Complex Systems Engineering
The Air Transportation Case Study

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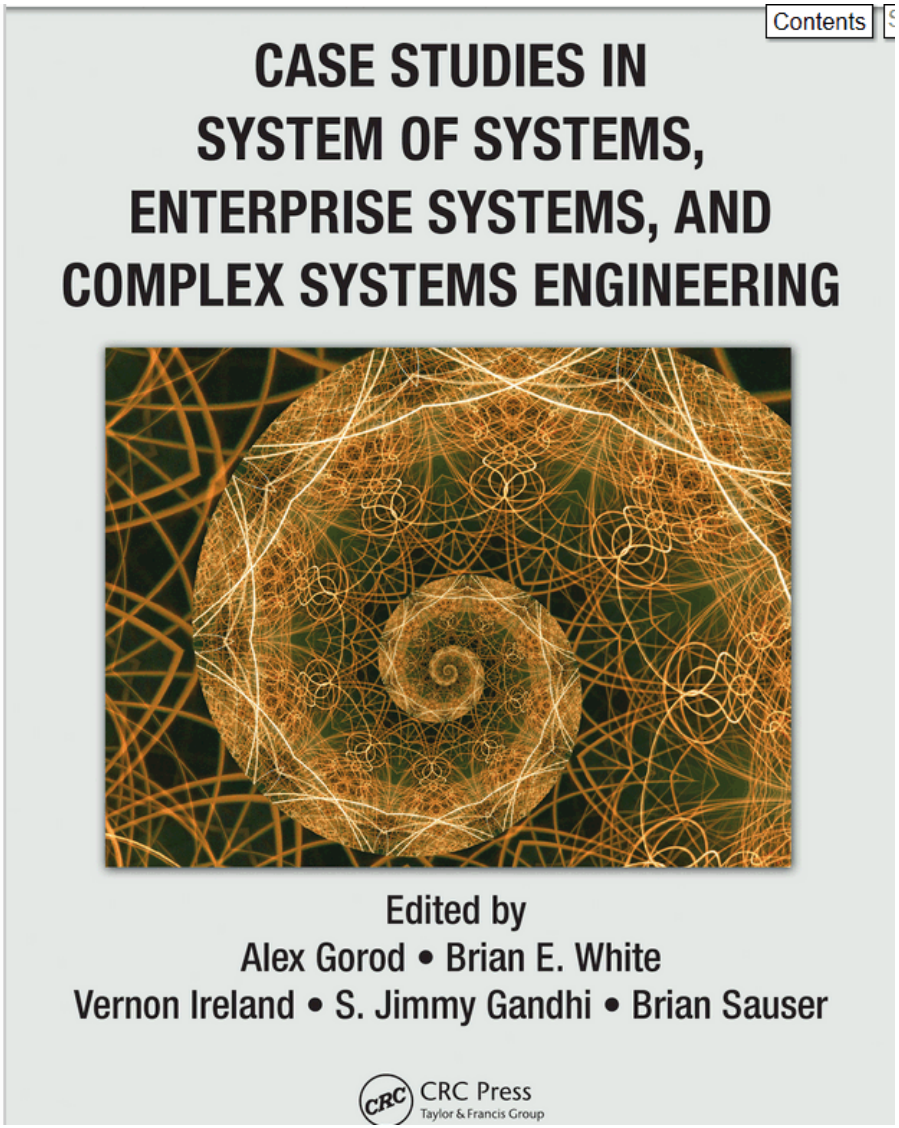
Outline

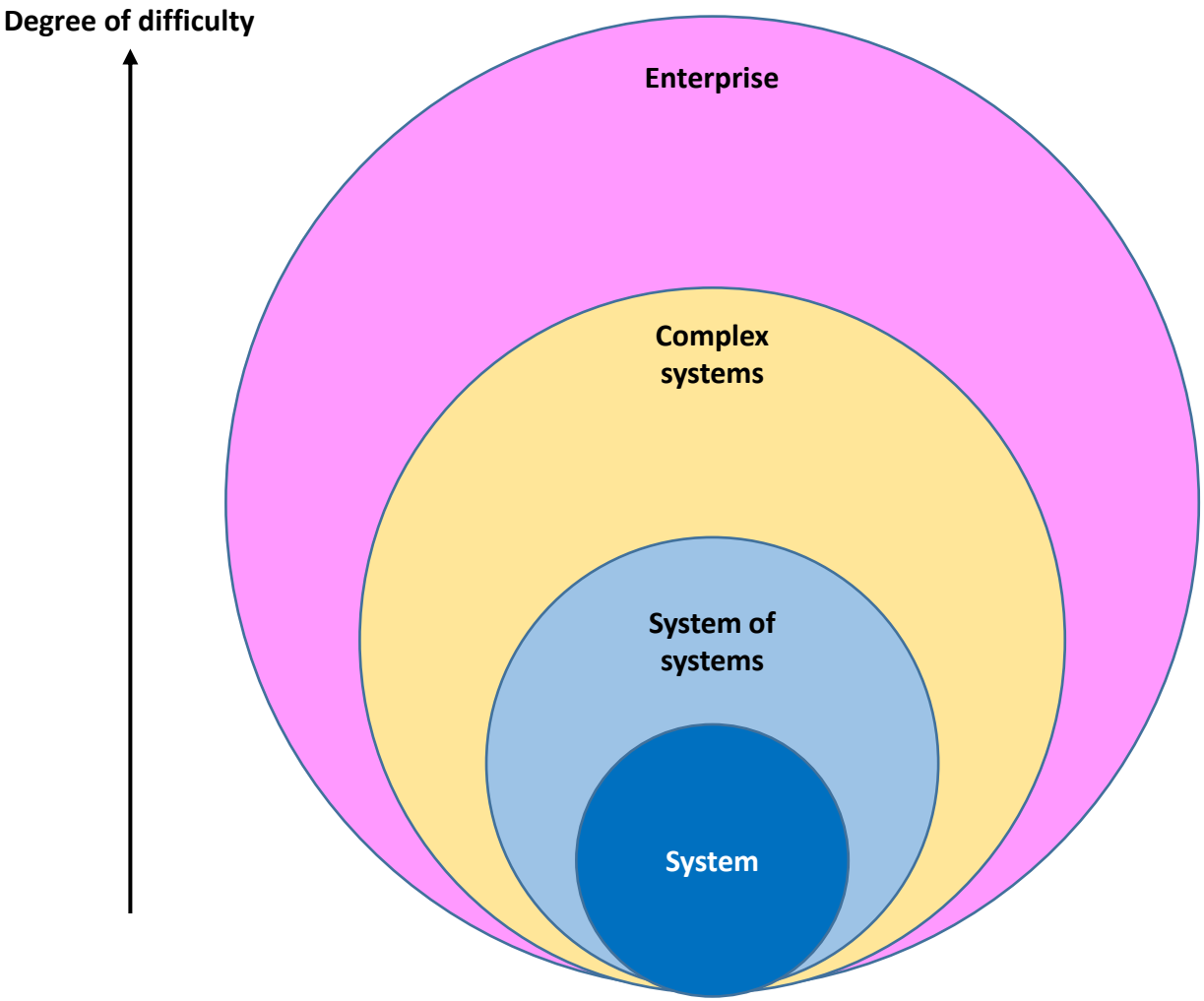
- Complex systems
- Transportation system case study
- Agent-based solution to air traffic
- Bayesian networks



- Commerce
- Culture
- Environment
- Finance
- Health Care
- Homeland Security
- Military
- Transportation

https://www.crcpress.com/Case-Studies-in-System-of-Systems-Enterprise-Systems-and-Complex-Systems/Gorod-White-Ireland-Gandhi-Sauser/p/book/9781466502390#googlePreviewContainer

Comparative Analysis of Systems

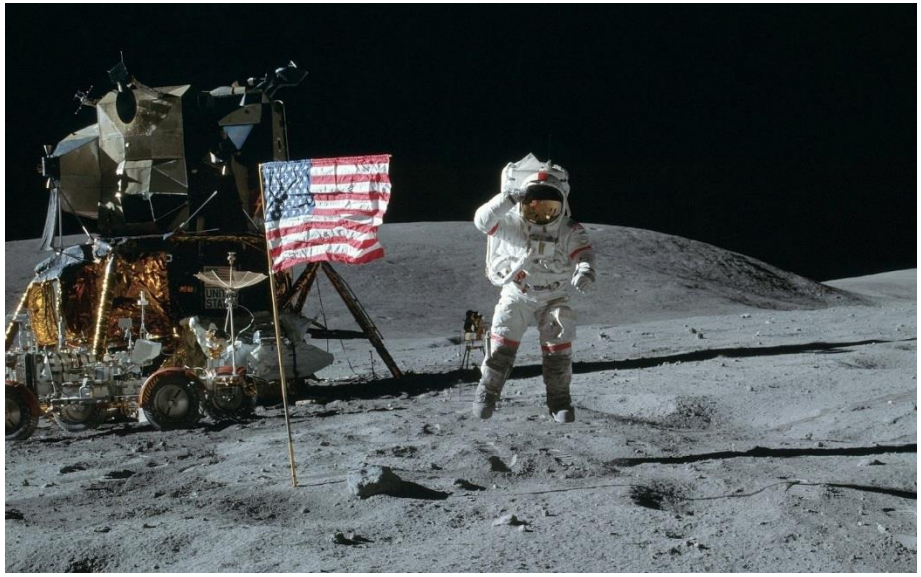


System of Systems (SoS)

- A set of several independently acquired systems, each under a nominal systems engineering process
- These systems are interdependent and form in their combined operations a multi-functional solution to an overall coherent mission
- The optimization of each system does not guarantee the optimization of the overall SoS

(Stevens 2009)

Complex? Complicated?



Complex systems

- Complex ≠ complicated
- Made up of a large number of parts that have many interactions
- Autonomy
- Autopoiesis
- Self-organization
- Adaptation
- Hierarchical organization
- Emergent properties
- Non reducible (behavior of each component depend on behavior of others)
- Vast parameter space (not optimizable)
- Networked causality
- Reduced predictability (not deterministic)
- Disturbances may propagate to a global context

Top-down approaches do not work with complex systems

Problem Statement

- The air transportation system is inefficient

In 2007 there were 4.3 million hours of flight delay in the US which raised airlines' operating costs by US$19 billion and consumed about 740 million additional gallons of fuel (Joint Economic Committee, Majority Staff 2008).

- Inefficiency costs will grow (non-linearly) with increased traffic load
- NextGen (the solution?)

NextGen is an unprecedented overhaul of the U.S. air transportation infrastructure and represents the largest investment ever made in civil aviation. Between US$29 billion and US$42 billion for equipment, software and training by 2025 (Huerta 2011)
In the U.S. civil aviation creates 10 million jobs and contributes 1.3 trillion dollars to the U.S. economy.

Problem Statement (II)

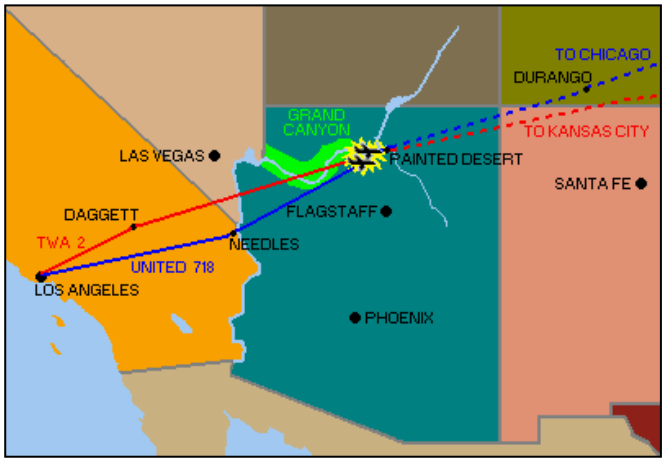
- NextGen does not introduce radical changes or new paradigms
- NextGen concepts rely on scaling capabilities hoping that modern automation will increase capacity and efficiency
- The problem is that air transportation system is a complex system that does not scale linearly with demand

Air Transportation – How did we get here?

First US controller, Archie Leage, 1920
Technology: a red flag (hold), checkered flag (go)

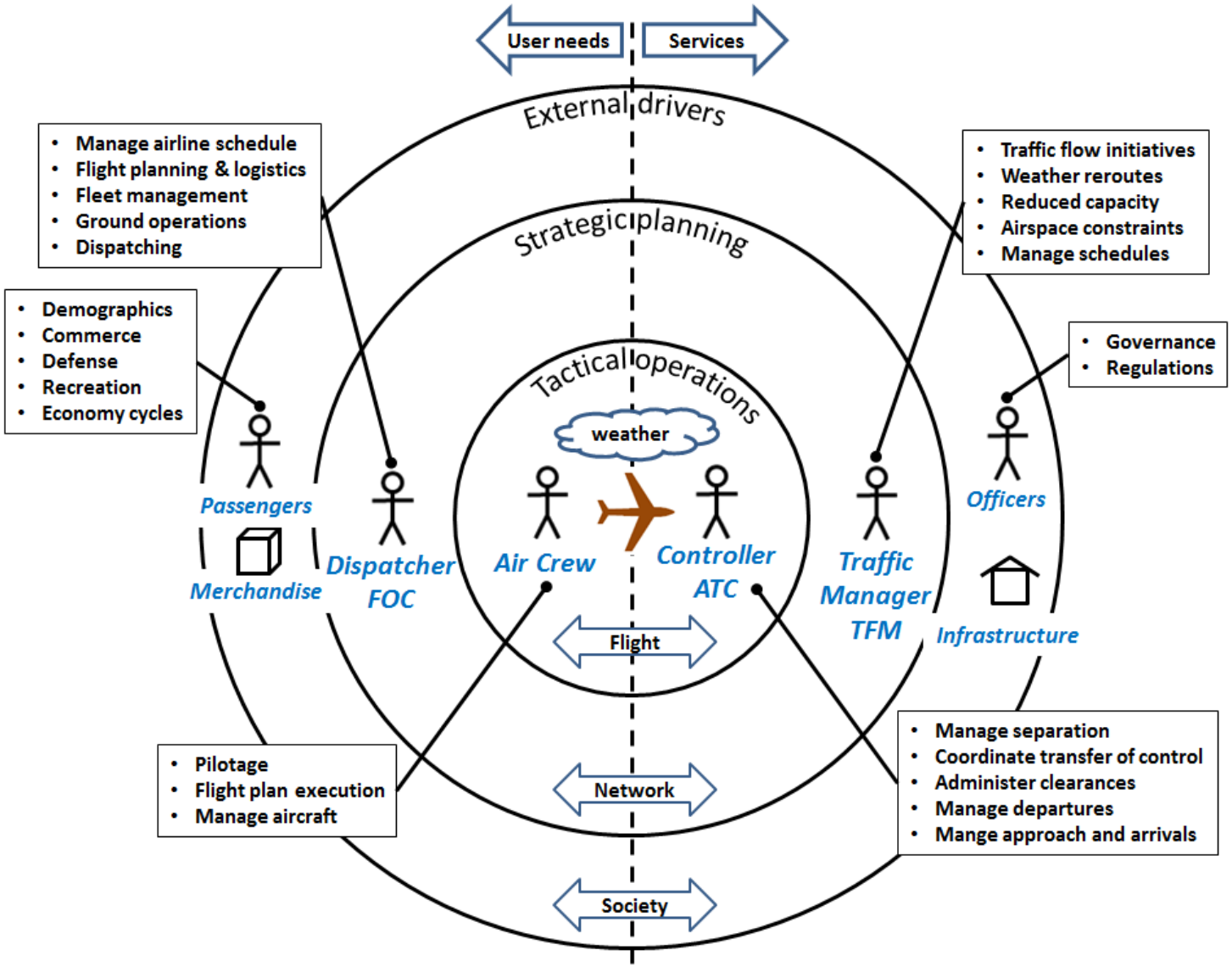
WWII Radar

June 30, 1956: TWA Lockheed Constellation and United Airlines DC-7 collided over the Grand Canyon

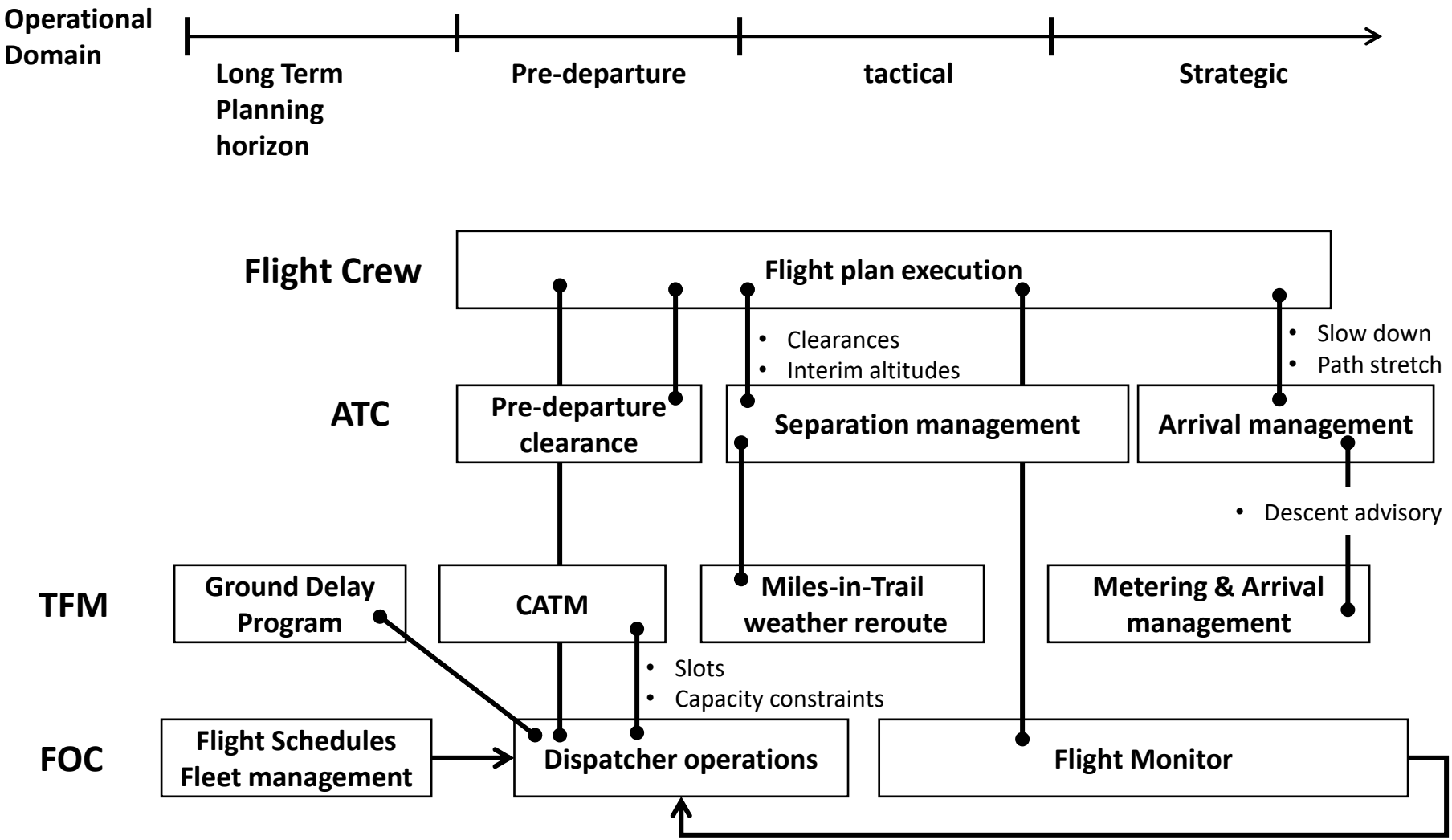


1958, FAA

Current Air Traffic System – Context Diagram



Control Loops in the National Airspace System



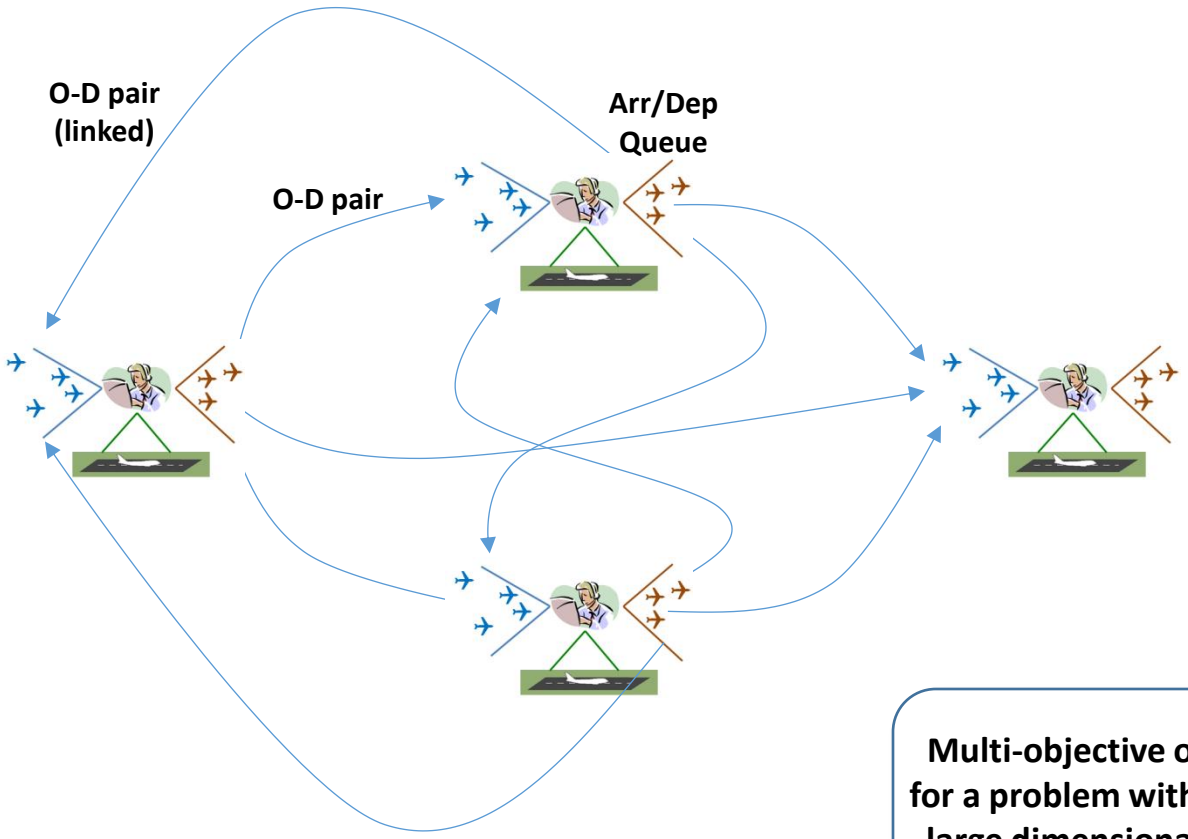
Limits of Predictability in the NAS

- TBO is predicated on the assumption of improved prediction accuracy, however there is a limit to the predictability of the NAS:
  - Air traffic is a stochastic process
  - Weather uncertainty
  - Guidance and Pilot options
  - Human behavior
  - Fidelity of mathematical models
  - Accuracy of aircraft performance models
  - Uncertainties in aircraft state
  - Unknown aircraft intent
  - Unpredictable tactical interventions

Traffic Flow Network Optimization

NAS model as a network of queuing servers

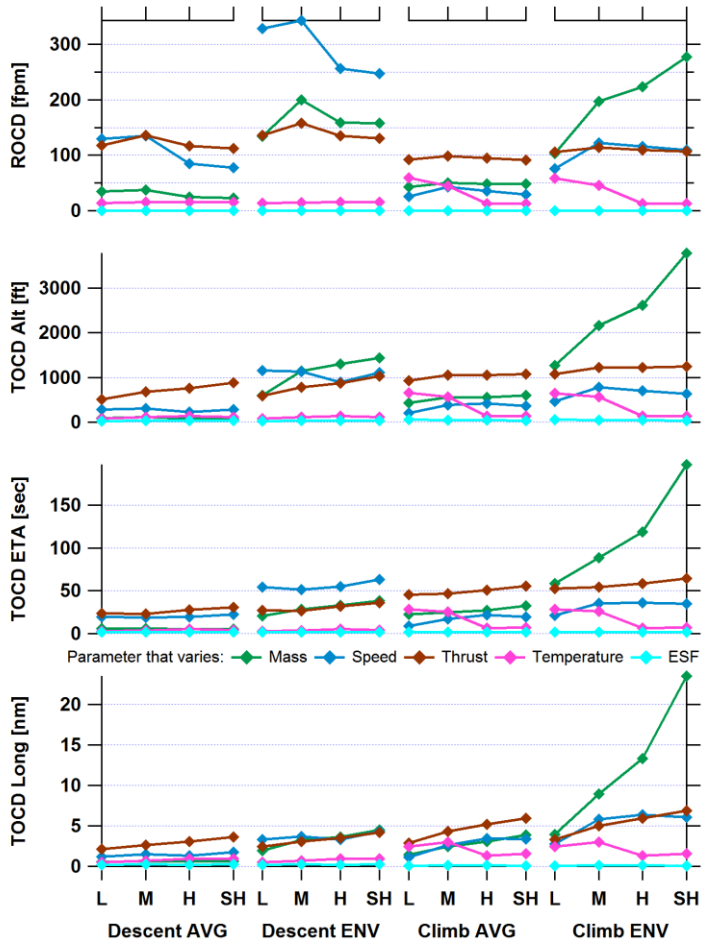
- Large Parameters space



Multi-objective optimization for a problem with exceedingly large dimensionality leads to combinatorial explosion

Trajectory Prediction Accuracy

- Varying one parameter at a time



← **Mass Group**

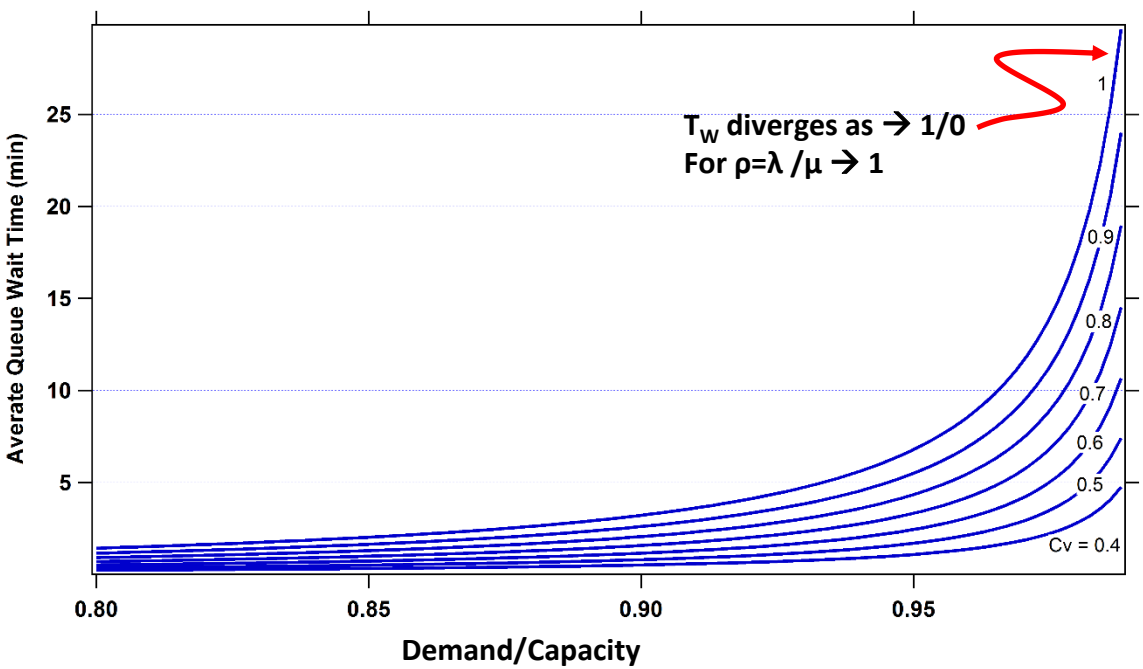
Source: Torres, S., "Trajectory Accuracy Sensitivity to Modeling Factors", 15th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Aviation Forum 2015, 22-26 June, 2015, Dallas, TX.

Time-Based Traffic Flow Management Insights from Queue Theory

In steady state the expected delay time in queue (T_W) increases with demand and variance of the arrival stream

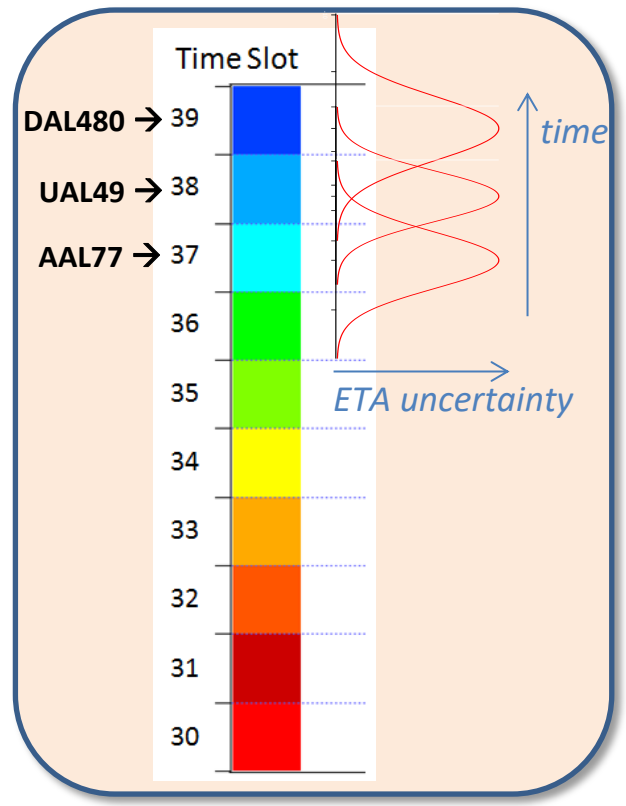
$$T_W = \left(\frac{C_V^2}{2}\right)\left(\frac{\lambda}{\mu-\lambda}\right)\tau$$

C_v = coefficient of variation (= $\sigma/avg)_{IATD}$
λ = arrival rate
μ = airport acceptance rate (AAR)
τ = service time



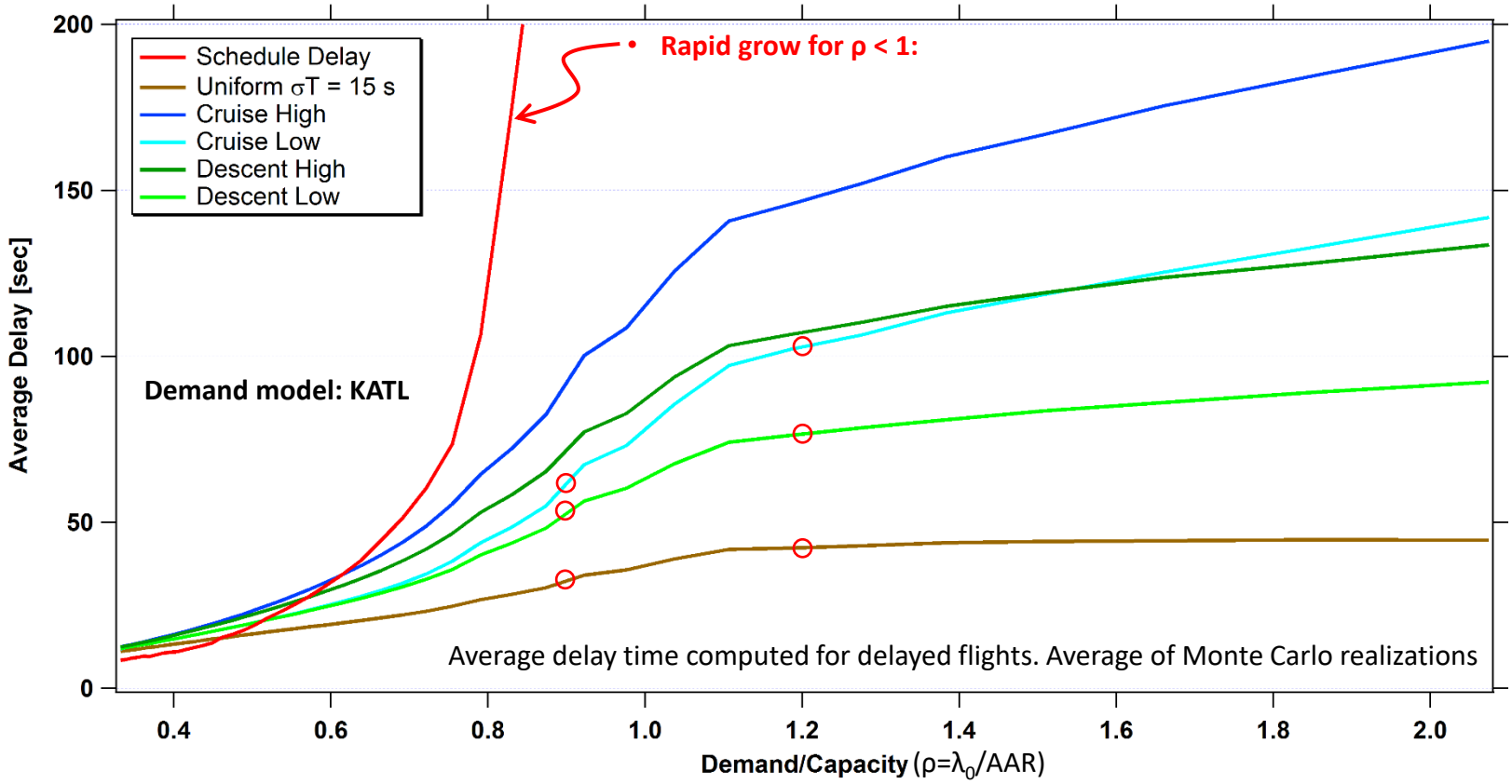
- **Estimated queue wait time as a function of Demand/Capacity ratio (ρ)**

Arrival Sequence



Tails of prediction uncertainty distributions overlap

Time-based Traffic Flow Management Efficiency Curves



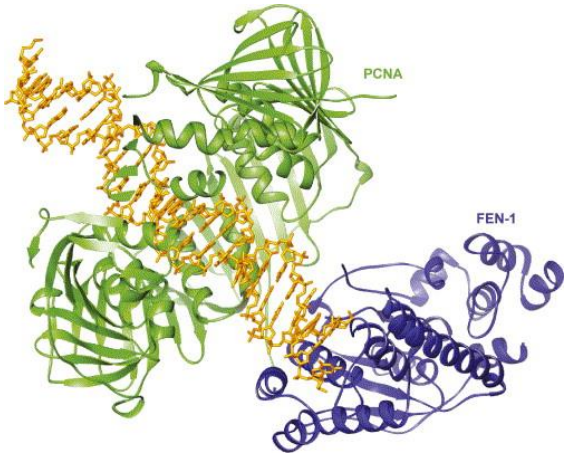
○ **Highlighted Measurements (delay in seconds)**

	ρ=0.9	ρ=1.2
DES Low	54	77
CRZ Low	62	103
Uniform (15s)	33	42

Source: Torres, S., Nagle, G., "Analysis of Prediction Uncertainty in Interval Management", 16th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Aviation Forum 2016, 13-17 June, 2016, Washington, D.C.

Complexity and Information Flow

Scaled solutions based on prediction and central planning are not effective to manage complex systems



(… on the other hand)

Swarm systems in nature exhibit remarkable efficiency in solving optimization problems.
This is possible by:

1. **Providing complete and accurate information flow between actors**
2. **Letting swarm members act as autonomous agents**

Agent-based Solution to Manage Air Traffic Flow

- Air traffic *is* a multi swarm system
- Provide pilots with complete and accurate information
- Delegate separation to the pilot
- Pilots become goal seeking agents that (like in a swarm) promote optimality of the system as a whole
- The flow of information between members of the swarm is necessary to drive the emergent behavior towards non-chaotic, coherent flows
- Central control is replaced by self agents that respond to market forces, thus creating conditions for a *swarm* emergent behavior (autonomy, distributed functioning and self organization) that naturally tends towards optimality

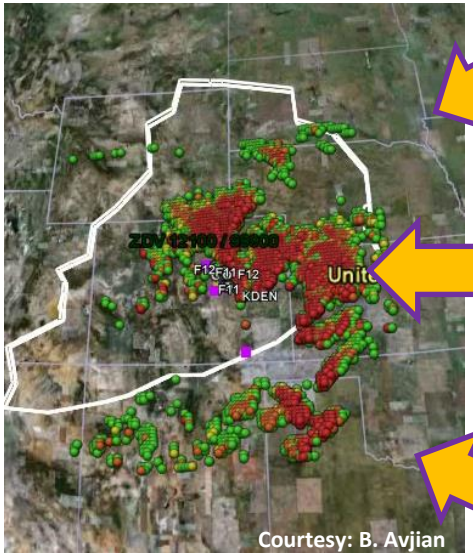
Agent-based Solution to Manage Air Traffic Flow

The business preferred trajectory closes the information loop

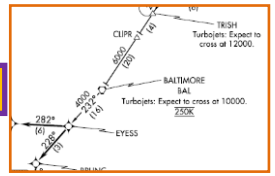
1. Provide complete and accurate information regarding available airspace

weather

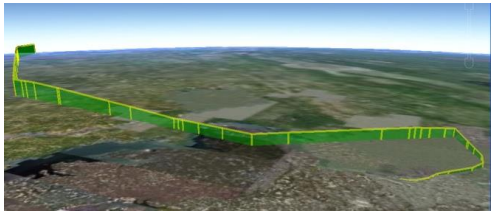
4D-Grid



restrictions & constraints



traffic



3. Build FMS trajectory according to plan

5. Fly FMS trajectory

6. Populate 4D-Grid with FMS trajectory

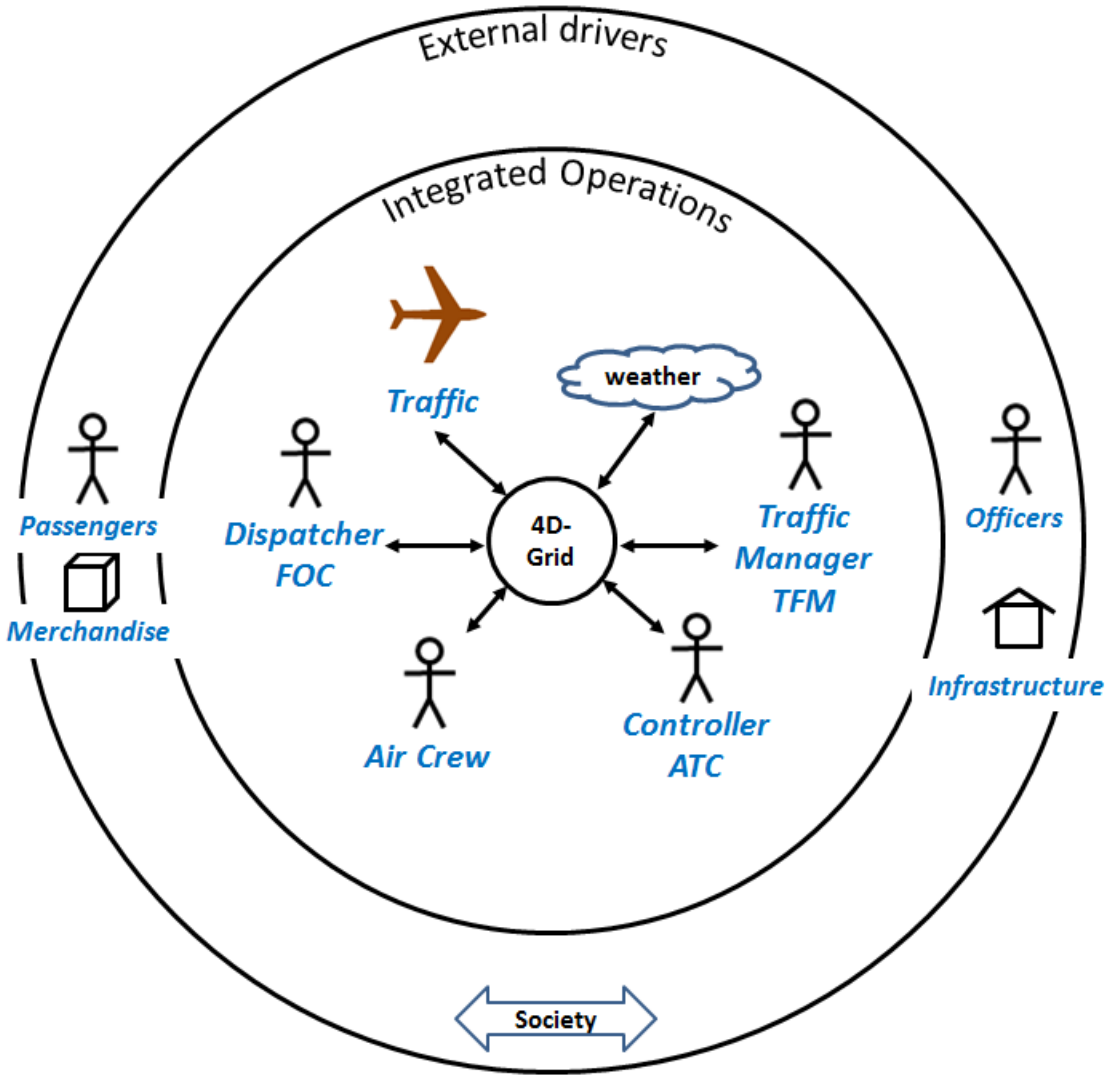
ATC

AOC

2. Operator plans according to user preferences and airspace availability

4. Obtain 4D-clearance

Agent-based Solution



Agent-based Solution to Air Traffic Management

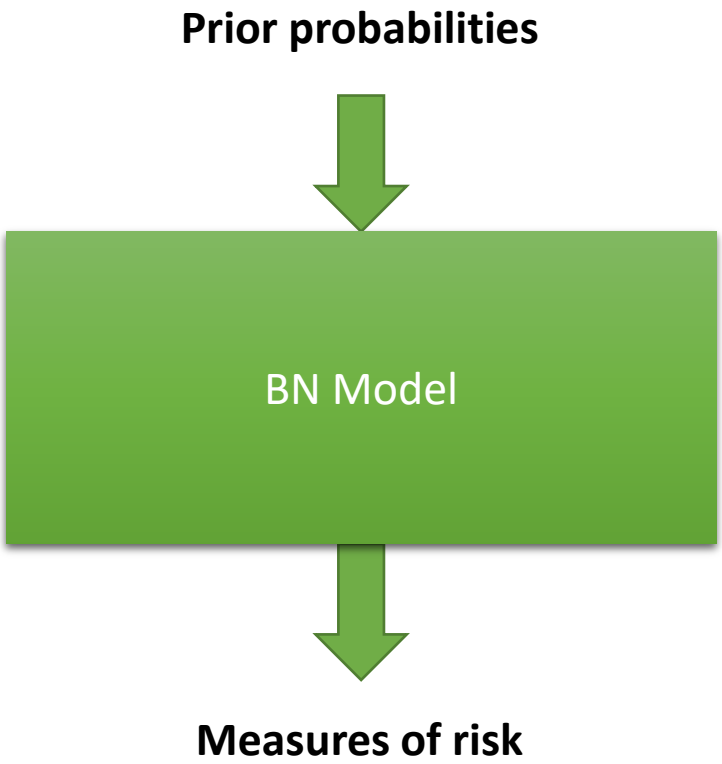
References

Torres,S. 2014,"US Air Traffic System: Autonomous Agent-Based Flight for Removing Central Control", in Case Studies in System of Systems, Enterprise Systems, and Complex Systems Engineering, Edited by Alex Gorod, Brian E. White, Vernon Ireland, S. Jimmy Gandhi, Brian Sauser, Taylor & Francis/CRC Press, 2014, pp. 701-729.

Torres, S., "Swarm Theory Applied to Air Traffic Flow Management," Procedia Computer Sciences, Elsevier (Ed. C.H. Dagli), Vol. 12, pp.463-470, 2012, Complex Adaptive Systems Conference, November 14-16, Dulles, Virginia

Torres, S., Delpome, K.L., "An Integrated Approach to Air Traffic Management to achieve Trajectory Based Operations", 31st Digital Avionics Systems Conference, October 14-18, 2012, Williamsburg, Virginia

Bayesian Network (BN) Analysis



Bayes Theorem

Tool to update ‘belief’ based on conditional probabilities

Bayes Theorem

Tool to update ‘belief’ based on conditional probabilities

Problem

In a chest clinic, 5% of all patients who have been to the clinic are ultimately diagnosed as having lung cancer, while 50% of patients are smokers.
Records of all patients previously diagnosed with lung cancer show that 80% were smokers.
A new patient comes into the clinic. The patient is a smoker.
What is the probability that this patient will be diagnosed as having lung cancer.

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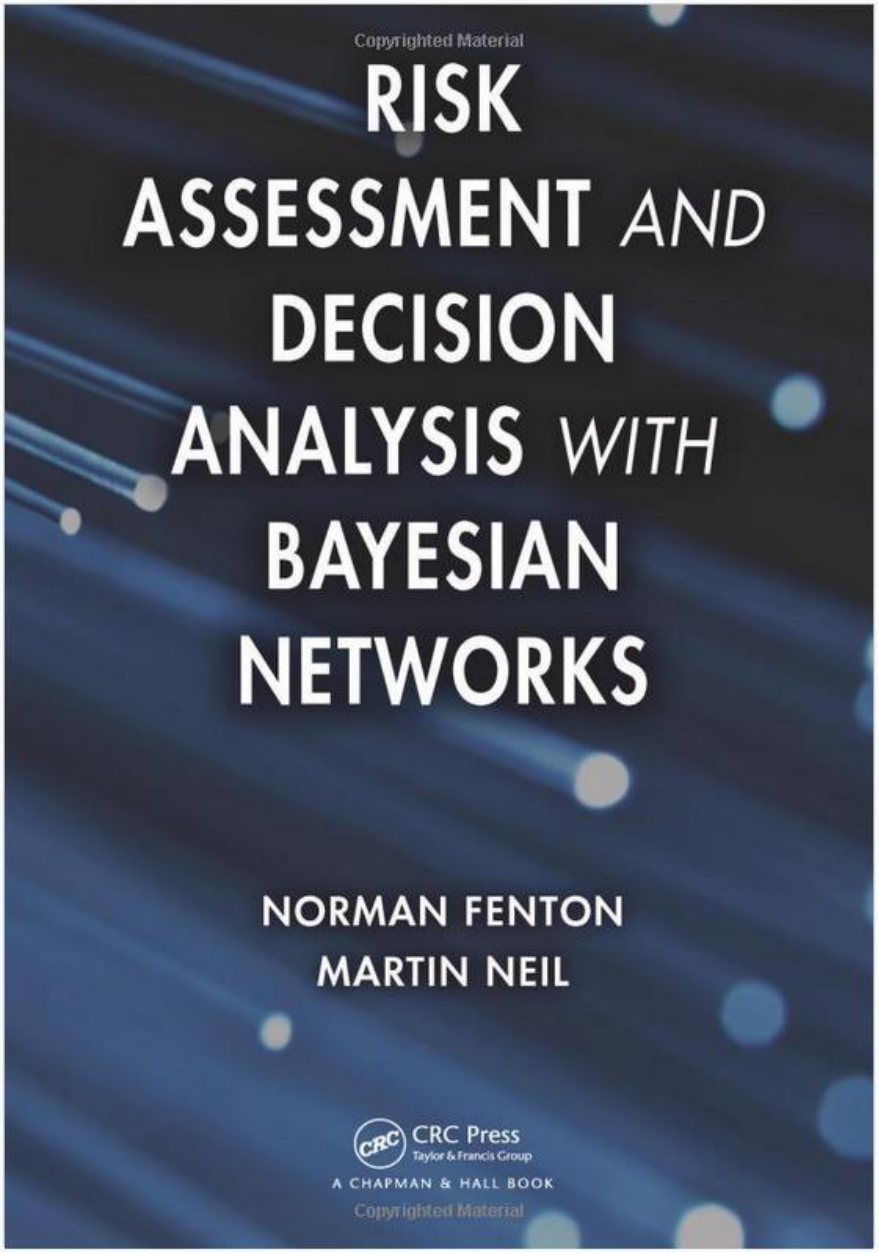
Analysis
H (hypothesis) = "patient has lung cancer"
E (evidence) = "patient is a smoker"

Prior belief:
$P(H) = 0.05$
$P(E) = 0.5$

We want to update our belief in H given evidence $E = P(H|E)$

Source: Fenton & Neil (2013)

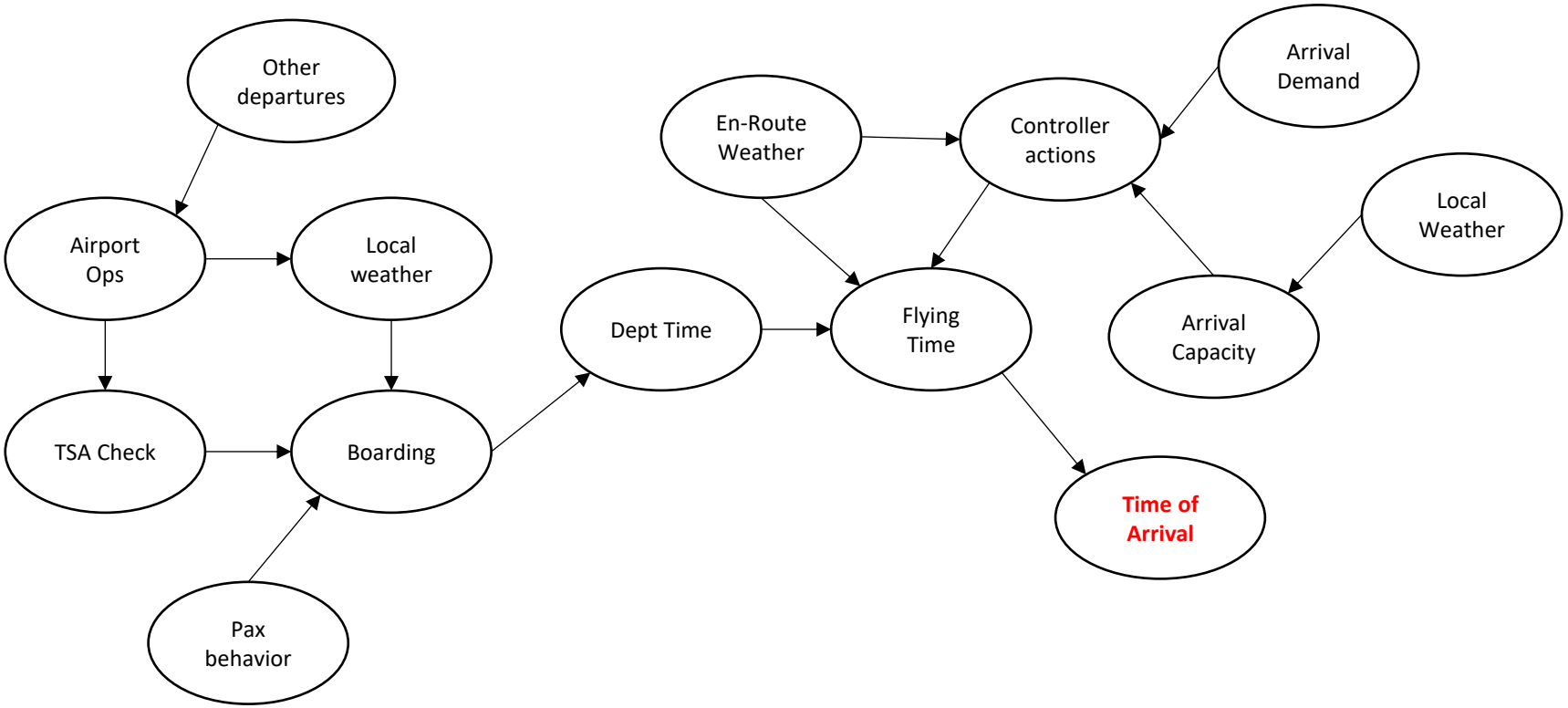


http://www.bayesianrisk.com/

Bayes Theorem

$$P(H|E) = \frac{P(E|H) \times P(H)}{P(E)}$$

The Air Traffic Bayesian Network



Risk assessment – decision making using updated probabilities
Explicit causal connections
Nodes = uncertain variables (conditional probabilities)
Node Probability Tables (NPT) – expert inputs, historical analysis, etc.