Assessment of the Airport Operational Dynamics Using a Multistate System Approach

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INTRODUCTION

1. Motivation
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3. Background
1. Motivation

- Airports are inter-modal transportation infrastructures that act as nodes in the air transport network.
- Failures or degradation of airport operations may easily propagate through the network and generate system-level effects.
- Airport dynamics depend on various and heterogeneous factors: a holistic view that considers different key performance areas is then essential.
- Analysis of the air-to-air process, which concentrates on the aircraft turnaround to enable efficient flight operations and reliable departure times.
- Need to overcome the “binary” concept of the system functioning / performance.
- Move from traditional corrective approaches to a predictive perspective.
INTRODUCCIÓN

2. Objectives: approach of the problem

- Description of the “visit” of an aircraft to the Terminal Manoeuvring Area (TMA) through a Multistate System (MSS) approach.
- Parameter/curve fitting to probability distributions (performance thresholds can be established attending to targets or to probability).
- Model of the Airport Operational Dynamics.
- Use of a Markov-chain model for a predictive analysis.
- Clustering of airport “states” (find behaviour patterns).
- Functionalities of the model (performance, time between failures, deficiency, recoverability, availability).
2. Objectives: spatial and time scale

- **Extended Airport Transit View** concept. E-TMA (200-500NM).
- Airspace/Airside integrated operations.
- **Tactical phase**.
INTRODUCCIÓN

3. Background

• Binary
• Isolated
• Partial
• Corrective

• Multistate
• Integrated
• Holistic
• Predictive

• Integrated view of the ATV processes (airside and surrounding airspace) and analyse the trade-offs between the various measures of airport operational behaviour such as capacity, delays, environmental performance and complexity (holistic perspective).

• Current system-wide congestion problems are worsened due to airport operational inefficiencies: operators need new conceptual tools to support airport management functions. In this sense, we propose a novel approach for assessing and predicting the airport’s operational behaviour, given certain operational circumstances.
1. Scenario definition
2. Preparation of data

SCENARIO & DATA
1. Scenario definition: case-study

- **Adolfo Suárez – Madrid Barajas (LEMD):** four runways (36L-18R, 36R-18L, 32L-14R, 32R-14L), two terminal areas (T123 and T4T4S) and 163 apron stands (*). 
- Observation period: **2016** (50,418,909 passengers and 378,151 aircraft movements) (*). 
- Two operational configurations (north and south). 
- A collection of **160,460 turnaround operations** at LEMD is used to describe the aircraft flow characteristics (radar & airport data). 

1. Scenario definition: potential for improvement

Source: CODA Digest (EUROCONTROL, 2017).
1. Scenario definition: dataset

- **Flight and route** details (including schedules and delay causes)
- **Airport** configuration and operating procedures (including regulations)
- Operational **timestamps** and duration of processes
- **Weather** features
- **Aircraft and airline** information
1. Scenario definition: milestone approach

Each actual (A) timestamp can be checked against a scheduled (S) one, or we can assess times between two milestones (duration of the process).
2. Preparation of data: process

The data preparation phase covered all activities required to assemble the final dataset from the initial raw operational and meteorological data provided by the airport, including locating and refining erroneous measurements. 156,386 final valid observations were appraised.
Each of the elements included in the final dataset is statistically appraised and fitted to a probability density function.

Three different statistical distributions were found to be candidates:
- Stable
- Logistic
- Kernel

Kolmogorov-Smirnov and Pearson's chi-squared tests to determine the goodness of fitting.

### Stable
- Parametric (parameters $\alpha$, $\beta$, $\gamma$ and $\delta$)
- Asymmetric

### Logistic
- Parametric (parameters $\mu$ and $\sigma$)
- Symmetric

### Kernel
- Non-parametric
- Smoothing function
2. Preparation of data: distribution fitting (II)

Histogram and distribution fitting for (a) In-Block Delay (seconds) and (b) Off-Block Delay (seconds)
3. Multistate Systems (MSS)
2. Markov Chains (MC)
3. Reliability model
Most real systems can develop their tasks in more than two performance levels. Additionally, real systems are usually composed of elements that can also be found in different states. When the performance rate of the system’s elements can vary because of their deterioration (fatigue, partial failure) or because of variable ambient conditions, the entire system may be considered a multistate system (MSS).

\[ g_j = \{g_{j1}, g_{j2}, ..., g_{jk_j}\} \]

Probabilities associated to each state

\[ P_j(t) = \{p_{j1}(t), p_{j2}(t), ..., p_{jk_j}(t)\} \]

\[ p_{ji}(t) = \Pr\{G_j(t) = g_{ji}\} \]

\[ \sum_{i=1}^{k_j} p_{ji}(t) = 1, \quad \text{for any } t: \quad 0 \leq t \leq T \]
When an MSS is composed of n elements, its performance rate is determined in an unambiguous way by the performance levels of the elements that compose it.

At each moment, the elements of the system have a performance level that corresponds to their current state. The state of the entire system is determined by the states of its elements.

Therefore, the definition of a MSS reliability model must include the performance stochastic process for each element j of the system: G_j (j=1,2,…,n) and the system structure function that generates the stochastic process corresponding to the output performance of the entire MSS: G(t)=φ(G_1(t),…,G_n(t))
Markov chains (MC) are discrete stochastic processes in which the probability of an event only depends on the previous state of the system (Markov property).

- The probability of transition between state \(X_{n-1} = i\) and \(X_n = j\) is given by \(γ_{i,j}\).
- Transition matrix \(P\) represents the one-step transition probabilities.

Markov property: 
\[
P(X_{n+1} = x_{n+1} | X_n = x_n, X_{n-1} = x_{n-1}, \ldots, X_2 = x_2, X_1 = x_1) = P(X_{n+1} = x_{n+1} | X_n = x_n)
\]

Transition matrix:
\[
P = \begin{pmatrix} 
γ_{1,1} & γ_{1,2} & \cdots & γ_{1,k} \\
γ_{2,1} & γ_{2,2} & \cdots & γ_{2,k} \\
\vdots & \vdots & \ddots & \vdots \\
γ_{k,1} & γ_{k,2} & \cdots & γ_{k,k} 
\end{pmatrix}
\]
• The vector $\pi_n^T$ defines the probability of finding the system in a particular state on the n-th transition.
• Ergodic (*) MC have unique limiting distributions; i.e., they have a unique stationary distribution to which every initial distribution converges.
• Therefore, the stationary (limiting) distribution is a long-term behavior indicator of the system.

**State vector**

$$\pi_n^T = [\pi_{1,n} \quad \pi_{2,n} \quad \ldots \quad \pi_{k,n}]$$

$$\pi_n^T = \pi_{n-1}^T P$$

**Stationary distribution**

$$\pi = \pi^T$$

$$T^\infty = \lim_{n \to \infty} T^n$$

(*) A MC is ergodic if it is both irreducible (it is possible to get to any state from any state) and aperiodic (any return to the previous state can occur in just one transition step).
3. Reliability model: continuity study

- The reliability model is trained for data corresponding to airport operations under conditions of continuous demand and aircraft queuing.
- Otherwise, recovery indicators may be affected by the transit time between operations. Moreover, when applying the MSS and MC methods, it is necessary to ensure that operations are equally spaced in time.

During the main operational hours of the airport (i.e., from 5 to 24, local time), we can assume that operations are continuous (3 min of mean time between operations, with an interquartile range of 1 min), and therefore the theory of MSS and MC is applicable.
METHODOLOGY & MODEL DEVELOPMENT

3. Reliability model: definition of blocks and state vector

AIRPORT MULTISTATE SYSTEM

1. Delay
   - A. In-Block Delay
   - B. Off-Block Delay
   - C. Turnaround Excess Time

2. Capacity
   - A. Throughput ASMA 60 NM
   - B. Congestion Index ASMA 60 NM
   - C. Demand/Capacity Balance
   - D. Departures/Arrivals Ratio

3. Environmental Impact
   - A. Additional Taxi-In Time
   - B. Additional Taxi-Out Time
   - C. Additional ASMA 60 NM Time

4. Complexity
   - A. Runway Configuration
   - B. Holdings
   - C. Season
   - D. Meteorological Indicator
3. Reliability model: definition of performance states and thresholds (I)

### Delay block

<table>
<thead>
<tr>
<th>States of blocks elements</th>
<th>In-Block Delay</th>
<th>Off-Block Delay</th>
<th>Turnaround Excess Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target time</strong> (state 1)</td>
<td>$-3\text{min} &lt; d &lt; 3\text{min}$</td>
<td>$-3\text{min} &lt; d &lt; 3\text{min}$</td>
<td>$-3\text{min} &lt; d &lt; 3\text{min}$</td>
</tr>
<tr>
<td><strong>Correct time</strong> (state 2)</td>
<td>$-15\text{min} &lt; d &lt; -3\text{min}$</td>
<td>$-15\text{min} &lt; d &lt; -3\text{min}$</td>
<td>$-15\text{min} &lt; d &lt; -3\text{min}$</td>
</tr>
<tr>
<td><strong>Incorrect time</strong> (state 3)</td>
<td>$d \leq -15\text{min}$</td>
<td>$d \leq -15\text{min}$</td>
<td>$d \leq -15\text{min}$</td>
</tr>
</tbody>
</table>
3. Reliability model: definition of performance states and thresholds (II)

Capacity block

<table>
<thead>
<tr>
<th>States of blocks elements</th>
<th>Throughput and Congestion Index</th>
<th>DCB</th>
<th>DAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target situation (state 1)</td>
<td>$x \leq 0.2$</td>
<td>$80% &lt; x &lt; 100%$</td>
<td>$0.1 &lt; x &lt; 1.1$</td>
</tr>
<tr>
<td>Correct situation (state 2)</td>
<td>$0.2 \leq x \leq 0.8$</td>
<td>$x \leq 80%$</td>
<td>$0.2 &lt; x \leq 0.1$ or $1.1 \leq x &lt; 2.2$</td>
</tr>
<tr>
<td>Incorrect situation (state 3)</td>
<td>$x &gt; 0.8$</td>
<td>$x \geq 100%$</td>
<td>$x &lt; 0.2$ or $x &gt; 2.2$</td>
</tr>
</tbody>
</table>

$DCB = \frac{\text{Aircraft landed}}{\text{Airport practical arrival capacity}}$

$DAR = \frac{\text{Departures}}{\text{Arrivals}}$

ASMA 40NM and ASMA 60 NM, along with the flight plan data and the radar track (including a holding pattern) for a flight approaching LEMD.
3. Reliability model: definition of performance states and thresholds (III)

Environmental impact block

<table>
<thead>
<tr>
<th>States of blocks elements</th>
<th>Additional Taxi-In Time</th>
<th>Additional Taxi-Out Time</th>
<th>Additional ASMA 60 NM Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target time (state 1)</td>
<td>$-3\text{ min} &lt; d &lt; 3\text{ min}$</td>
<td>$-3\text{ min} &lt; d &lt; 3\text{ min}$</td>
<td>$-3\text{ min} &lt; d &lt; 3\text{ min}$</td>
</tr>
<tr>
<td>Correct time (state 2)</td>
<td>$\begin{cases} -15\text{ min} &lt; d &lt; -3\text{ min} \ 3\text{ min} \leq d &lt; 15\text{ min} \end{cases}$</td>
<td>$\begin{cases} -15\text{ min} &lt; d &lt; -3\text{ min} \ 3\text{ min} \leq d &lt; 15\text{ min} \end{cases}$</td>
<td>$\begin{cases} -15\text{ min} &lt; d &lt; -3\text{ min} \ 3\text{ min} \leq d &lt; 15\text{ min} \end{cases}$</td>
</tr>
<tr>
<td>Incorrect time (state 3)</td>
<td>$\begin{cases} d \leq -15\text{ min} \ d \geq 15\text{ min} \end{cases}$</td>
<td>$\begin{cases} d \leq -15\text{ min} \ d \geq 15\text{ min} \end{cases}$</td>
<td>$\begin{cases} d \leq -15\text{ min} \ d \geq 15\text{ min} \end{cases}$</td>
</tr>
</tbody>
</table>
3. Reliability model: definition of performance states and thresholds (IV)

<table>
<thead>
<tr>
<th>States of blocks elements</th>
<th>Runway Configuration</th>
<th>Number of Holdings</th>
<th>Season (as IATA calendar)</th>
<th>Meteorological Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard operation (state 1)</td>
<td>North</td>
<td>$h = 0$</td>
<td>Winter</td>
<td>$m &lt; 3$</td>
</tr>
<tr>
<td>Complex operation (state 2)</td>
<td>South</td>
<td>$h \geq 1$</td>
<td>Summer</td>
<td>$m \geq 3$</td>
</tr>
</tbody>
</table>

- The Meteorological Indicator considers different variables: cloudiness (height and quantity), visibility, wind (intensity and direction) and special meteorological phenomena (e.g. presence of fog, snow, rain).
- It ranges from 0 to 7 and it is calculated by weighting the impact of weather elements on the operational conditions of the airport.
RESULTS

1. Partial transition matrices
2. Global states
3. Global transition matrix
4. Airport dynamics
RESULTS

1. Partial transition matrices (I)

- Establishment of the **different performance states for each block**. These were defined by the **amount of component failures that lead to the block failure** and settled according to **expert knowledge**.

<table>
<thead>
<tr>
<th>States of the block</th>
<th>Delay, capacity and environmental impact blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (Optimal)</td>
<td>All parameters in correct or optimal states</td>
</tr>
<tr>
<td>S2 (Correct)</td>
<td>Only one parameter in an incorrect state</td>
</tr>
<tr>
<td>S3 (Incorrect)</td>
<td>Two or more parameters in incorrect states</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>States of the block</th>
<th>Complexity block</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (Standard)</td>
<td>One or less parameters in complex states</td>
</tr>
<tr>
<td>S2 (Complex)</td>
<td>Two or more parameters in complex states</td>
</tr>
</tbody>
</table>
1. Partial transition matrices (II)

• Transition matrices and steady state vectors (stationary distributions) for the system’s blocks: (a) delay; (b) capacity; (c) environmental impact blocks; and (b) complexity.

\[ X_{\text{delay}}^\infty = [0.5194, 0.1332, 0.3474] \]

\[ X_{\text{capacity}}^\infty = [0.8772, 0.1221, 0.0007] \]

\[ X_{\text{environmental impact}}^\infty = [0.9762, 0.0226, 0.0012] \]
2. Global states for the model

- The combination of the blocks’ states \((3^3 \times 2)\) results in 54 possible different states for the global model.
- This amount of states difficulties the appraisal of the system reliability performance. Therefore, to reduce this number, we used clustering techniques to group states for the global model (associating those states which provide similar operational outcomes).
- We used the Fuzzy c-Means (FCM) clustering algorithm:
  \[
  J_m = \sum_{i=1}^{D} \sum_{j=1}^{N} \mu_{ij}^m \|x_i - c_j\|^2
  \]
- Silhouette value for the \(i\)-th point, \(S_i\), is defined as
  \[
  S_i = \frac{(b_i - a_i)}{\max(a_i, b_i)}.
  \]
- Performance rate for each Cluster: \(R = \frac{n_1 + 0.5n_2}{n_3}\).
## RESULTS

### 3. Global transition matrix

Performance rate (R)

\[
X_\infty = [0.4002, 0.0998, 0.0513, 0.0679, 0.2551, 0.0525, 0.0733]
\]

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.478</td>
<td>0.114</td>
<td>0.005</td>
<td>0.066</td>
<td>0.271</td>
<td>0.004</td>
<td>0.063</td>
</tr>
<tr>
<td>C2</td>
<td>0.452</td>
<td>0.120</td>
<td>0.004</td>
<td>0.060</td>
<td>0.292</td>
<td>0.006</td>
<td>0.067</td>
</tr>
<tr>
<td>C3</td>
<td>0.037</td>
<td>0.009</td>
<td>0.400</td>
<td>0.074</td>
<td>0.023</td>
<td>0.384</td>
<td>0.074</td>
</tr>
<tr>
<td>C4</td>
<td>0.389</td>
<td>0.085</td>
<td>0.056</td>
<td>0.103</td>
<td>0.224</td>
<td>0.047</td>
<td>0.096</td>
</tr>
<tr>
<td>C5</td>
<td>0.427</td>
<td>0.112</td>
<td>0.004</td>
<td>0.059</td>
<td>0.318</td>
<td>0.005</td>
<td>0.074</td>
</tr>
<tr>
<td>C6</td>
<td>0.039</td>
<td>0.011</td>
<td>0.381</td>
<td>0.062</td>
<td>0.022</td>
<td>0.414</td>
<td>0.072</td>
</tr>
<tr>
<td>C7</td>
<td>0.335</td>
<td>0.093</td>
<td>0.050</td>
<td>0.088</td>
<td>0.258</td>
<td>0.058</td>
<td>0.117</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance rate (R)</td>
<td>0.8958</td>
<td>0.8333</td>
<td>0.7396</td>
<td>0.6500</td>
<td>0.6458</td>
<td>0.5833</td>
<td>0.4659</td>
</tr>
</tbody>
</table>
4. Airport operational dynamics

- The system dynamics methodology **models the dynamical behaviour of a system** over time (or over operational steps in our case), by analysing the relationships between the different elements of the system.
- The system and its components can **transit to various performance states during its functioning periods**.
- The probability of being in each state \((j)\) at step \(n\) for component \(i\) \((P_{ij}(n))\) is obtained from Chapman-Kolmogorov equations.

\[
\frac{dP_{i0}(n)}{dt} = \sum_{j=1}^{M} \lambda_{j0}^i P_{ij}(n) - \sum_{j=1}^{M} \mu_{0j}^i P_{i0}(n) + \gamma_{0j}^i P_{i0}(n)
\]

\[
\frac{dP_{ik}(n)}{dt} = \sum_{j=k+1}^{M} \lambda_{jk}^i P_{ij}(n) + \sum_{j=0}^{k-1} \mu_{jk}^i P_{ij}(n) - P_{ik}(n) \left( \sum_{j=0}^{k-1} \lambda_{jk}^i + \sum_{j=k+1}^{M} \mu_{jk}^i \right) + \gamma_{ik}^i P_{ik}(n)
\]

\[
\frac{dP_{iM}(n)}{dt} = \sum_{j=0}^{M-1} \mu_{jM}^i P_{ij}(n) - \sum_{j=0}^{M-1} \lambda_{Mj}^i P_{iM}(t) + \gamma_{M}^i P_{iM}(n)
\]

\(\lambda_{jk}^i\) and \(\mu_{jk}^i\) are the failure and repair rates from state \(j\) to state \(k\) for component \(i\) respectively; and \(\gamma_{ik}^i\) is the stabilization rate (transition probabilities).
1. Indicators
2. Examples and interpretation of parameters
5 RELIABILITY ANALYSIS

1. Indicators

- Mean Instantaneous Performance
  \[ E_n = \sum_{k=1}^{N} g_k p_k(n) \]

- Mean Instantaneous Deficiency
  \[ D_n = \sum_{i=1}^{N} p_i(n) \max(w - g_i, 0) \]

- Mean Instantaneous Availability
  \[ A_n = \sum_{i=1}^{K} p_i(n) \]

Stationary (limiting) distribution

- \[ E_t = 75.32\% \]
- \[ D_t = 0.25\% \]
- \[ A_t = 87.42\% \]

Examples (initial states)
- Case 1: Random initial operational state
- Case 2: Cluster 7 as an initial state (degraded state)
- Case 3: Cluster 1 as the initial state (fully operating state)
2.1. Case 1 \( P_0 = \left[ \frac{1}{7}, \frac{1}{7}, \frac{1}{7}, \frac{1}{7}, \frac{1}{7}, \frac{1}{7}, \frac{1}{7} \right] \)

Evolution with steps (operations) of:
- (a) states’ probability;
- (b) \( E_n \);
- (c) \( D_n \);
- and (d) \( A_n \)

for 
\[ P_0 = \left[ 1/7, 1/7, 1/7, 1/7, 1/7, 1/7, 1/7 \right]. \]
2.2. Case 2 ($P_0 = [0, 0, 0, 0, 0, 0, 1]$)

Evolution with steps (operations) of:

(a) states’ probability; (b) $E_n$; (c) $D_n$; and (d) $A_n$ for $P_0=[0,0,0,0,0,1]$. 

![Graphs showing the evolution of states' probability, $E_n$, $D_n$, and $A_n$.]
2.3. Case 3 ($P_0 = [1, 0, 0, 0, 0, 0, 0]$)

Evolution with steps (operations) of:

(a) states’ probability; (b) $E_n$; (c) $D_n$; and (d) $A_n$ for $P_0 = [1, 0, 0, 0, 0, 0, 0]$. 

CONCLUSIONS

1. Findings
2. Applicability
3. Limitations and future work
CONCLUSIONS

1. Main findings

• **Good behaviour of the environmental impact and complexity blocks** (showing high tendency to be in optimal and standard states).

• **Moderate behaviour of the capacity block** (showing a high tendency for remaining in the optimal and correct states).

• **Deficient behaviour of the delay block** (showing a significant probability to be in an incorrect state): Delays are major drivers for airport performance dynamics and reduce the ability of the system to recover itself.

• **Good management for arrival operations** (which helps to drive the environmental and the delay blocks towards optimal states).

• Cluster 1 (C₁) is the most probable state (40% probability in the stationary distribution). The system tends to operate with the higher performance rates in the long-term.

• **Fast evolution towards the stationary (limiting) distribution**, which illustrates that the system is reparable.
2. Applicability and expected benefits

- Time between failures.
- **Transition probability** among states (predictability).
- Probability for reaching the **operational saturation of the airport** (airport dynamics).
- Analysis of the **most influential parameters** (insights on how different factors influence performance).
- Corrective measures.

- Better performance due to better **predictability** of airport dynamics and significant resilience benefits through better management of forecasted or unexpected operational shortfalls.
- Improvement of airspace/airside operations, situational awareness and collaborative decision-making **processes** through the integration and monitoring of aircraft flows throughout the ATV cycle.
CONCLUSIONS

3. Limitations & future work

• Improve the **accuracy of the model** (more complete testing data and methodological enhancements – like weighting the parameters’ influence when defining block states).

• Compare the results when the methodology is applied to **other airports** (generalisation of the case study).

• Analyse **potential response strategies/measures** (how specific actions impact the airport system state)

• Development of the **model functionalities**: partial influence of each block, corrective measures.

• Consideration of **other performance areas** as safety and financial results.

• Analysis of the **cost to repair incorrect states and maintenance of a good airport performance**.

• **Turnaround operations have been addressed as a single compact block**: this “macro” approach should be completed with a **disaggregated view** to provide operators with a “micro” analysis for obtaining concrete actions and for evaluating costs and requirements (e.g. if the airport layout and the ground handling services are able to support the operational decisions).
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