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
CASE STUDIES IN SYSTEM OF SYSTEMS, ENTERPRISE SYSTEMS, AND COMPLEX SYSTEMS ENGINEERING

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• Commerce
• Culture
• Environment
• Finance
• Health Care
• Homeland Security
• Military
• Transportation
Comparative Analysis of Systems

Degree of difficulty

Enterprise

Complex systems

System of systems

System
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
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

External drivers:
- Manage airline schedule
- Flight planning & logistics
- Fleet management
- Ground operations
- Dispatching
- Demographics
- Commerce
- Defense
- Recreation
- Economy cycles
- Traffic flow initiatives
- Weather reroutes
- Reduced capacity
- Airspace constraints
- Manage schedules
- Governance
- Regulations

Strategic planning:

Tactical operations:
- Weather
- Pilotage
- Flight plan execution
- Manage aircraft
- Manage separation
- Coordinate transfer of control
- Administer clearances
- Manage departures
- Manage approach and arrivals

Network
Society
Infrastructure

User needs
Services
Control Loops in the National Airspace System

Operational Domain
- Long Term Planning horizon
- Pre-departure
- tactical
- Strategic

Flight Crew
- Flight plan execution
  - Clearances
  - Interim altitudes
  - Slow down
  - Path stretch
- Pre-departure clearance
- Separation management
- Arrival management
  - Descent advisory

ATC
- Pre-departure clearance
- Separation management
- Arrival management

TFM
- Ground Delay Program
- CATM
- Miles-in-Trail weather reroute
- Metering & Arrival management
  - Slots
  - Capacity constraints

FOC
- Flight Schedules
- Fleet management
- Dispatcher operations
- Flight Monitor
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

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 \((= \sigma/\text{avg}_{\text{IATD}})\)
- \(\lambda = \) arrival rate
- \(\mu = \) airport acceptance rate (AAR)
- \(\tau = \) service time

\(T_W\) diverges as \(\rho = \frac{\lambda}{\mu} \rightarrow 1\)

**Estimated queue wait time as a function of Demand/Capacity ratio \((\rho)\)**
Time-based Traffic Flow Management Efficiency Curves

![Graph showing efficiency curves](image)

Rapid growth for $\rho < 1$:

<table>
<thead>
<tr>
<th>Demand model</th>
<th>$\rho = 0.9$</th>
<th>$\rho = 1.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DES Low</td>
<td>54</td>
<td>77</td>
</tr>
<tr>
<td>CRZ Low</td>
<td>62</td>
<td>103</td>
</tr>
<tr>
<td>Uniform (15s)</td>
<td>33</td>
<td>42</td>
</tr>
</tbody>
</table>

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

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

1. Provide complete and accurate information regarding available airspace

2. Operator plans according to user preferences and airspace availability

3. Build FMS trajectory according to plan

4. Obtain 4D-clearance

5. Fly FMS trajectory

6. Populate 4D-Grid with FMS trajectory

The business preferred trajectory closes the information loop

4D-Grid

weather
restrictions & constraints
traffic

AOC

ATC

Courtesy: B. Avjian
Agent-based Solution
Agent-based Solution to Air Traffic Management

References


Bayesian Network (BN) Analysis

Prior probabilities

BN Model

Measures of risk
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.
Bayes Theorem

Tool to update ‘belief’ based on conditional probabilities

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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)

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.