The Structure and Dynamics of the Multilayer Air transport System

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Motivation

• Human-centered air transport complex system
  — The main function of air transportation system is to transfer passengers and goods.
  — It consists of large number of technical systems (ATM system, airports, airlines, etc.), but humans are always in the center of the system
  — The interactions between subsystems are not well understood yet, which makes it is difficult to solve the emerged problems, such as flight delay.
The characteristics of complex system

Do we understand air transport system very well?

Uncertainty

Complexity
BIG DATA

Types of data recorded
• Flight trajectory (traffic flow)
• Flight on-time performance
• Weather
• Airspace structure
• Airport layout
• Aircraft performance
• Passengers/Customers
• Operators behaviors: controllers, pilots, displacers
• ............

The 5 Vs of big data
• Volume
• Variety
• Velocity
• Variability
• Veracity
Network science

- Network science is an **interdisciplinary** academic field which studies complex networks such as information networks, biological networks, cognitive and semantic networks, and social networks. It draws on theories and methods including (Wiki)
  - **Graph theory** from mathematics, e.g., Small-world
  - **Statistical mechanics** from physics, e.g., Rich get richer,
  - **Data mining** and **information visualization** from computer science,
  - **Inferential modeling** from statistics, e.g., Collaborative filtering
  - **Social structure** from sociology, e.g., weak tie, structural holes

Network Analysis

- Network Topological Analysis:
  - Random, SF, and SW Networks
- Node level analysis
- Link Analysis
Motivation

- **Objective:** to understand air transportation complex system
- **Tools:** Data science + Network science + Domain knowledge
How can we characterize the structure of air transport system?

MULTILAYER NETWORK

Picture was copied from the Air Transportation Systems Laboratory, Virginia Tech
Why structure?

- **Structure** is an arrangement and organization of interrelated elements in a material object or system.
- The aim of study structure is to discover law-governed relations between the elements forming a given system.
- Structure is the law or set of laws that determine a system’s composition and functioning, its properties and stability.
Present research

Essential question:
How to characterize the structure of air transport system?
- Operation point of view
- Macroscopic level

Existing research
- Airport networks
- Airline networks
- Air route networks
- Sector networks

Existing research
- Multilayer networks
Airport network

- The airport networks: Structure from transportation point of view
  - Nodes: airports
  - Links: defined by the direct flights between airports
- The purposes are to (i) study the reachability/efficiency of air transport service; (ii) identify the vital nodes (airports) in the network (robustness).
Airport Network

• Example studies on airport networks

Metrics:
• degree distribution, betweenness, clustering coefficients
• Robustness of network

<table>
<thead>
<tr>
<th>Network investigated</th>
<th># Nodes/#Edges</th>
<th>Average path length</th>
<th>Clustering coefficient</th>
<th>Degree distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>da Rocha et al.</td>
<td>Brazil</td>
<td>142/-</td>
<td>2.34</td>
<td>0.63 power-law distribution</td>
</tr>
<tr>
<td>Guida et al.</td>
<td>Italy</td>
<td>42/310</td>
<td></td>
<td>0.1 double power-law distribution</td>
</tr>
<tr>
<td>Bagler</td>
<td>India</td>
<td>79/442</td>
<td>2.26</td>
<td>0.657 power-law distribution</td>
</tr>
<tr>
<td>Li-Ping Chi</td>
<td>US</td>
<td>215/-</td>
<td>2.4</td>
<td>0.618 double power-law distribution</td>
</tr>
<tr>
<td>Barrat et al.</td>
<td>North American</td>
<td>935/-</td>
<td>4</td>
<td>- double power-law distribution</td>
</tr>
<tr>
<td>Guimerà</td>
<td>Worldwide</td>
<td>3883/27051</td>
<td>4.4</td>
<td>0.62 double power-law distribution</td>
</tr>
</tbody>
</table>

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A complex network approach towards modelling the Australian Airport Network

Md. Murad Hossain, Sameer Alam
School of Engineering & IT, University of New South Wales, UNSW, Canberra

Received 2 October 2015, Revised 14 November 2016, Accepted 11 December 2016, Available online 28 December 2016

Robustness analysis metrics for worldwide airport network: A comprehensive study

Sun Xiaojian, Volker Golnick, Sebastian Wandelt
Airport Network

- The time-varying airport networks
  - Since the flights between airports are time-dependent, thus airport networks can have different topologies in different timeframe.

(a) Time: 0600-0700    (b) Time: 0700-0800
Airline networks

• Airline networks are the network forming by its own flights.
  – Nodes: airports at which airline operates
  – Edges: Its flights

• The aggregation of all the airline networks forms airport network
Another widely investigated network is air route network or air navigation route network.

- Nodes: navigation points
- Edges: linkage between nodes
Sector Networks

- **SECTOR**: small part of the controlled airspace, in order to manage the air traffic.
- Sector network:
  - Nodes: sectors (controllers)
  - Edges: determined by traffic flow
Multilayer nature of network can help to dig a lot important information that is neglected in a single layer network.

The decomposing of air transport network

- Flight networks
- Airlines networks
- Airport networks
- Air route networks
- Sector networks
Multilayer Structure of ATS

- The statistical characteristics of three networks

<table>
<thead>
<tr>
<th></th>
<th>Airport Network</th>
<th>Air Route Network</th>
<th>Sector Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>167</td>
<td>763</td>
<td>428</td>
</tr>
<tr>
<td>Number of Edges</td>
<td>1900</td>
<td>1415</td>
<td>973</td>
</tr>
<tr>
<td>Network Density</td>
<td>0.14</td>
<td>0.005</td>
<td>0.01</td>
</tr>
<tr>
<td>Average Degree</td>
<td>22.75</td>
<td>3.60</td>
<td>4.55</td>
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<tr>
<td>Maximum Degree</td>
<td>124</td>
<td>12</td>
<td>17</td>
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<tr>
<td>Average Shortest Path Length</td>
<td>2.07</td>
<td>9.84</td>
<td>6.55</td>
</tr>
<tr>
<td>Network Diameter</td>
<td>4</td>
<td>28</td>
<td>16</td>
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<tr>
<td>Assortativity</td>
<td>-0.36</td>
<td>0.02</td>
<td>0.05</td>
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<tr>
<td>Average Clustering Coefficient</td>
<td>0.70</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>Average Betweenness</td>
<td>0.006</td>
<td>0.01</td>
<td>0.01</td>
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</table>
Multilayer Structure of ATS

- The statistical characteristics of three networks
Ongoing work

• The most difficult and important part of the study is the interactions among the networks
  – Delay impact on airlines network
  – The impact of airlines network on ATM network (Traffic demand change)
How flight delays spatially distributed in the system?
How flight delay/congestion propagate?

DELAY/CONGESTION PROPAGATION
Present research

- Empirical data
- Analysis primary delays

Secondary delays

How do the delays/congestion propagate through the system?
- How fast can it propagate?
- How big is the wave?

Build a "safety wall", stop the propagation

Essential question:

Existing research

- Queueing theory

Flight delay

• What happens if one airport/route point/sector is suddenly shut down?
• Which node(s) in the network can trigger unexpected catastrophic consequence?
Static relations in cascading failure

The concept of spatial correlation

\[ C(r) = \frac{1}{\sigma^2} \frac{\sum_{i,j,i \in F} (x_i - \bar{x})(x_j - \bar{x}) \delta(r_{ij} - r)}{\sum_{i,j,i \in F} \delta(r_{ij} - r)} \]

- \( x_i = 1, (\text{Flightdelay} > \alpha) \); Otherwise, \( x_i = 0 \).
- \( r \) is the Euclidean distance between \( i \) and \( j \).
- \( \sigma^2 = \sum_{j,j \in F} (x_j - \bar{x})^2 / N_F \), \( F \) is the set of cascading failed components
- \( \delta() \) is selecting function (nodes whose Euclidean distance to failure node is \( r \))

Positive values of \( (C(r)) \) indicates positive correlations between failures

Determination of node failure

➢ Airport network
   Threshold (α): average delay of airports
   Example:
     If average delay > 45min, \( x_i = 1 \)
     Else \( x_i = 0 \).

➢ Air route network
   Threshold (α): flow per hour
   Example:
     If average flow > 30 aircraft, \( x_i = 1 \);
     Else \( x_i = 0 \).
Spatial correlation
Spatial correlation

Airport network

Air route network
Coupling effects of $\alpha$ and $r$

morning  afternoon  evening
• How congestion propagate in sector/route networks?
• Operational constraints
Modeling cascading failure

When a sector (or route point) is suddenly shunted down, the traffic has to be controlled by the adjacent sectors (or route points). It may trigger the cascading events.

- A node is overload and failed;
- Traffic Load of A will be transferred to B, C, and D;
- Calculate the redundancy of B, C, and D (available resource);
- Traffic will be transferred to adjacent nodes based on the proportion.
Cascading failure
Important nodes

• All 943 route points were selected as the starting failure node
• 29 route points can trigger cascading failure.
• 20 route points can cause more than 400 nodes failure
Relations between nodes rank

\[ y = -0.943x + 590 \]
Conclusion

• Contributions
  – We have presented the structure of the air transport system from both operational and academic point of view.
  – The cascading failure was studied at airport network and air route network level.

• Further studies
  – More research efforts are needed to investigate the properties of sectors networks, as well as the interactions between different layers of the network.
THANK YOU!