_i + pa_i \forall i \in T$$

$$10............d_i = \text{actual\_departure}_i + pd_i \forall i \in T$$

Minimum ground time constraints

$$11............d_i - a_i \geq \text{MGT} \forall i \in T$$

Changed constraints

overlap constraint: $y_{ik} + y_{jk} + ad_{ij} + ad^1_{ij} \leq 3 \forall i \in T \wedge j \in T \wedge k \in G$

adjacent gate constraint: $y_{ik} + y_{jk^1} + ad^2_{ij} + ad^3_{ij} \leq 3 \forall i \in T \wedge j \in T \wedge k \in G \wedge k^1 \in G \wedge \; k,k^1 \; \in \text{ADJACENT\_GATE}$

$equipment_i, equipment_j \; \in \text{ADJACENT+GATE\_RESTRICTED\_EQUIPMENT}$

Math Model: Operations Problem (Retiming)

ad_{ij}	ad_{ij}^1	Meaning
1	1	Turn i and Turn j overlap (adding minimum gate rest) and cannot be gated in same gate
1	0	Turn i departs before Turn j leaving sufficient gate rest so these two turns can be gated in same gate
0	1	Turn j departs before Turn i leaving sufficient gate rest so these two turns can be gated in same gate
0	0	Impossible case

Data Sets

- Data Provided:
  - Turn.dat: Set of all turns
  - Flight.dat: Set of all flights
  - Itin_mct.dat: Set of all connections along with pax and revenue

Features	Dataset#1	Dataset#2
Number of ORD turns	583	619
Number of ORD Connections	32695	25724
Revenue of ORD Connections	$28.5 m	$42 m
Number of Gates	73	73
Number of unassigned turns	1	-
Number of connections at risk	245	335
Revenue of connections at risk	$323,144	$5,310,377
Unassigned turns	UA 7115 - UA 7054 (3227)	-

Model Performance: Maximize Connection Revenue

- *Base* model is the given model that only aims to assign gates to turns
- *Connection* model built by us aims to optimize the connection revenues
- Connection model take slightly longer run time, but gives a lift of about $4,000 in revenues

Dataset#1	Base Model	Connection Model
Minimum Gate Rest (ML; UAX)	19; 14 min	19; 14 min
Unassigned Penalty	$10,000	$10,000
Run Time for Extraction / Selection	1 min	3 min
Run Time to Setup / Generate	2 min	3 min
Run Time for Optimizer	3 min	6 min
Absolute Relative Gap	0%	0.02%
Number of unassigned turns	1	1
Revenue of critical connections	$318,214	$322,278

Model Performance: Maximize Connection Revenue

- *Base* model is the given model that only aims to assign gates to turns
- *Connection* model built by us aims to optimize the connection revenues
- Connection model take slightly longer run time, but gives a lift of $31,414 in revenues

Dataset#2	Base Model	Connection Model
Minimum Gate Rest (ML; UAX)	20; 15 min	20; 15 min
Unassigned Penalty	$100,000	$100,000
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	3 min
Run Time for Optimizer	24 min	32 min
Absolute Relative Gap	0.02%	0.02%
Revenue of critical connections	$5,278,963	$5,310,377

Model Performance: Maximize Connection Revenue

- *Base* model is the given model that only aims to assign gates to turns
- *Connection* model built by us aims to optimize the connection revenues
- Decreasing the gate rest could potentially improve the revenue and decrease the run time

Dataset#2	Base Model	Connection Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$100,000	$100,000
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	3 min
Run Time for Optimizer	17 min	14 min
Absolute Relative Gap	0%	0.02%
Revenue of critical connections	$5,278,963	$5,310,377

Model Performance: Minimize Zone Usage

- *Base* model is the given model that only aims to assign gates to turns
- *Manpower* model built by us aims to optimize the zone usage
- Manpower model produces best results within reasonable run time when fewer *sparse* work shifts are considered
- Sparse work shifts are four or eight hour periods when the there are fewer arrivals and departures at the hub airport

Dataset#2	Base Model	Manpower Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$1,000	$1,000
Shifts (4 hour block) Considered	-	6
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	11 min	29 min
Absolute Relative Gap	0%	1%
Zone Usage across Shifts	21	10

Model Performance: Minimize Zone Usage

- *Base* model is the given model that only aims to assign gates to turns
- *Manpower* model built by us aims to optimize the zone usage
- Manpower model can be run in conjunction with the Connection model lifting revenues by $31,414 and decreasing 11 zones

Dataset#2	Base Model	Manpower Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	6
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	17 min	21 min
Absolute Relative Gap	0%	0.02%
Zone Usage across Shifts	21	10
Revenue of critical connections	$5,278,963	$5,310,377

Model Performance: Minimize Zone Usage

- *Base* model is the given model that only aims to assign gates to turns
- *Manpower* model built by us aims to optimize the zone usage
- Increasing shifts under consideration improves the zone usage up to a point but increases the run time

Dataset#2	Base Model	Manpower Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	7
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	17 min	31 min
Absolute Relative Gap	0%	0.02%
Zone Usage across Shifts	28	14
Revenue of critical connections	$5,278,963	$5,310,377

Model Performance: Minimize Zone Usage

- *Base* model is the given model that only aims to assign gates to turns
- *Manpower* model built by us aims to optimize the zone usage
- Increasing gate rest improves the model robustness but increases the zone usage as well as the run time

Dataset#2	Base Model	Manpower Model
Minimum Gate Rest (ML; UAX)	20; 15 min	20; 15 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	7
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	24 min	42 min
Absolute Relative Gap	0.02%	0.02%
Zone Usage across Shifts	28	14
Revenue of critical connections	$5,278,963	$5,310,377

Model Performance: Maximize Robustness

- *Base* model is the given model that only aims to assign gates to turns
- *Robustness* model built by us aims to optimize the gate rest between two turns based on the historical pattern of delays
- Though it is the easiest model to envision, it ends up as the killer in terms of solution complexity

Dataset#2	Base Model	Robustness Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$1,000	$1,000
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	11 min	26 min
Absolute Relative Gap	0%	1%
Gate Rest Provided for Delay	2181 min	2382 min

Model Performance: Maximize Robustness

- *Base* model is the given model that only aims to assign gates to turns
- *Robustness* model built by us aims to optimize the gate rest between two turns based on the historical pattern of delays
- Robustness model can be run in conjunction with the Connection model lifting revenues by $31,225

Dataset#2	Base Model	Robustness Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	6
Run Time for Extraction / Selection	1 min	5 min
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	17 min	33 min
Absolute Relative Gap	0%	0.02%
Gate Rest Provided for Delay	2181 min	2382 min
Revenue of critical connections	$5,278,963	$5,310,188

Model Performance: Maximize Robustness

- *Base* model is the given model that only aims to assign gates to turns
- *Robustness* model built by us aims to optimize the gate rest between two turns based on the historical pattern of delays
- Robustness model can be run in conjunction with both Connection as well as Manpower model

Dataset#2	Base Model	Robustness Model
Minimum Gate Rest (ML; UAX)	15; 10 min	15; 10 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	7
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	17 min	60 min
Absolute Relative Gap	0%	0.02%
Gate Rest Provided for Delay	2181 min	2382 min
Zone Usage across Shifts	28	16
Revenue of critical connections	$5,278,963	$5,310,188

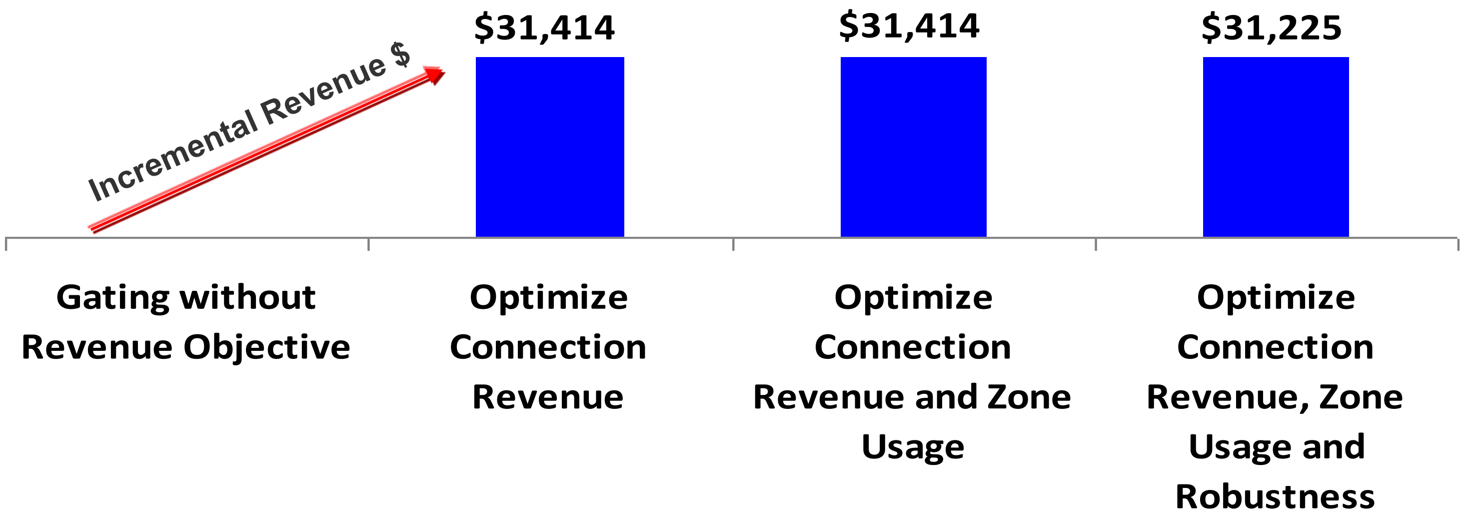
Model Performance: Maximize Robustness

- *Base* model is the given model that only aims to assign gates to turns
- *Robustness* model built by us aims to optimize the gate rest between two turns based on the historical pattern of delays
- When the minimum gate rest is increased, the model faces run time issues

Dataset#2	Base Model	Robustness Model
Minimum Gate Rest (ML; UAX)	20; 15 min	20; 15 min
Unassigned Penalty	$100,000	$100,000
Shifts (4 hour block) Considered	-	7
Run Time to Setup / Generate	2 min	4 min
Run Time for Optimizer	17 min	180 min
Absolute Relative Gap	0%	1%
Gate Rest Provided for Delay	2181 min	2331 min
Zone Usage across Shifts	28	16
Revenue of critical connections	$5,278,963	$5,310,188

Results: Maximize Connection Revenues (Schedule Planning)

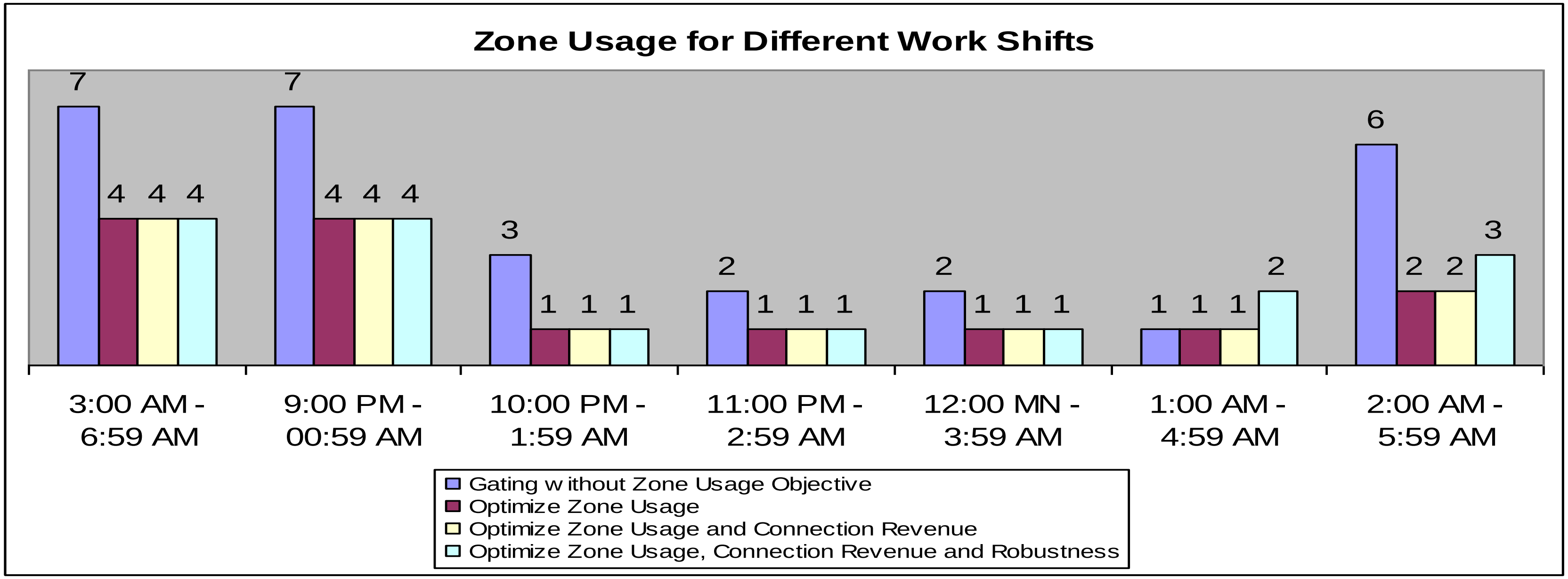
- Lift in revenue observed for this objective when evaluated separately as well as in conjunction with other objectives
- Run time increases with the complexity of objectives



Objective	Run Time
Gating without Revenue Objective	24 min
Gating with Optimizing Connection Revenue	32 min
Gating with Optimizing Connection Revenue and Zone Usage	42 min
Gating with Optimizing Connection Revenue, Zone Usage and Robustness	3 hours

Results: Minimize Zone Usage (Schedule Planning)

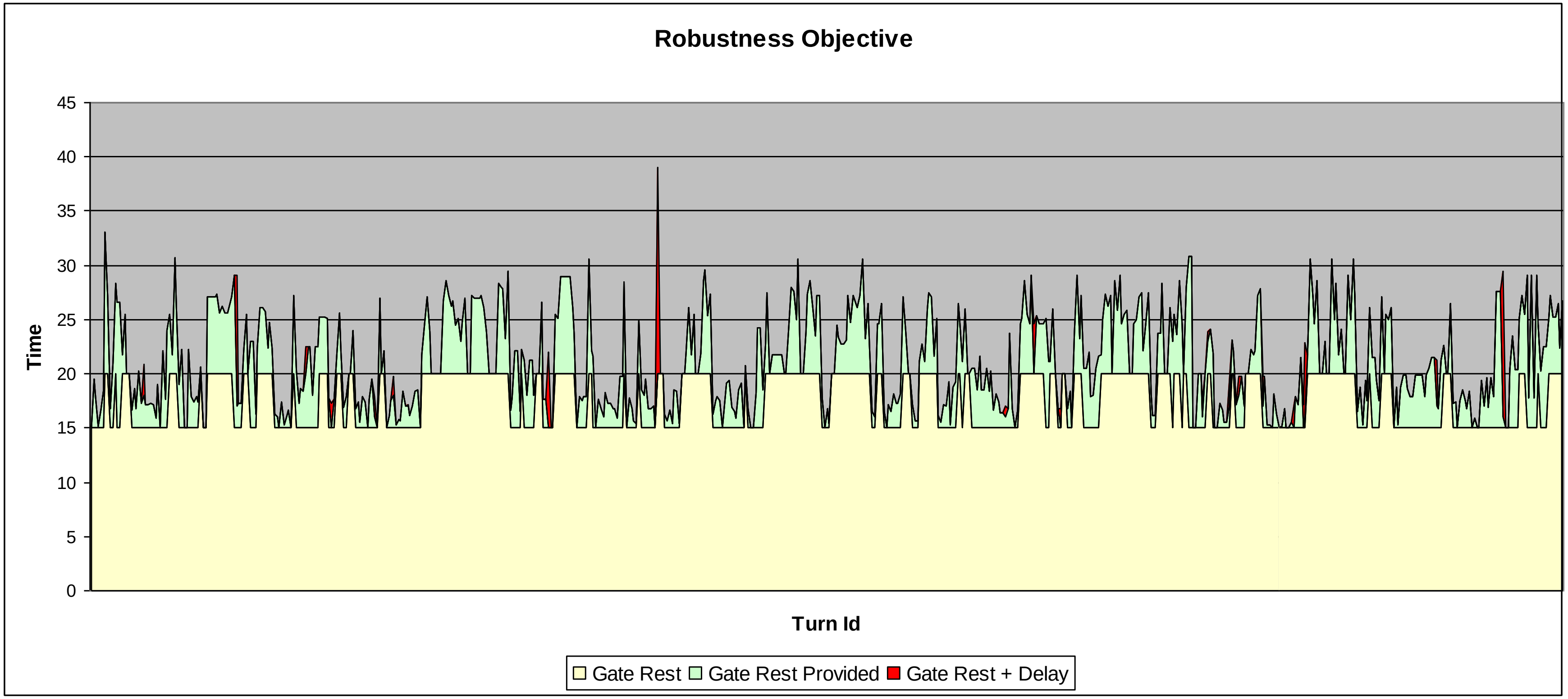
- Reduction in zone usage observed for this objective when evaluated separately as well as in conjunction with other objectives
- Run time increases with the complexity of objectives



Objective	Run Time
Gating without Zone Usage Objective	24 min
Gating with Zone Usage Objective	55 min
Gating with Optimizing Zone Usage and Connection Revenue	42 min
Gating with Optimizing Zone Usage, Connection Revenue and Robustness	3 hours

Results: Optimize Gate Rest Time (Schedule Planning)

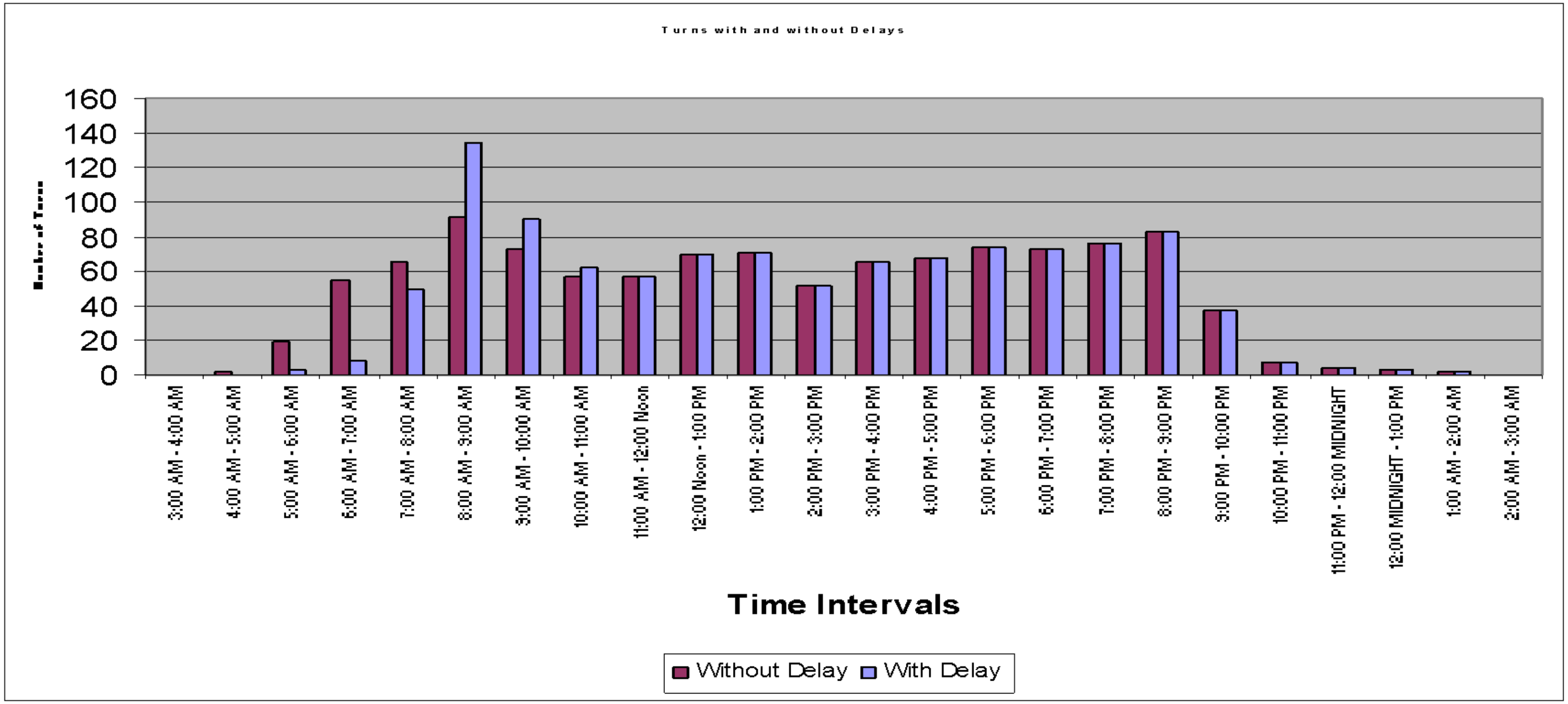
- Desired gate rest is obtained based on historical pattern of delays; violation is only 0.4% when evaluated separately as well as with other objectives



Objective	% Violation	Run Time
Gating without Robustness Objective	1.5%	24 min
Gating with Robustness Objective	0.4%	67 min
Gating with Optimizing Robustness and Connection Revenue	0.4%	125 min
Gating with Optimizing Robustness, Zone Usage and Connection Revenue	0.4%	3 hours

Model Performance Report: Operations Model Data

- Generated exponential (0.5 hrs) delays for all turns that arrive before 8:00 AM at ORD for Dataset #2
- A 50% spurt in the number of flights between 8:00 – 9:00 AM
- Tried to generate more data sets with 1 and 2 hour delays, but could not manage high skew level during the peak periods as in this case
- We generate two scenarios in the following manner:
  - Case#1: Penalties consistent for both delayed and non-delayed turns
  - Case#2: Double penalization for disturbing a non-delayed turn



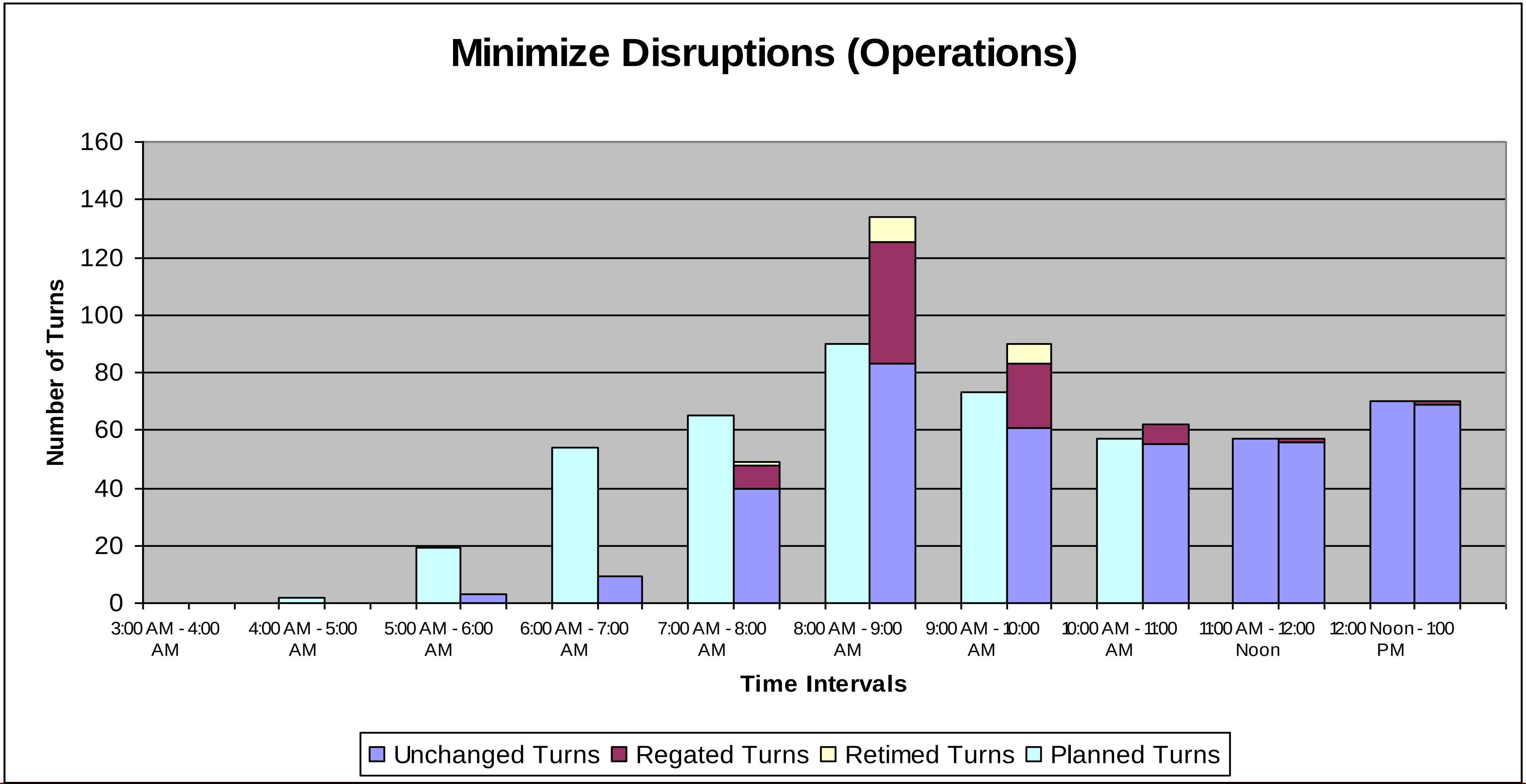
Model Performance Report: Operations Model

- Run time is a major consideration for Operations models. All models need to give a “reasonable” solution within a “few” minutes

Parameter	Case #1	Case #2
Unassigned Penalty	$100,000	$100,000
Reassignment Penalty	$100	$100
Penalty for changes within zone	$20	$20
Number of Re-gating	51	57
Run time for Setup and Generation	2m:30s	2m
Run Time for Optimizer	45s	30s
Absolute Relative Gap	0.01%	0.01%
Number of Retimed Turns	9	10
Average Arrival Retiming	73 min	61 min
Average Departure Retiming	52 min	46 min
Number of Un-gated Turns	0	0

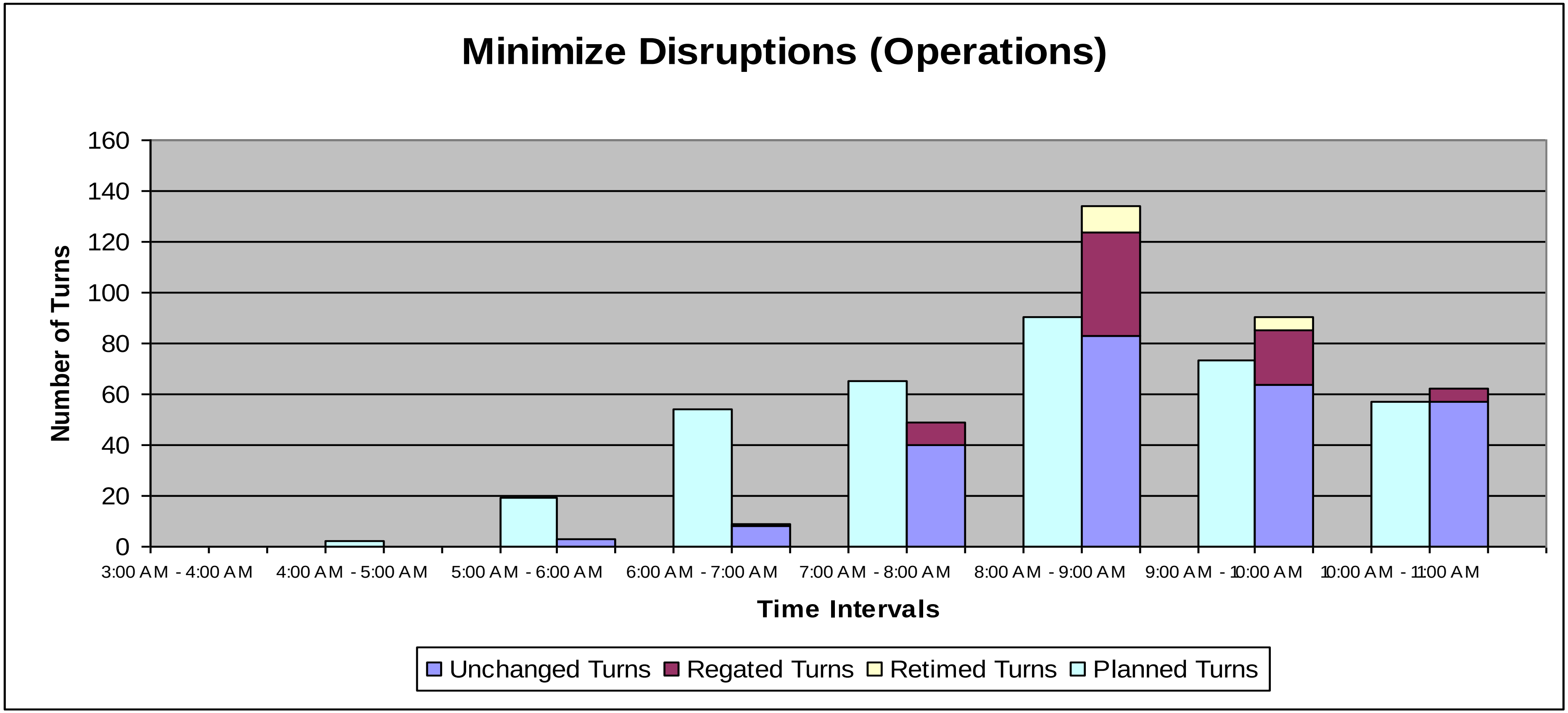
Results: Operations Model (Case#1)

- Minimize Disruptions
  - Schedule normalizes after 1:00 PM
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



Results: Operations Model (Case#2)

- Minimize Disruptions
  - Schedule normalizes after 11:00 AM
  - Our model able to gate 80% of these additional turns without retiming
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



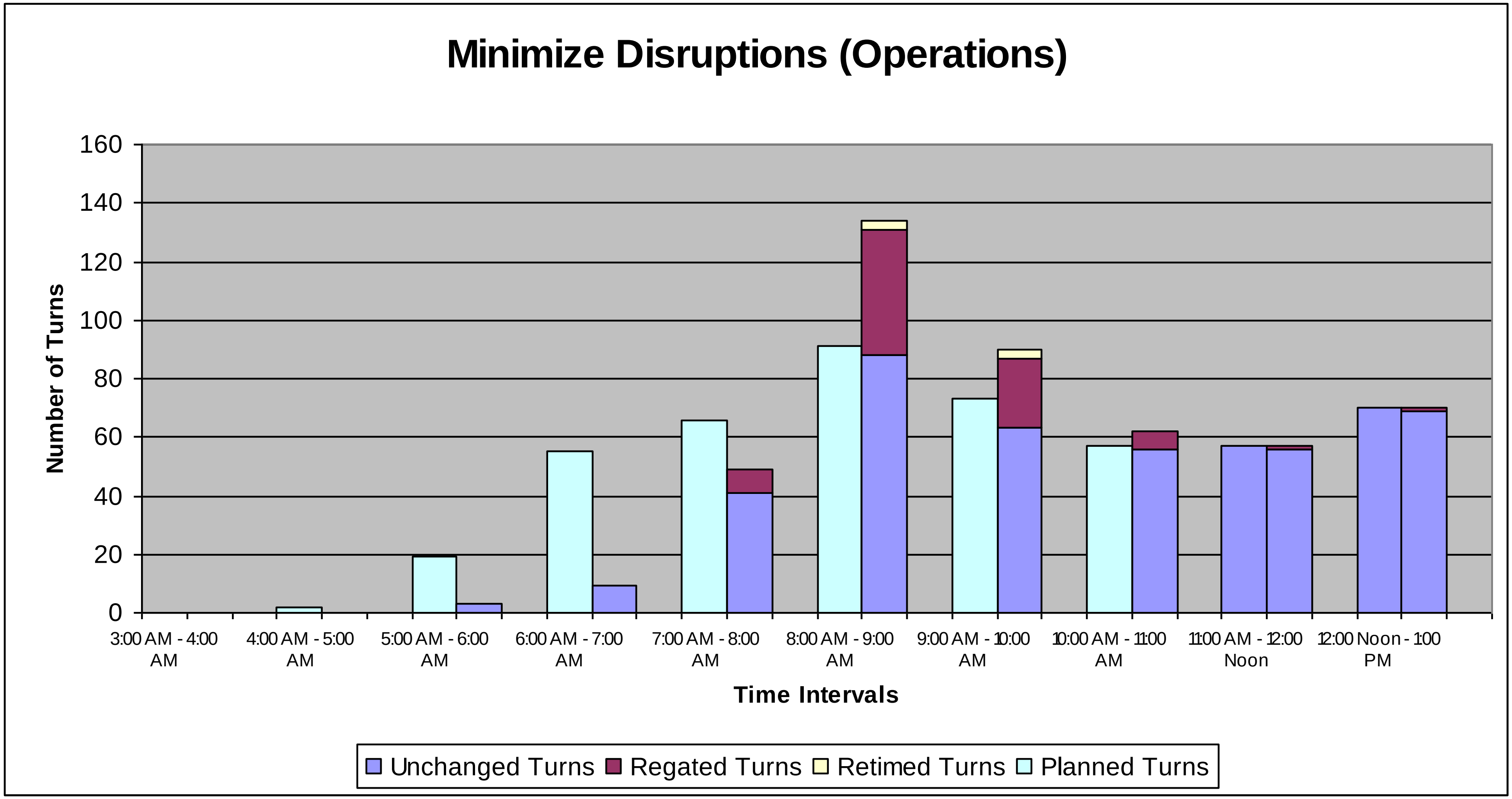
Model Performance Report: Operations Model

- Spare gates are utilized in the model

Parameter	Case #1	Case #2
Unassigned Penalty	$100,000	$100,000
Reassignment Penalty	$100	$100
Penalty for changes within zone	$50	$50
Number of Re-gating	52	54
Run time for Setup and Generation	2m	1m:45s
Run Time for Optimizer	30s	30s
Absolute Relative Gap	0.01%	0.01%
Number of Retimed Turns	3	3
Average Arrival Retiming	46 min	24 min
Average Departure Retiming	42 min	23 min
Number of Un-gated Turns	0	0

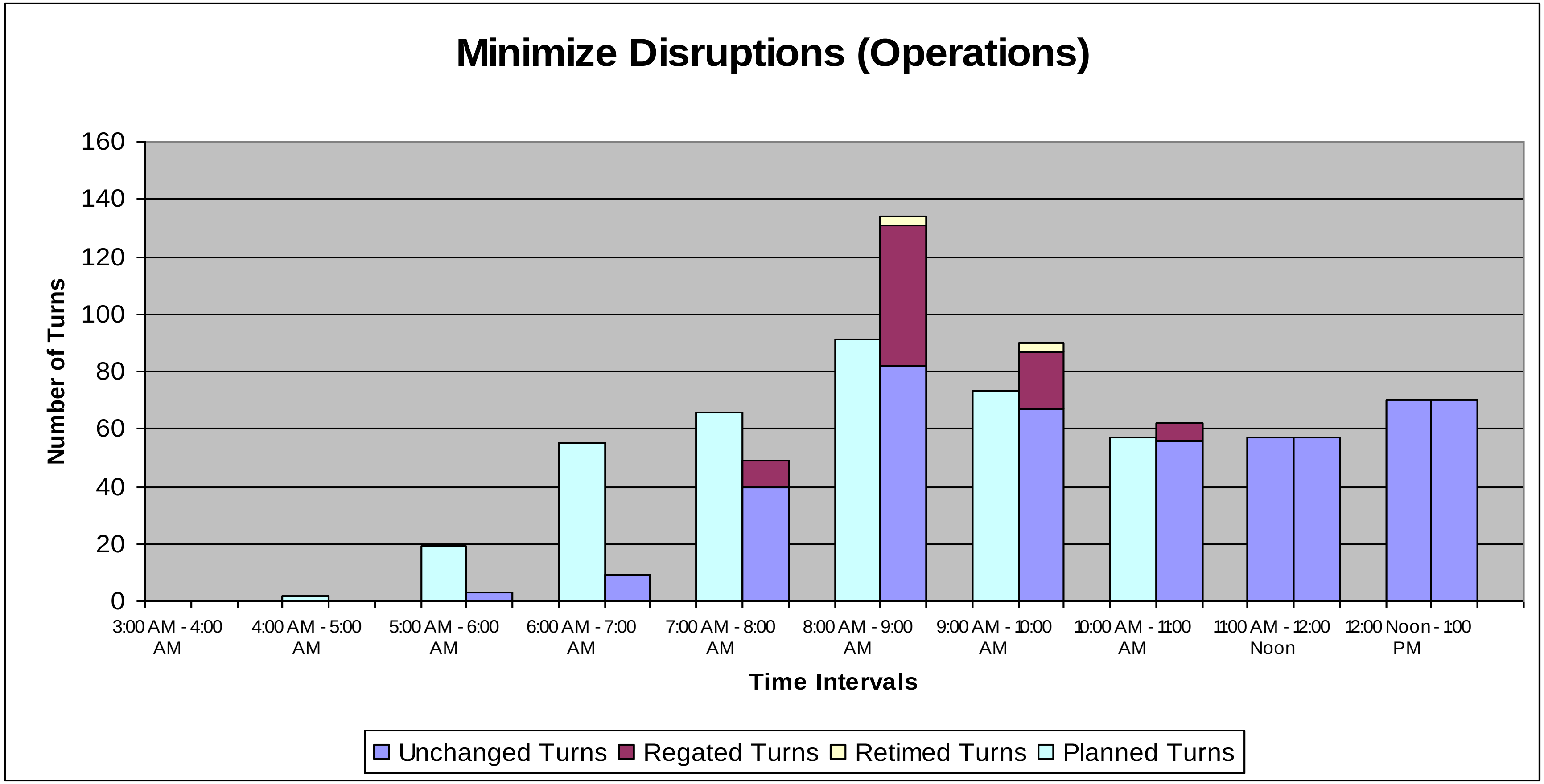
Results: Operations Model (Spare Gates Used - Case#1)

- Minimize Disruptions
  - Schedule normalizes after 1:00 PM
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



Results: Operations Model (Spare Gates Used: Case#2)

- Minimize Disruptions
  - Schedule normalizes after 11:00 AM
  - Our model able to gate over 95% of these additional turns without retiming
- Maintain Feasibility by Retiming turns
  - ALL turns gated when retiming is allowed



Areas of Improvement

- Better pre-processing to limit the connection at risk based on the body type and gate restriction combination
- Explore alternative models or solution approach (such as column generation) to improve the manpower (objective of zone minimization) model
- Identify ways to reduce long run times associated with incremental gate rest
- Retiming in Operations model currently considers only un-gated turns from the basic model as candidates for retiming. Find some way of introducing a larger set of "competing" turns without impacting the run times considerably