Supporting the design of a state aviation safety plan

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SPONSORS: AESA, MINECO, AXA
Agenda

- Safety in Air Transportation
- Elaborating the State Safety Program
- RIMAS: An R architecture for aviation safety risk management
- Discussion
Safety vs Security

- Critical in Civil Aviation.
  - Country
  - Company


- Security. Purposeful (terrorism, ...)

- Frequently dissociated (Even for resource allocation purposes!!!)
Safety vs Security
SAFETY

Safety is Critical in Civil Aviation

We are doing well but...  ...not enough
SAFETY

Safety Critical in Civil Aviation

- Increasing complexity of global air transportation system;
- Interrelated and complex nature of aviation activities;
- Traffic growth and;
- Increasing competition forcing cost reduction (even more under crisis)...

Need assure safe operation of aircrafts through tools and methodologies supporting continuous evolution of a proactive strategy improving safety performance

However... relatively simple tools for safety risk analysis for commercial aviation operations
## SAFETY MANAGEMENT

### Table: Occurrence Category / Event Type

<table>
<thead>
<tr>
<th>Risk Matrix</th>
<th>Without Safety Effect</th>
<th>Significant Incident</th>
<th>Major Incident</th>
<th>Serious Incident</th>
<th>Accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely Remote</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reasonably Possible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cox (2008) criticisms

ARMS, Bowtie, IRP,...
STATE SAFETY PROGRAMME?

- ICAO: “Integrated set of regulations and activities established by a State aimed at managing civil aviation safety”
- Support strategic decision-making in adopting better decisions when allocating scare resources to higher safety risk areas
- To implement preventive approach for safety oversight and to manage safety at a State level, States must develop a State Safety Program (SSP)
SPANISH AVIATION SYSTEM

- Aircraft Design and Production: 14
- Airlines: 88
- Aerial Work Companies: 219
- Aircraft Maintenance Org.: >150
- Training Organizations: 117
- Aircraft (total): 6,400
- Licensed personnel: >40,000
- 232 airfields (47 airports)
- 62 ATM dependencies
- 340 Air Navigation Aids
SPANISH AVIATION SYSTEM (2014)

- Operations 7311006
- Safety events 15394
- Accidents 42
- Safety events (type A) 453
- Accidents (type A) 10
To our knowledge, first time that DA used in processes related with preventive approach to safety oversight in civil aviation.

Aviation remains one of the most advanced means of transportation technologically wise. But industry and regulators have implemented little modern DA, RA, BS methodologies beyond risk matrices...
Agenda

• Safety in Air Transportation
• **Elaborating the Spanish State Safety Program**
• RIMAS: An R architecture for aviation safety risk management
• Discussion
SAFETY RISK AREAS/ISSUES

88 types of occurrences. Registered in ECCAIRS. Reporting ‘compulsory’. Other databases: ASN, Eurocontrol, DOT, ESTOP,…

• Flight operations
  • Hard landing,…

• Navigation services
  • TCAS warnings,…

• Aeronavigability
  • Motor failure,…

• Airport
  • Impact with vehicle,…

• External factors
  • Bird strike,…

5 severity degrees (ICAO and EUROCONTROL)
  Minor, Significant, Major, Serious, Accident

4 types of aircrafts  T1, T2, T3, T4 (No. of passengers)
METHODOLOGY

(Continuously) improve safety in Spanish skies

- Incident forecasting
  - Number of incidents
  - Severity of incidents
- Incident consequence forecasting
- Incident consequence assessment
- Usage
  - Monitoring
  - Screening, via risk mapping (and matrices)
  - Resource allocation
- Detailed analysis of chosen incidents
INCIDENT FORECASTING

- (Non-homogeneous) Poisson processes
- Dynamic number of operations
- Dynamic rate
- Expert prior elicitation

- Forecasting incidents
  - Annual forecasts for risk assessment and management
  - Monthly, Weekly forecasts for tracking incidents, alarm setting
INCIDENT RATES. FEATURES

(a) Stress

(b) Seasonal

(c) Linear

(d) Group

(e) Underreporting
INCIDENT FORECASTING. Models

**ID**

![Diagram showing relationships between variables](diagram.png)

**Model**

\[ X_k|\lambda, n_k \sim Po(n_k \lambda) \]
\[ \lambda \sim Ga(a, p) \]

\[
\begin{align*}
X_k|\lambda, n_k & \sim Po(n_k \lambda), \\
\lambda &= an_k + b + \epsilon_k, \quad \epsilon_k \sim N(0, \sigma^2), \\
p(a, b, \sigma^2) & \propto \frac{1}{\sigma^2}.
\end{align*}
\]

\[ x_i^k|\lambda^i, n_k^i \sim Po(\lambda^i n_k^i) \]
\[ \lambda^i \sim Ga(a^i, p^i) \]
\[ a^i \sim Ga(\alpha, \beta) \]
\[ p^i \sim Ga(\gamma, \delta) \]
INCIDENT FORECASTING. Models

- ID

- Model

\[
\begin{align*}
\begin{cases}
  n_i = H_i \theta_i + z_i, 
  &z_i \sim N(0, \Sigma_i) \\
  \theta_i = J_i \theta_{i-1} + \xi_i, 
  &\xi_i \sim N(0, S_i) \\
  \theta_0 \sim N(\eta_0, S_0) \\
  x_i | \lambda_i, n_i \sim P_0(\lambda_i n_i) \\
  \lambda_i = \exp(u_i)
\end{cases}
\end{align*}
\]

\[
\begin{align*}
\begin{cases}
  u_i = F_i \theta_i + v_i, 
  &v_i \sim N(0, V_i) \\
  \theta_i = G_i \theta_{i-1} + w_i, 
  &w_i \sim N(0, W_i) \\
  \theta_0 \sim N(\mu_0, W_0),
\end{cases}
\end{align*}
\]
INCIDENT SEVERITY FORECASTING. UNDERREPORTING

- **ID**

- **Model**

\[ \lambda \sim Ga(a, \varphi), \]
\[ X_k \sim Po(\lambda n_k), \]
\[ p \sim Dir(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5), \]
\[ m \mid p, X_k \sim M(X_k; p_1, p_2, p_3, p_4, p_5). \]

\[ \varphi = (\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5), \text{ con } \varphi_i \in [0, 1], \]
\[ \beta \sim \beta(\alpha_i, \beta_i). \]

\[ z = (z_1, z_2, z_3, z_4, z_5) \]
\[ z_i \sim \text{Bin}(m_i, \varphi_i). \]
USES: FORECASTING AND MONITORING

<table>
<thead>
<tr>
<th>$m'$</th>
<th>$\sigma'$</th>
<th>$\alpha'_1$</th>
<th>$\alpha'_2$</th>
<th>$\alpha'_3$</th>
<th>$\alpha'_4$</th>
<th>$\alpha'_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.48</td>
<td>10.68</td>
<td>2</td>
<td>4</td>
<td>27</td>
<td>1055</td>
<td>99</td>
</tr>
</tbody>
</table>
FORECASTING INCIDENT CONSEQUENCES

- Multiattribute hierarchy

```
Optimize AS
  ├── Min. Health Impact
  │   ├── Min. Fatalities  # fatalities
  │   └── Min. Injuries
  │       ├── # severe injuries
  │       └── # minor injuries
  │
  └── Min. Operational Impact
      ├── Min. Delays  # hours delay
      │
      └── Min. Cancellations  # cancellations
          └── Min. Material damage
              ├── Min. Repairs  # repairs
              └── Min. Image loss  # destroys
```

# accidents
FORECASTING DEATHS

For a given type of event and aircraft

\[ n_F = p_F \cdot q \cdot M \]

\[ p_F \sim \tau_1 I_0 + \tau_2 Be(a, b) + \tau_3 I_1 \]

\[ (\tau_1, \tau_2, \tau_3) | dados \sim Dir(a_1 + \varphi_1^1, a_2 + \varphi_2^1, a_3 + \varphi_3^1) \]

\[ p_F | D_g \sim Be\left(a + \sum_{i=1}^{g} \eta_{F_i}, b + \sum_{i=1}^{g} (a_i - \eta_{F_i})\right) \]

\[ q | dados \sim Be\left(c + \sum_{i=1}^{f} p_{Oi}, d + \sum_{i=1}^{f} (1 - p_{Oi})\right) \]

<table>
<thead>
<tr>
<th>( \varphi_1 )</th>
<th>( \varphi_2 )</th>
<th>( \varphi_3 )</th>
<th>( \hat{\tau}_1 )</th>
<th>( \hat{\tau}_2 )</th>
<th>( \hat{\tau}_3 )</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
<th>( d )</th>
<th>( \hat{q} )</th>
<th>( \hat{p}_F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>36</td>
<td>57</td>
<td>241</td>
<td>0.11</td>
<td>0.17</td>
<td>0.72</td>
<td>269</td>
<td>487</td>
<td>136.58</td>
<td>199.42</td>
<td>0.41</td>
</tr>
<tr>
<td>T2</td>
<td>25</td>
<td>94</td>
<td>270</td>
<td>0.07</td>
<td>0.24</td>
<td>0.69</td>
<td>1509</td>
<td>1106</td>
<td>163.19</td>
<td>227.81</td>
<td>0.42</td>
</tr>
<tr>
<td>T3</td>
<td>3</td>
<td>22</td>
<td>142</td>
<td>0.02</td>
<td>0.18</td>
<td>0.8</td>
<td>2185</td>
<td>647</td>
<td>83.79</td>
<td>95.21</td>
<td>0.47</td>
</tr>
<tr>
<td>T4</td>
<td>4</td>
<td>14</td>
<td>60</td>
<td>0.06</td>
<td>0.19</td>
<td>0.75</td>
<td>1464</td>
<td>124</td>
<td>22.74</td>
<td>57.26</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Statistical value of life. EUROCONTROL
EVALUATING CONSEQUENCES. Utility... Loss

\[(n_{um}, n_{h}, t_{d}, n_{c}, n_{rm}, s_{1}),\]

Image costs

\[v(n_{um}, n_{h}, t_{d}, c_{c}, n_{rm}, d_{img}) = -c_{vm}n_{vm} - \sum_{i=1}^{2} c_{i}^{1}n_{h}^{1} - c_{at}t_{d} - c_{c}n_{c} - (c_{rm}^{1}n_{rm}^{1} + c_{rm}^{2}n_{rm}^{2}) - c_{img}s_{1}\]

\[u(v) = -\exp(kv)\]

\[l_{2}(v) = a + b\exp(kv),\]
RISK MAPPING

Mapping (forecasted) incident numbers vs (forecasted) incident costs (expected, boxplots)

<table>
<thead>
<tr>
<th>Less but more expensive</th>
<th>More and more expensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less and less expensive</td>
<td>More but less expensive</td>
</tr>
</tbody>
</table>
USES: SCREENING

<table>
<thead>
<tr>
<th>Suceso</th>
<th>Ref.</th>
<th>ADREP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Presencia de obstáculos / FOD</td>
<td>123</td>
</tr>
<tr>
<td>2</td>
<td>Láser</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Golpes de aves</td>
<td>651</td>
</tr>
<tr>
<td>4</td>
<td>Incursión aeronave en otras superficies</td>
<td>321-1</td>
</tr>
<tr>
<td>5</td>
<td>Fallos de sistema motor</td>
<td>441</td>
</tr>
<tr>
<td>6</td>
<td>Fallos de sistema NO motor</td>
<td>431</td>
</tr>
<tr>
<td>7</td>
<td>Turbulencias meteorológicas</td>
<td>621</td>
</tr>
<tr>
<td>8</td>
<td>Vientos</td>
<td>622</td>
</tr>
<tr>
<td>9</td>
<td>Colisión con aves</td>
<td>651</td>
</tr>
<tr>
<td>10</td>
<td>Toma de tierra dura, pesada, rápida o larga</td>
<td>231</td>
</tr>
<tr>
<td>11</td>
<td>Manejo de la aeronave</td>
<td>2121</td>
</tr>
<tr>
<td>12</td>
<td>Cizalladura</td>
<td>612</td>
</tr>
<tr>
<td>13</td>
<td>Cizalladura en cabeceras</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Fallos técnicos sin identificar</td>
<td>451</td>
</tr>
<tr>
<td>15</td>
<td>Otras condiciones meteorológicas</td>
<td>641</td>
</tr>
<tr>
<td>16</td>
<td>Pérdida de control en vuelo</td>
<td>282</td>
</tr>
</tbody>
</table>
USES: RESOURCE ALLOCATION

\[
\begin{align*}
\text{max} & \quad v(z) \\
\text{s.a.} & \quad \sum_{i=1}^{16} z_i = 0.48 \\
& \quad 0.015 \leq z_i \leq 0.3, \quad i = 1, \ldots, 16
\end{align*}
\]

<table>
<thead>
<tr>
<th>Presencia de obstáculos / FOD</th>
<th>Tasa máx</th>
<th>Tasa act</th>
<th>Tasa mín</th>
<th>( \delta^j )</th>
<th>( \rho^j )</th>
<th>( \kappa^j )</th>
<th>% Insp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Láser</td>
<td>97.2</td>
<td>87.37</td>
<td>37.1</td>
<td>36.62</td>
<td>60.58</td>
<td>15.58</td>
<td>1.5</td>
</tr>
<tr>
<td>Golpes de aves</td>
<td>75.3</td>
<td>59.27</td>
<td>12.2</td>
<td>12.18</td>
<td>63.12</td>
<td>25.78</td>
<td>1.5</td>
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<tr>
<td>Incursión aeronave en otras superficies</td>
<td>91.2</td>
<td>81.12</td>
<td>31.5</td>
<td>31.1</td>
<td>60.1</td>
<td>16.16</td>
<td>1.5</td>
</tr>
<tr>
<td>Fallos de sistema motor</td>
<td>75.98</td>
<td>65.2</td>
<td>20.7</td>
<td>20.55</td>
<td>55.43</td>
<td>19.03</td>
<td>1.5</td>
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<tr>
<td>Fallos de sistema NO motor</td>
<td>70.5</td>
<td>57.28</td>
<td>24.2</td>
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<td>29.58</td>
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<td>Turbulencias meteorológicas</td>
<td>200.5</td>
<td>174.86</td>
<td>40.6</td>
<td>39.16</td>
<td>161.34</td>
<td>15.23</td>
<td>15.18</td>
</tr>
<tr>
<td>Vientos</td>
<td>28.2</td>
<td>21.65</td>
<td>4.6</td>
<td>4.6</td>
<td>23.6</td>
<td>28.6</td>
<td>11.4</td>
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<tr>
<td>Colisión con aves</td>
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<td>37.92</td>
<td>14.6</td>
<td>14.6</td>
<td>35.6</td>
<td>37.23</td>
<td>7.94</td>
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<tr>
<td>Toma de tierra dura, pesada, rápida o larga</td>
<td>212.3</td>
<td>191.77</td>
<td>46.2</td>
<td>40.93</td>
<td>171.37</td>
<td>11.23</td>
<td>1.5</td>
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<tr>
<td>Manejo de la aeronave</td>
<td>8.63</td>
<td>6.7</td>
<td>0.72</td>
<td>0.72</td>
<td>7.91</td>
<td>24.6</td>
<td>11.57</td>
</tr>
<tr>
<td>Cizalladura</td>
<td>178.2</td>
<td>132.37</td>
<td>20.72</td>
<td>20.71</td>
<td>157.49</td>
<td>30.26</td>
<td>13.44</td>
</tr>
<tr>
<td>Cizalladura en cabeceras</td>
<td>82.45</td>
<td>59.19</td>
<td>25.96</td>
<td>25.96</td>
<td>56.49</td>
<td>46.69</td>
<td>5.65</td>
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<tr>
<td>Fallos técnicos sin identificar</td>
<td>58.45</td>
<td>38.89</td>
<td>15.37</td>
<td>15.37</td>
<td>43.08</td>
<td>53.26</td>
<td>1.5</td>
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<tr>
<td>Otras condiciones meteorológicas</td>
<td>75.25</td>
<td>59.19</td>
<td>34.84</td>
<td>34.84</td>
<td>40.41</td>
<td>44.58</td>
<td>5.59</td>
</tr>
<tr>
<td>Pérdidas de control en vuelo</td>
<td>31.13</td>
<td>18.81</td>
<td>11.26</td>
<td>11.26</td>
<td>19.87</td>
<td>85.15</td>
<td>3.62</td>
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<tr>
<td><strong>Total</strong></td>
<td>1.78</td>
<td>1.39</td>
<td>0.62</td>
<td>0.62</td>
<td>1.16</td>
<td>36.06</td>
<td>2.25</td>
</tr>
</tbody>
</table>
DECIDING ON INTERVENTIONS

- Pick those in the anti-Pareto frontier
- Pick some of those more costly
- Pick some of those more frequent
- Pick those that go worse
- Pick novel issues

- Relate with resource allocation

- Screened by experts
- Finally decided by politicians
RESULTS
DETAILED ANALYSIS FOR SOME INCIDENTS

- Motor failure
- Unintended slide deployment
- Fuel for holding
- Runway excursions
MOTOR FAILURE

- Effects affecting rates
- Cluster of companies
- Consequences
- Resource allocation among and within clusters
UNINTENDED SLIDE DEPLOYMENT

Changed in procedures
**FUEL FOR HOLDING**

- Competition forces companies to reduce costs, without jeopardising safety.
- Fuel costs more than 25% DOC
- ATFM delays at congested airports.
- Airline fuel policies and regulatory requirements should ensure every flight carries enough fuel for planned route, and additional reserve to cover deviations; e.g. ATFM delays.
- When delays at destination, holding may be required by ATC.
- Flight crew will be able to hold depending on remaining fuel quantity. Inability to hold will cause divert to alternative airport. It entails significant DOCs.

- Model to provide optimal F4H
Some recommendations
Agenda

- Safety in Air Transportation
- Elaborating the State Safety Program
- **RIMAS** (Risk Management in Aviation Safety)
- Discussion
RIMAS

R: dplyr, plotly, leaflet, DT, Shiny, dlm,....
RIMAS

• Forecasting models for numbers of various types of occurrences
• Forecasting models for occurrence severity classes
• Forecasting models for consequences
• Construction of multiattribute utility function to assess such consequences of occurrences
  – Monitoring
  – Screen riskier occurrences
  – Assigning resources optimally to mitigate aviation hazards
  – Reporting
EXPLORATORY ANALYSIS
EFFECT ANALYSIS: GROUP
EFFECT ANALYSIS: SEASONAL
GEO MAPS

Mapa Sucesos Aeropuertos

Año:

Seleccionar filtro:

Tasa

Mapa de España y Norte de África con marcadores rojos en diferentes ciudades.
Agenda

- Safety and Security in Air Transportation
- Elaborating the State Safety Program
- RIMAS
- Discussion
DISCUSSION

- R
- (Big Data), Large Data, Standard data, Little data, No data
- Industrial stats in action
  - Large volume for some variables
  - Not so large for others. Other data sources. Expert judgement
  - Used for decision support

- Through earlier collaboration with Iberia
- 2 year project, with several training periods
- Improving the forecasting models (with SGDLMs)
- Strong sponsor
DISCUSSION

- Exporting to other countries for their national agencies
- Exporting to aviation companies, other aviation services
- Exporting to other business.
- Big Data! AERODATA
- Integrating Safety (RA) and Security (ARA)

See Banks et al (2015) Adversarial Risk Analysis
Thanks

Collabs welcome!!!

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