Service Network Design: Applications in Transportation and Logistics

Professor Cynthia Barnhart
Center for Transportation and Logistics
Operations Research Center
Massachusetts Institute of Technology

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Problem Definition

- Service network design problems in transportation and logistics, subject to limited resources and variable service demands
  - Determine the cost minimizing or profit maximizing set of services and their schedules
    - What is the best location and size of terminals such that overall costs are minimized?
    - What is the best fleet composition and size such that service requirements are met and profits are maximized?

Service Network Design Applications

- Examples
  - Determining the set of flights and their schedules for an airline
  - Determining the routing and scheduling of tractors and trailers in a trucking operation
  - Jointly determining the aircraft flights, ground vehicle and package routes and schedules for time-sensitive package delivery

Research on Service Network Design

- Rich history of research on network design applications
  - *Network Design*
    - Balakrishnan et al (1996); Desaulniers, et al (1994); Gendron, Crainic and Frangioni (1999); Gendron and Crainic (1995); Kim and Barnhart (1999); Magnanti (1981); Magnanti and Wong (1984); Minoux (1989)
  - *Freight Transportation Service Network Design*
    - Armacost, Barnhart and Ware (2002); Crainic and Rousseau (1986); Crainic (2000); Farvolden and Powell (1994); Lamar, Sheffi and Powell (1990); Newton (1996); Ziarati, et al (1995)
  - *Fleet Routing and Scheduling*
    - Appelgren (1969, 1971); Desaulniers, et al (1997); Desrosiers, et al (1995); Dumas, Desrosiers, Soumis (1991); Leung, Magnanti and Singhal (1990); Ribeiro and Soumis (1994)

Challenges

- Service network design problems in transportation and logistics are characterized by
  - Costly resources, tightly constrained

Both models and algorithms are critical to tractability

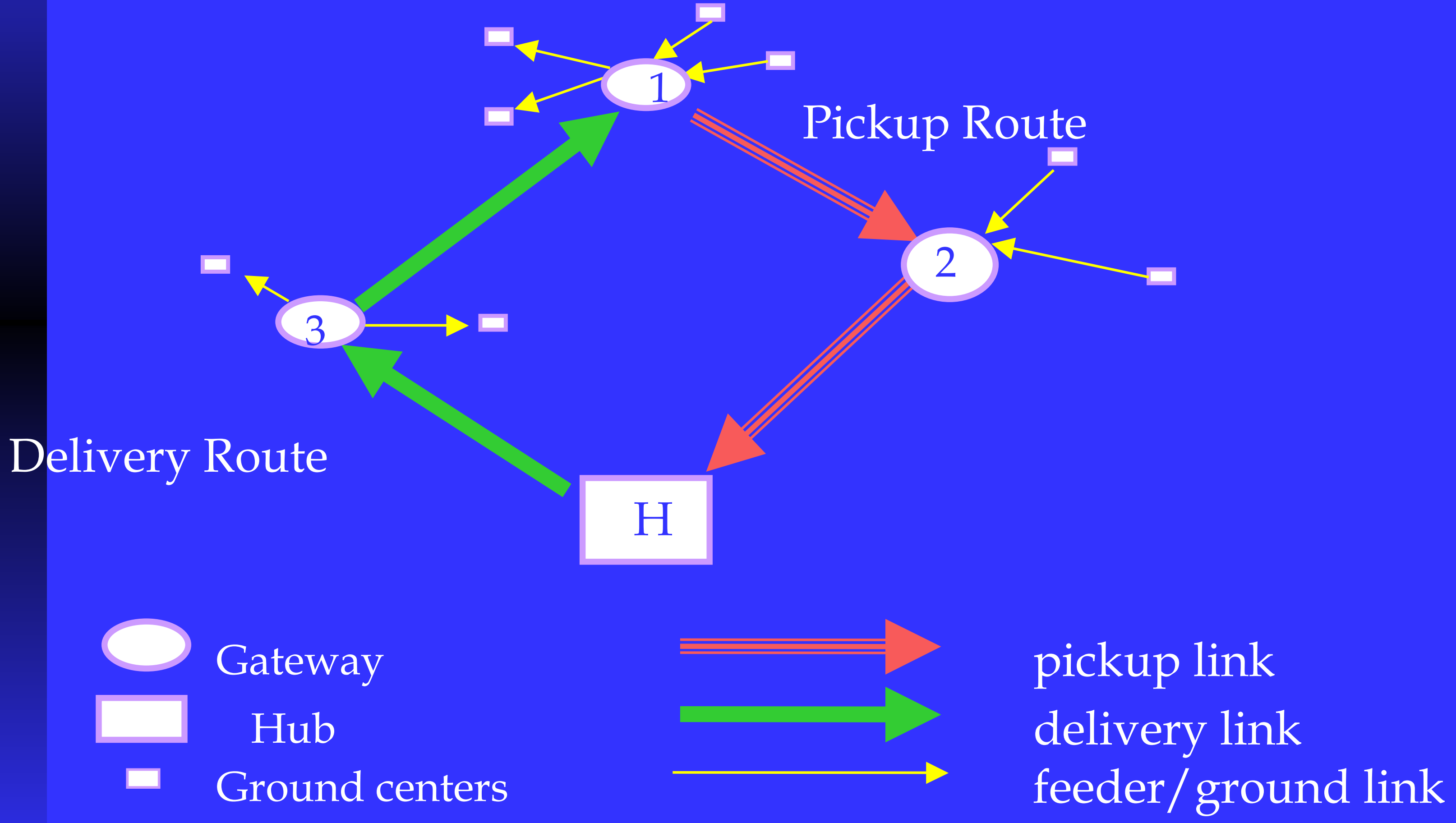
    - Associated with sets of design decisions, not a single design decision
- *Huge* mathematical programs
- Notoriously weak linear programming relaxations

Designing Service Networks for Time-Definite Parcel Delivery

- Problem Description and Background
- Designing the Air Network
  - Optimization-based approach
- Case Study

Research conducted jointly with
Prof. Andrew Armacost, USAFA

Problem Overview



UPS Air Network Overview

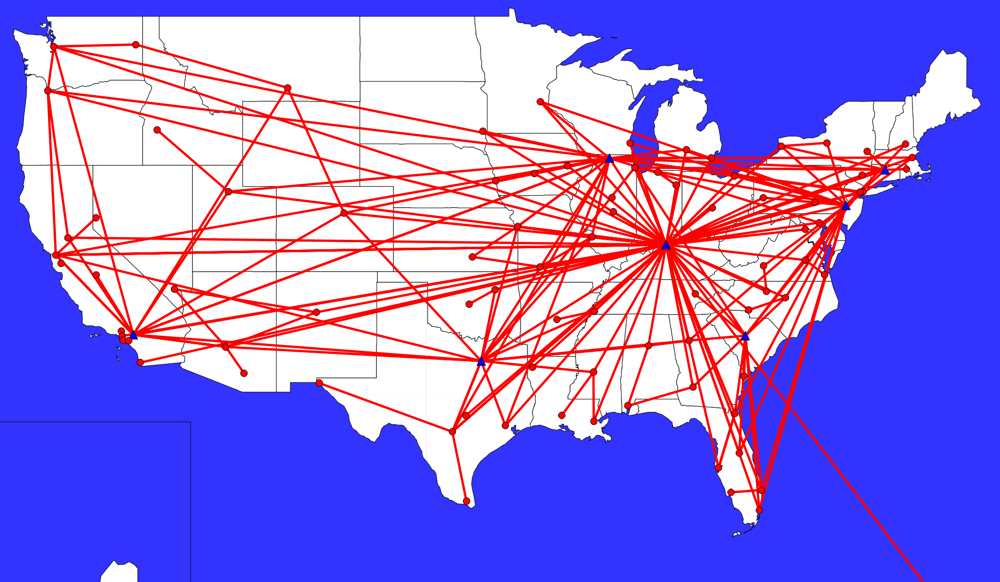
- Aircraft
  - 168 available for Next-Day Air operations
  - 727, 747, 757, 767, DC8, A300
- 101 domestic air "gateways"
- 7 hubs (Ontario, DFW, Rockford, Louisville, Columbia, Philadelphia, Hartford)
- Over one million packages nightly

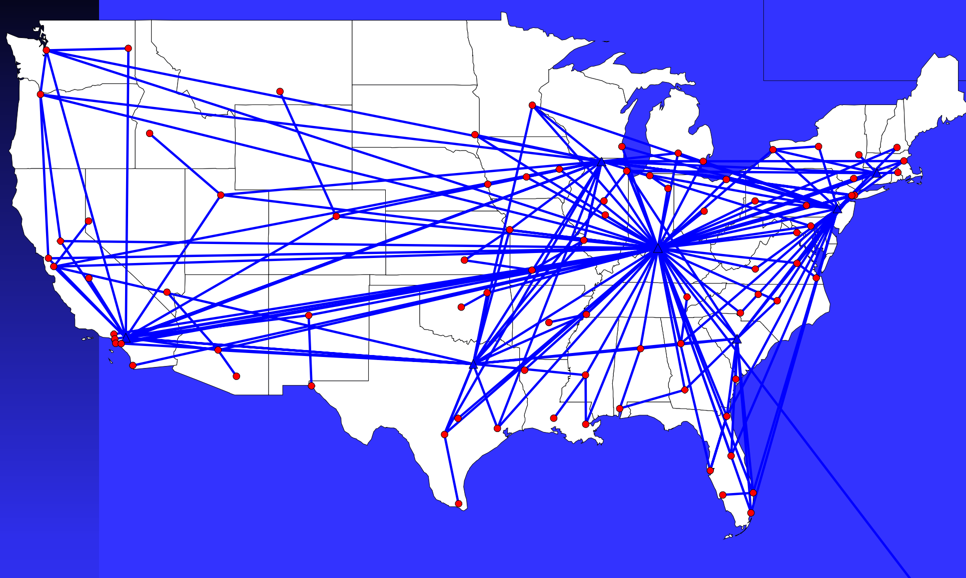
Research Question

- What aircraft routes and schedules provide on-time service for all packages while minimizing total costs?

UPS Air Network Overview

Delivery Routes





Pickup Routes

Problem Formulation

- Select the minimum cost routes, fleet assignments, and package flows
- Subject to:
  - Fleet size restrictions
  - Landing restrictions
  - Hub sort capacities
  - Aircraft capacities
  - Aircraft balance at all locations
  - Pickup and delivery time requirements

Express Shipment Service Network Design Problem

$$\min \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k + \sum_{f \in F} \sum_{r \in R^f} d_r^f y_r^f$$

$$\sum x_{ij}^k \le \sum \sum \delta_{ij}^{fr} u^f y_r^f \quad (i,j) \in A$$

$$\sum_{j:(i,j) \in A} x_{ij}^k - \sum_{j:(j,i) \in A} x_{ji}^k = \begin{cases} b^k & \text{if } i = O(k) \\ -b^k & \text{if } i = D(k) \end{cases}$$

$$\sum \sum \delta^h x^k \le \ldots \quad h \in H$$

$$\sum_{r \in R^f} \beta_i^r y_r^f = 0 \quad i \in N, f \in F$$

$$\sum_{r} y_r^f \le n^f \quad f \in F$$

$$\sum_{f} \sum \delta_h^r y_r^f \le a_h \quad h \in H$$

$$x_{ij}^k \ge 0 \quad (i,j) \in A, k \in K$$

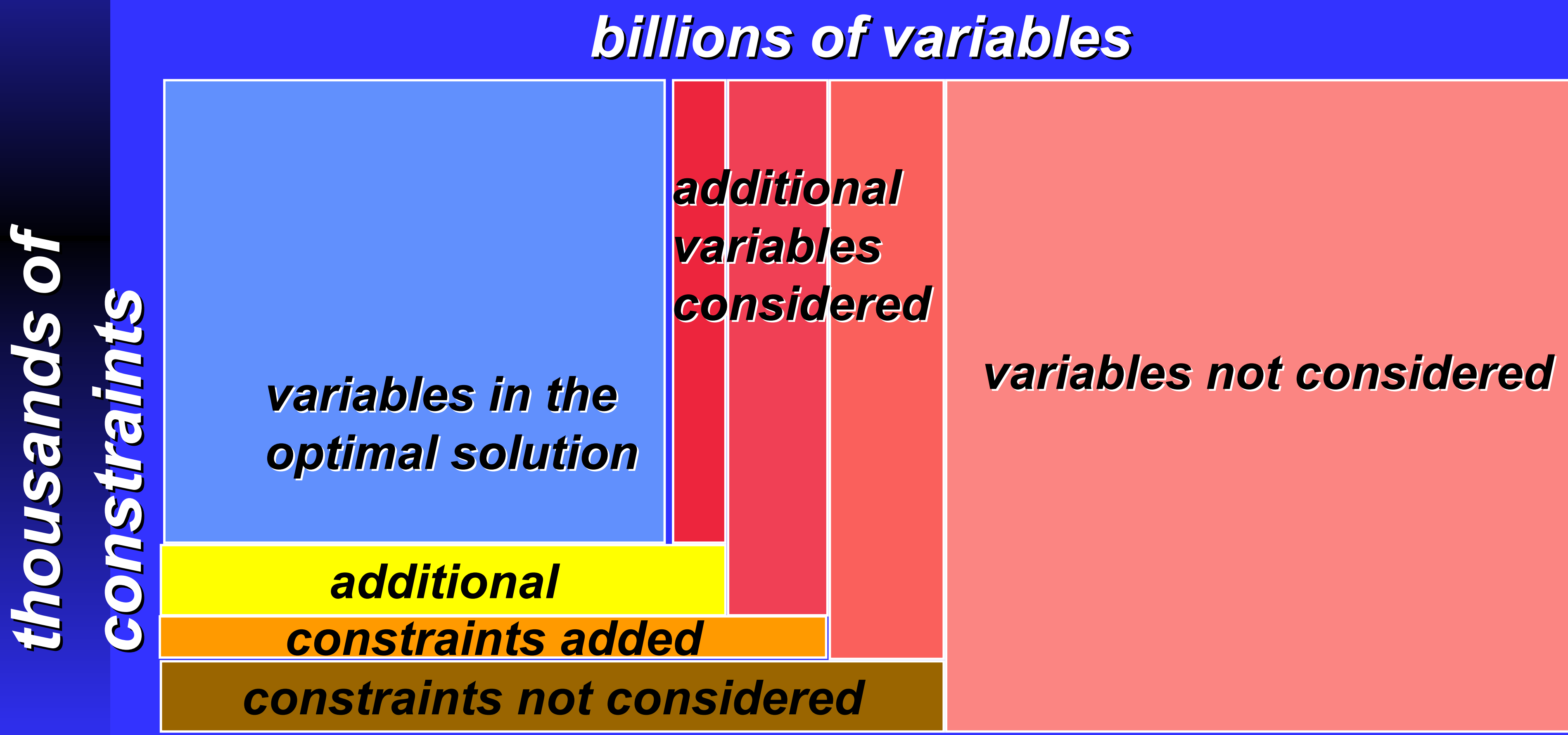
$$y_r^f \in \mathbb{Z}_+ \quad r \in R^f, f \in F$$

The Size Challenge

- Conventional model
  - Number of variables exceeds one billion
  - Number of constraints exceeds 200,000

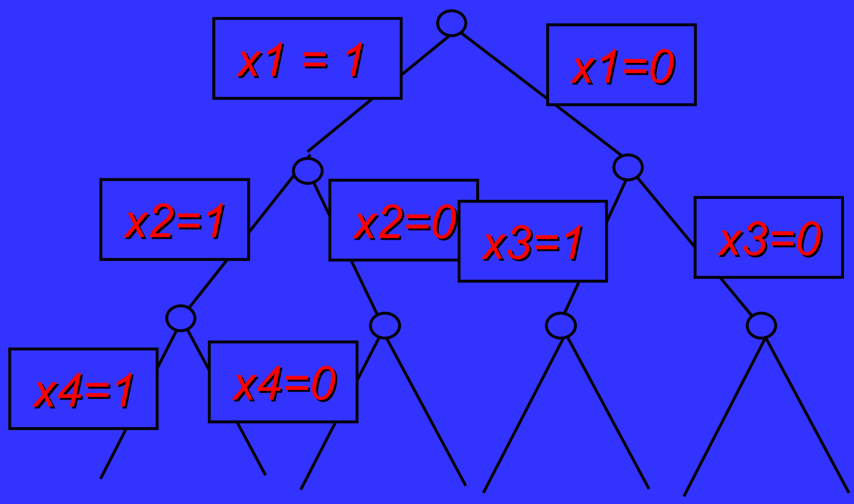
Column and Cut Generation

Constraint Matrix



Algorithms for Huge Integer Programs: Branch-and-Price-and-Cut

- Determines Optimal Solutions to Huge Integer Programs
  - Combines Branch-and-Bound with Column Generation and Cut Generation to solve the LP's



The Integrality Challenge

- Initial feasible solution about triple the best bound
  - Multiple day runtimes to achieve first feasible solution

Resolution of Challenges

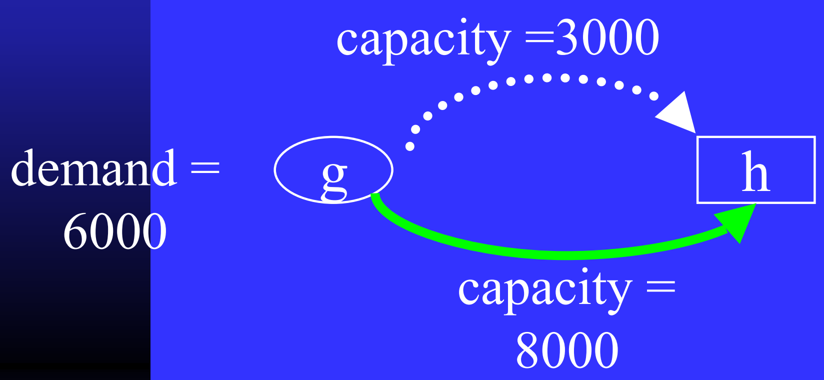
- Algorithms are not enough
- Key to successful solution of these very large-scale problems are the models themselves

Alternative Formulations

- A given problem may have different formulations that are all logically equivalen yet differ significantly from a computationa point of view
- This has motivated the study of systematic procedures for generating and solving *alternative* formulations

Reformulation: Key Ideas

rcraft Route Variables



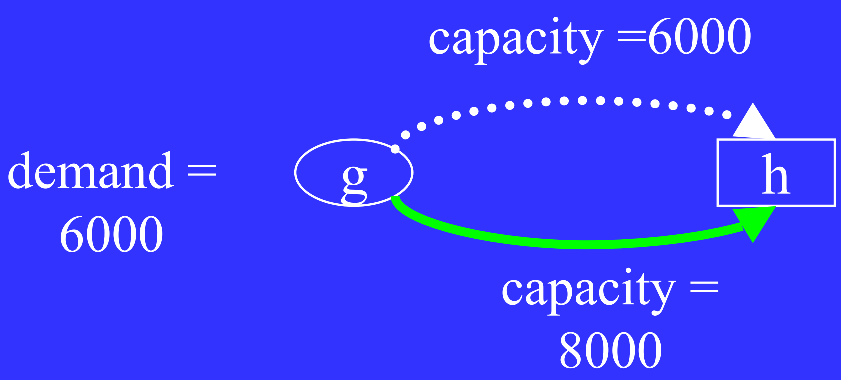
Capacity-demand:

$$3000y_1 + 8000y_2 \geq 6000$$

Cover:

$$y_1 + y_2 \geq 1$$

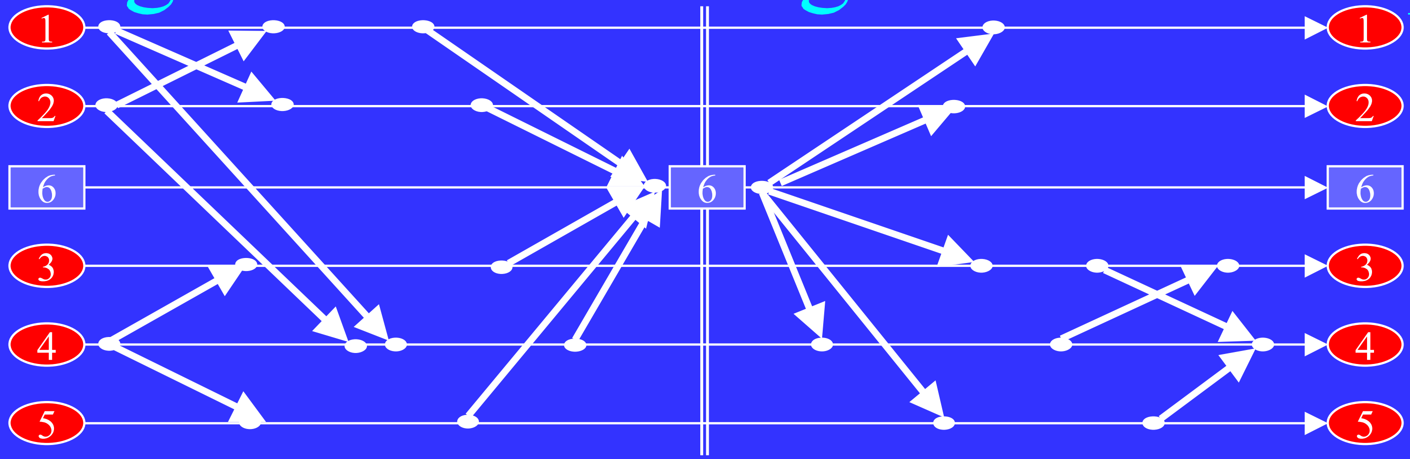
Composite Variables



Cover:

$$y_3 + y_2 \geq 1$$

Strength Results: Single Hub Example



Time-Space Representation of
Plane/Package Movements

	ESSND	ARM
Rows	53	34
Cols	67	42
NZ	274	255
LP Solution	10663	28474
IP Solution	28474	28474
B&B Nodes	781	1
LP-IP Gap	167%	0%

ARM vs UPS Planners

Minimizing Operating Cost for UPS

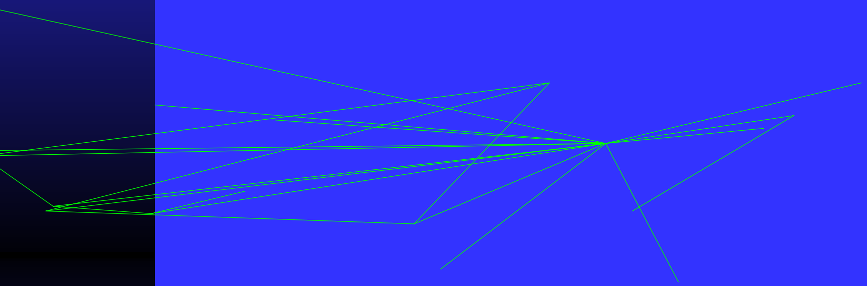
- Improvement (reduction)
  - Operating cost: 6.96 %
  - Number of Aircraft: 10.74 %
  - Aircraft ownership cost: 29.24 %
  - Total Cost: 24.45 %
- Running time
  - Under 2 hours

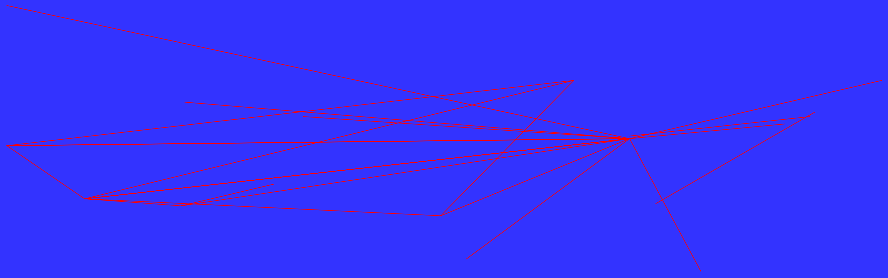
ARM vs. Planners

Routes for One Fleet Type

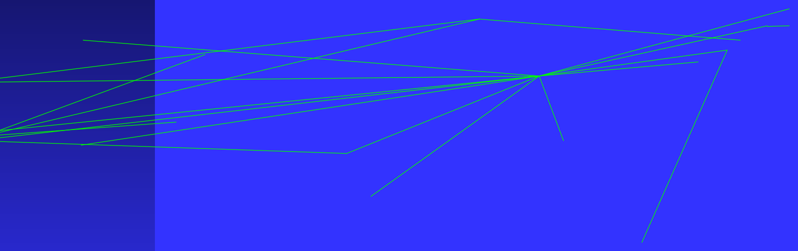
Pickup Routes

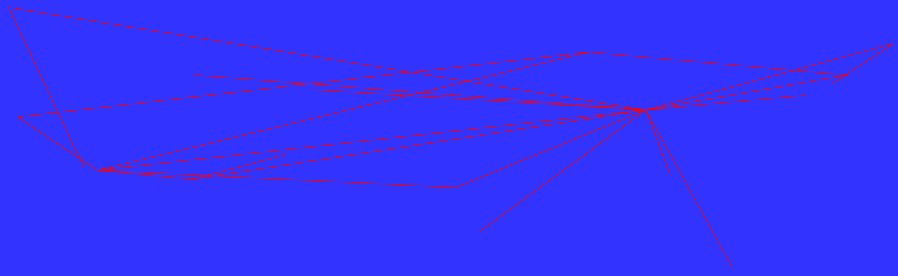
Delivery Routes





Planners' Solution

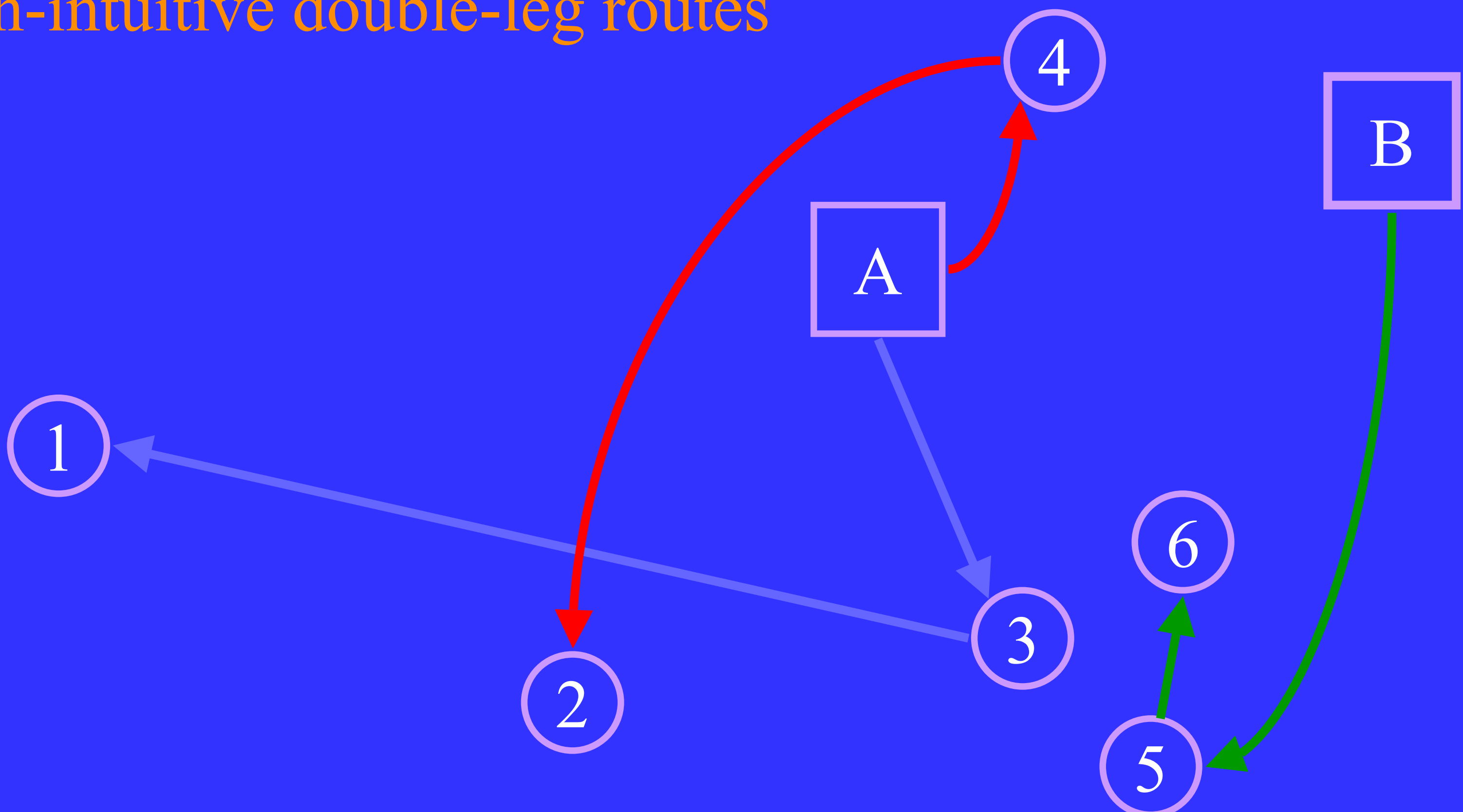




ARM Solution

ARM Solution

Non-intuitive double-leg routes



Model takes advantage of timing requirements, especially in case of A-3-1, which exploits time zone changes

Model takes advantage of ramp transfers at gateways 4 and 5

Conclusions

- Solving large-scale service network design problems
  - Blend art and science
  - Composite variable modeling can often facilitate
    - Tractability
    - Extendibility

Service Network Design and Passenger Service in the Airline Industry

- Problem Description and Background
- Analysis
- Some Research Findings

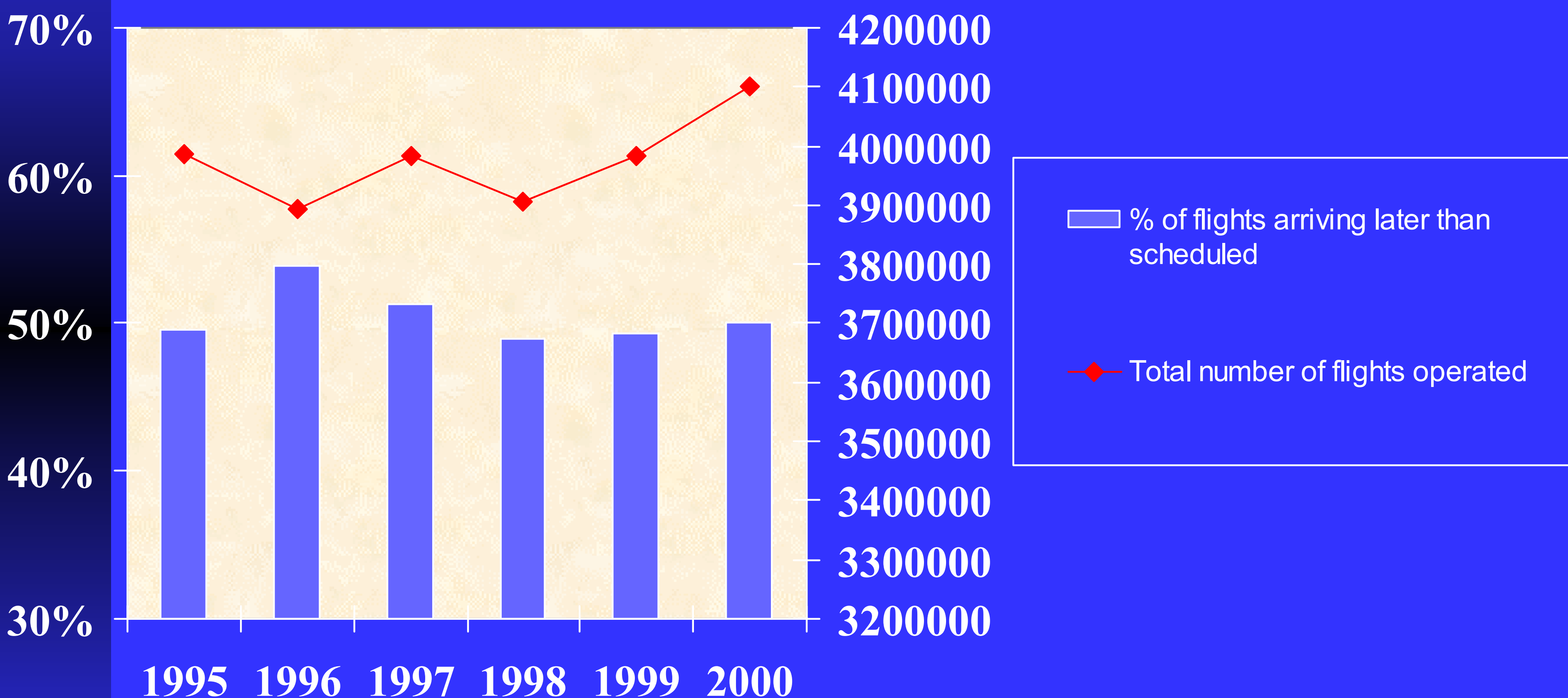
Research conducted jointly with
Stephane Bratu

Airline Schedule Planning

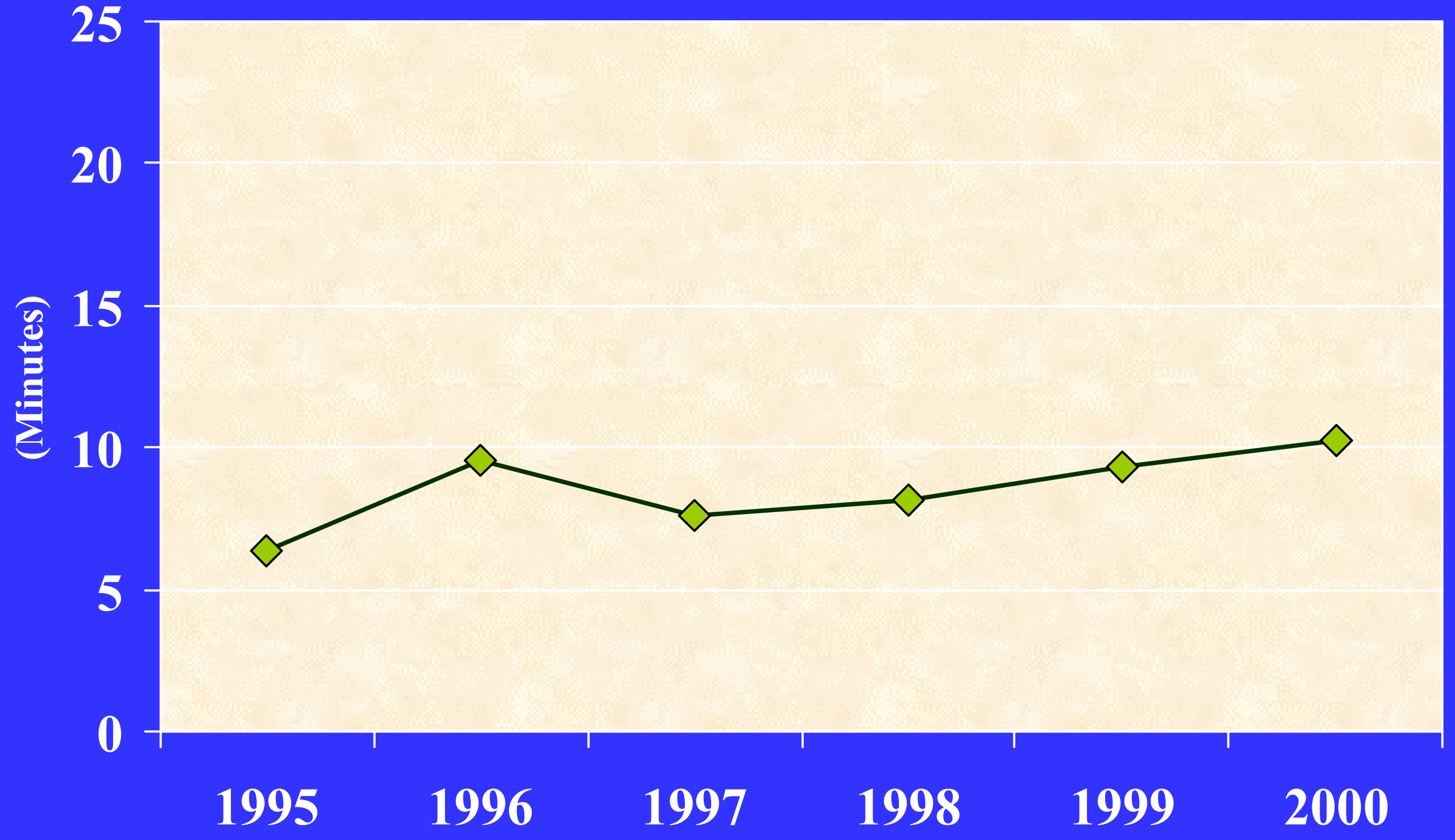
Schedule Design	Select optimal set of *flight legs* in a schedule
Fleet Assignment	Assign aircraft types to flight legs such that *contribution* is maximized
Aircraft Routing	Route individual aircraft honoring maintenance restrictions
Crew Scheduling	Assign crew (pilots and/or flight attendants) to flight legs

Some Simple Statistics …

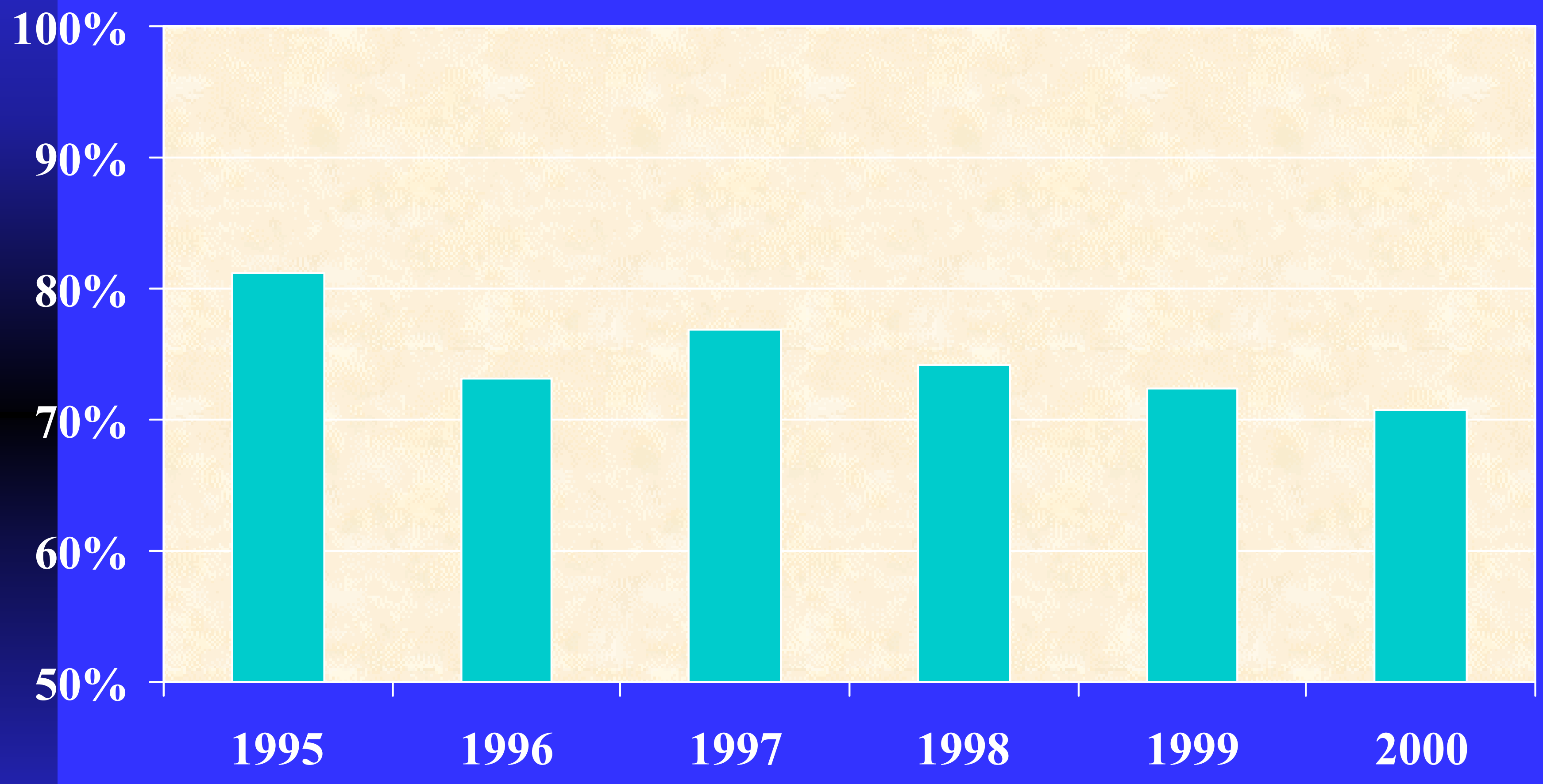
Number and Percentage of Delayed Flights



Average Delay Duration of Operated Flights



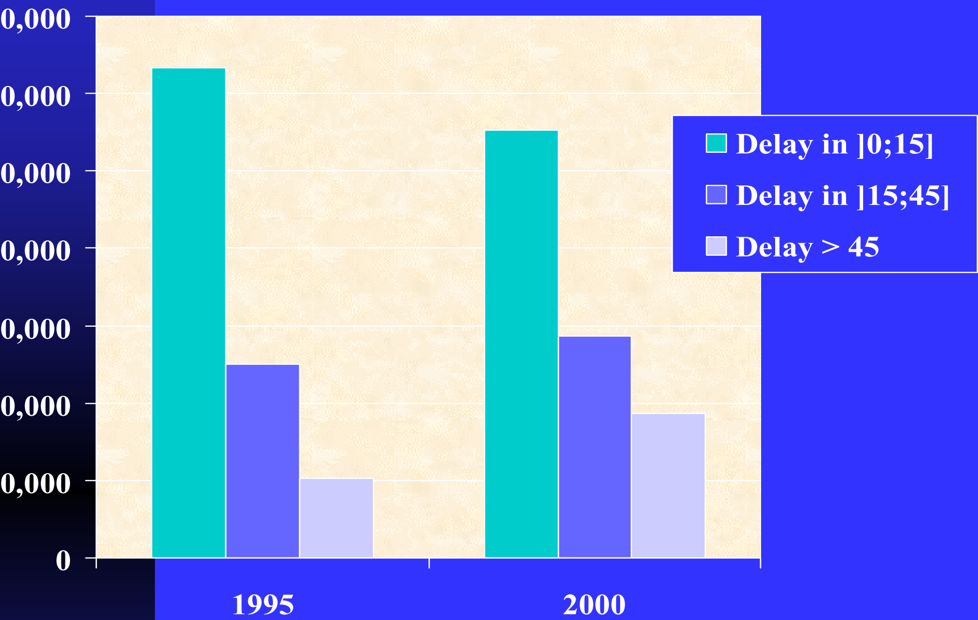
15-minute On-Time Performance



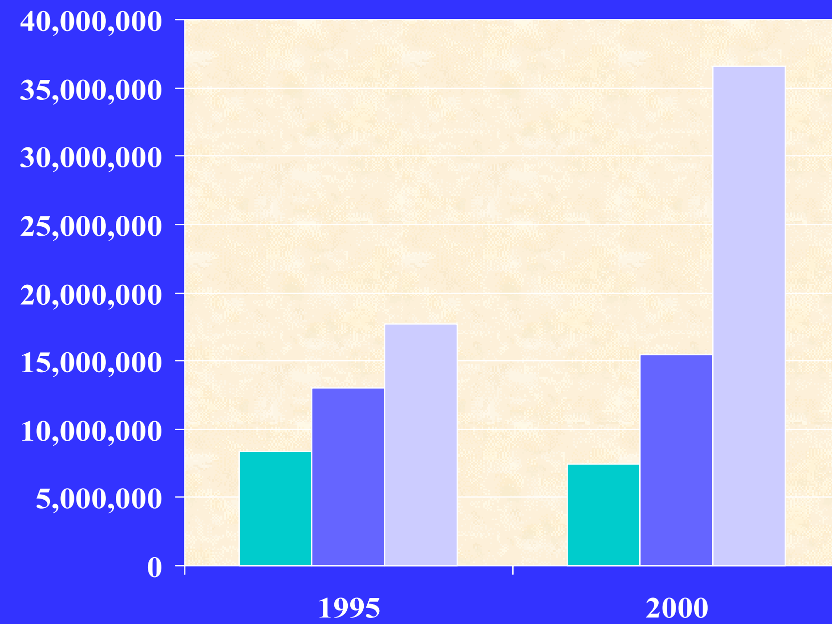
Important Factors Not Accounted For in Simple Statistics

1. Distribution of flight delays
2. Hub-and-Spoke Networks
3. Flight cancellation rate

Factor 1: Shift to Longer Flight Delays



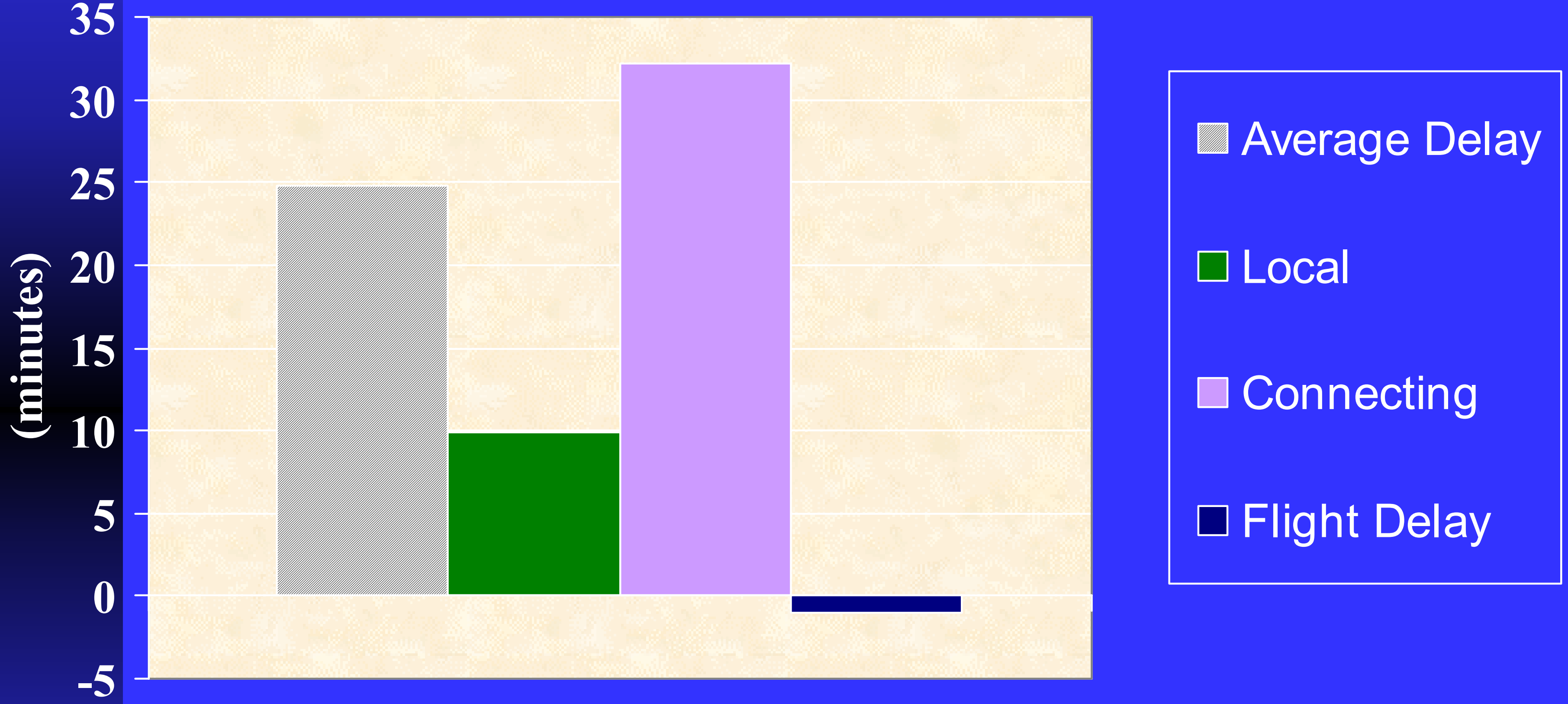
Number of Delayed Flights



Total Delay Minutes

- The delay distribution has shifted from short to long delays

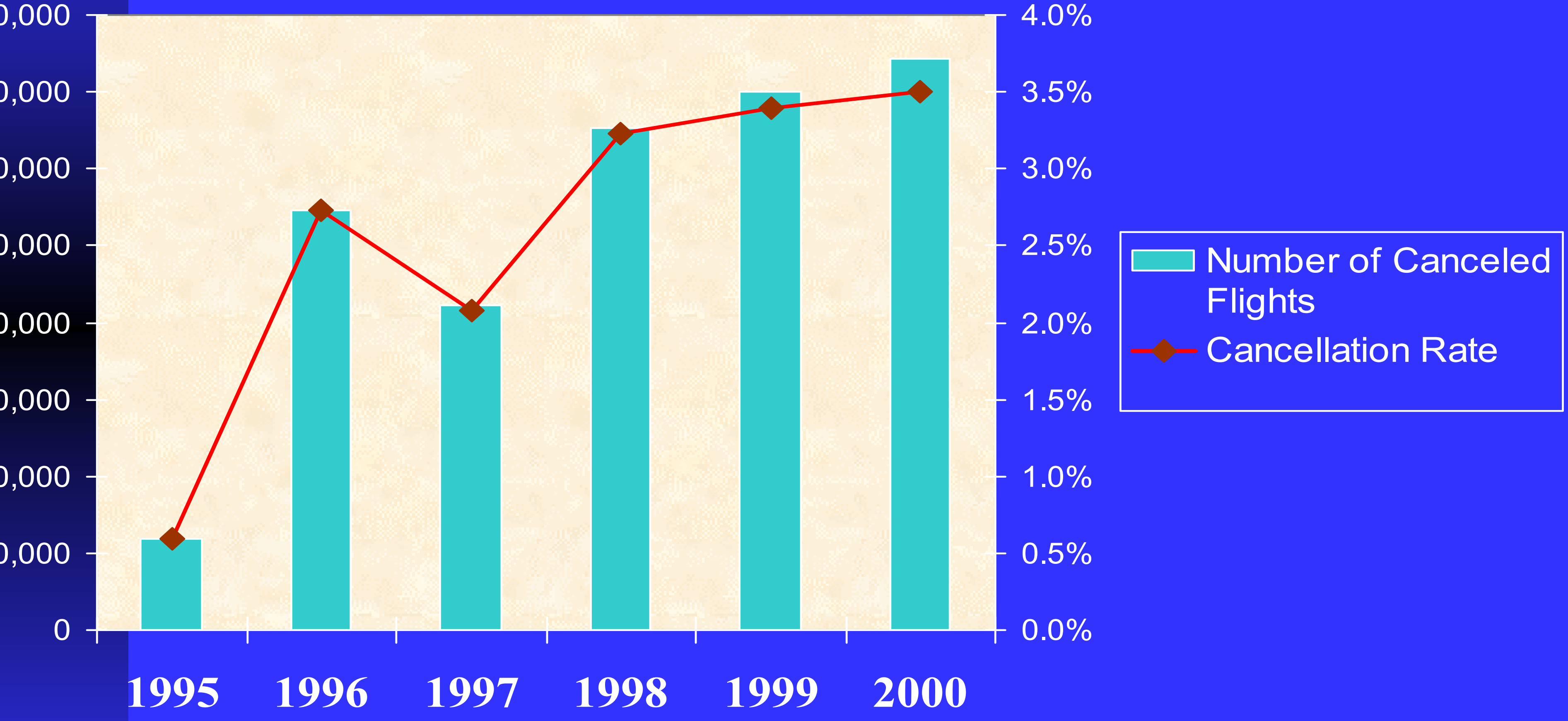
Factor 2: Hub-and-Spoke and Connecting Passengers



Average Passenger and Flight Delays

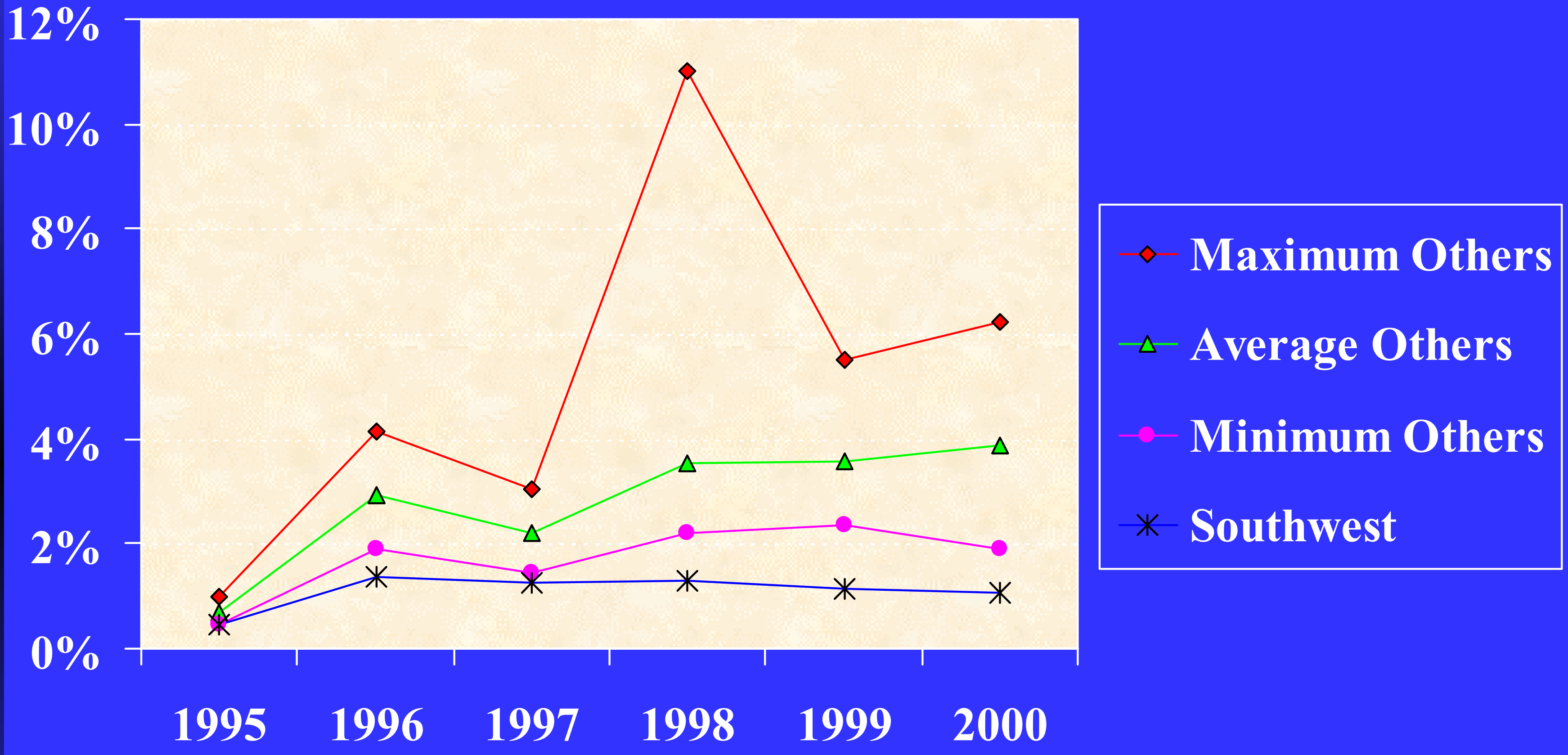
Flight delays underestimate passenger delays
Key explanation lies in the connecting passengers

Factor 3: Number of Canceled Flights and Cancellation Rates



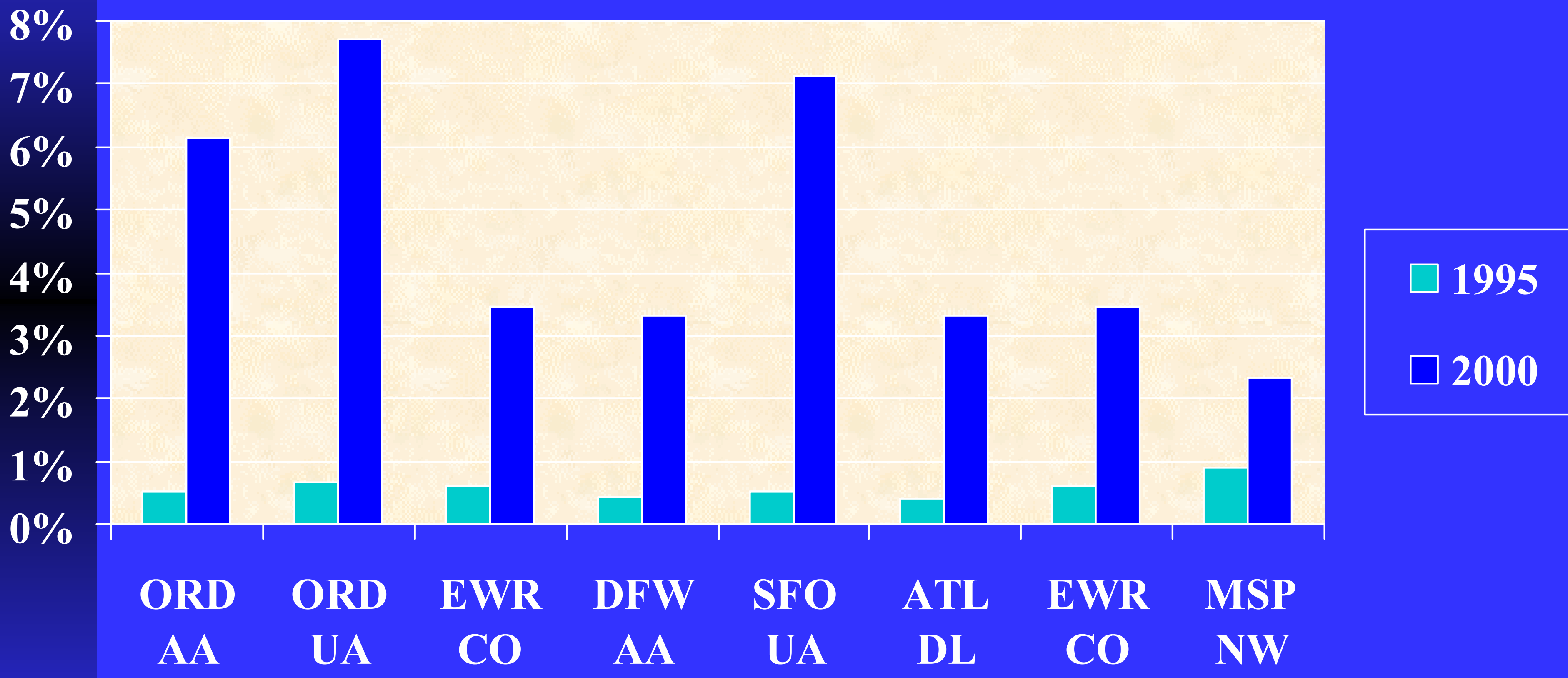
Delay statistics do not consider cancellations

Cancellation Rate: Southwest and the Other Majors Airlines



Southwest has a lower cancellation rate than any other Major from 1995 to 2000 due in part to increases in cancellation rates at some congested hubs

Hub Cancellation Rates



Research Findings: Service Network Design and Passenger Service

- DOT 15 minute on-time-performance is inadequate
- There are a number of alternative "flight schedules" with similar associated costs and profitability, but vastly different associated passenger delays
  - *Service* network design needs to incorporate *service considerations*
- Flight cancellations can reduce overall passenger delay
  - High load factors together with flight delays can result in excessive passenger delays
- De-banking can result in much longer planned connection times, but only slightly longer connection times in actuality