ANALYSIS OF SATURATION AT THE AIRPORT-AIRSPACE INTEGRATED OPERATIONS

A case study regarding delay indicators and their predictability

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Outline

1. Introduction, Motivation & Objectives
2. Context & Problem Statement
3. Methodology
4. Business Process Model for the Aircraft Flow
5. Characterization of Processes
6. Saturation Analysis
7. Causal Analysis (Predictability Model)
8. Conclusions, Applications & Future Work
INTRODUCTION, MOTIVATION & OBJECTIVES
Introduction

- **Air transport** depends on a complex network architecture, where several facilities, processes and agents are interrelated and interact with each other.

- In this large-scale and dynamic system, airports represent the interconnection nodes that facilitate aircraft distribution through the network and transport modal changes for passengers.

- **Potential incidents**, failures and delays (due to service disruptions, unexpected events or capacity constraints) *may propagate throughout the different nodes of the network*, making it vulnerable.

- This situation has led to system-wide congestion problems and has worsened due to the strong growth in the number of airport operations during the last decades.
Motivation

• Delays have a substantial impact on the economic performance of airlines, but also in the schedule adherence of airports and airlines, passenger experience, customer satisfaction and system reliability.

• A significant portion of delay generation occurs at airports, where aircraft connectivity acts as a key driver for delay propagation.

• “Rotation” (flight cycle through the airport and its surrounding airspace, from inbound to outbound processes) has great influence on punctuality and on the operational efficiency of the entire system.

• This study focuses on the rotation stage and analyzes the aircraft flow through the airport operational environment (one of the mechanisms by which delays propagate through the air transport network).
Objectives

• **Research questions:**
  • Can we define indexes or **indicators that represent the system’s level of congestion/saturation**?
  • Is it possible to **predict this level of congestion/saturation** and the amount of delay propagated?

• Analyze and **characterize the aircraft flow of processes**.
• Define **metrics and indicators that enable airport operators and air navigation service providers to assess the system’s state** (in terms of time-saturation).
• Generate a **practical probabilistic model that predicts the system’s level of saturation** given different explanatory variables.
Characterisation of processes (milestones & length)
ANALYSIS OF SATURATION AT THE AIRPORT-AIRSPACE INTEGRATED OPERATIONS

1. BUSINESS PROCESS MODEL & A-CDM (AIRCRAFT FLOW MODEL)
2. FLOW CHARACTERIZATION (MILESTONES & PROCESSES)
3. SYSTEM’S SATURATION (INDEXES & INDICATORS)
4. CAUSAL ANALYSIS (INTERDEPENDENCIES AMONG FACTORS, PREDICTABILITY & LOCATION OF PREDICTORS)
Context & Problem Statement

• The evolution of a flight can be described as a **sequential flow of events or processes**. Each of these events occurs consecutively, and if any of them gets delayed, this may result in subsequent processes also being delayed (unless certain buffers or “slacks” are added into the times allocated to the completion of certain events).

• To analyze the evolution of the aircraft flow and the potential delays in the successive phases, this study follows a **“milestone approach”** by assigning completion times to each event. This view is in line with the Airport Collaborative Decision Making (A-CDM) methodology.

• **Saturation** is here understood as the **lack of capacity at the airport-airspace system to “receive and transmit” aircraft flows in an appropriate time.**
• **Spatial boundary: Extended Terminal Manoeuvring Area (E-TMA):** 200-500 NM.

• The system is “not only” the airport but also its surrounding airspace (airport-airside integrated operations): integrate delay propagation in the airport system with global delays in the air traffic network.

• **Focus on “airside” operations.**

• **Inbound and outbound timestamps are considered.**
- Description of the "visit" of an aircraft to the E-TMA, as an extension of the SESAR’s “Airport Transit View” concept.
- This “visit” consists basically of three separate sections:
  - The **final approach and inbound ground section** of the inbound flight.
  - The **turnaround process** section in which the inbound and the outbound flights are linked.
  - The **outbound ground section and the initial climb** segment of the outbound flight.
- In time, we restrict actions to a **tactical phase** (day of operations) in order to consider the primary and initial inefficiencies of the system.
METHODOLOGY

2. **Flow characterisation**: Case-study at LEMD + statistical analysis.

3. **Definition of Indexes**: Economic theory of market concentration $\rightarrow$ congestion/saturation.

4. **Causal analysis**: Bayesian Networks + statistical inference.
BUSINESS PROCESS FOR THE AIRCRAFT FLOW

1. BUSINESS PROCESS MODEL & A-CDM (AIRCRAFT FLOW MODEL)
2. FLOW CHARACTERIZATION (MILESTONES & PROCESSES)
3. SYSTEM’S SATURATION (INDEXES & INDICATORS)
4. CAUSAL ANALYSIS (INTERDEPENDENCIES AMONG FACTORS, PREDICTABILITY & LOCATION OF PREDICTORS)
BPM (Business Process Modelling) + A-CDM

• By combining the BPM and the milestone approach (A-CDM) we create a conceptual diagram for the E-TMA (airport-airspace stage). This diagram allows us to:
  • **Determine significant events** in order to track the progress of the flight (arrival, landing, taxi-in, turnaround, taxi-out and departure) and the distribution of these key events as milestones.
  • Ensure **linkage between arriving and departing flights**.
  • Assess **time efficiency performance**, which is measured for each milestone or between two milestones (time-saturation analysis).
  • Enable early **decision making** when there are disruptions to an event.
Developing the conceptual structure of the aircraft flow within the E-TMA requires input from various sources and consists of four main steps:

1. The first step is a **review** of relevant literature and existing **aircraft flow models**.

2. Next, a **hierarchical task analysis** is developed. This appraisal follows a top-down approach that incorporates several sources of information:
   a) Analysis of operations manuals, standards and procedures.
   b) Observations at Adolfo Suárez Madrid-Barajas Airport (LEMD) during 2015.
   c) Structured communications with relevant stakeholders.

3. The previous steps lead to an initial process model.

4. Finally, the initial model is refined and validated with the help of **subject-matter experts**.
We employ Unified Modelling Language (UML) to graphically represent the BPM. UML is a visual modelling language that can be used to create a pattern of a system.

The conceptual structure designed for the airport-airspace integrated operations is basically a UML sequence diagram.

The diagram has three major components:

- **Architecture** (facilities). In UML, known as lifelines.
- **Flow units** (aircraft). In UML, known as actors.
- **Processes** (operations at the E-TMA). Connect flow units and architecture. Each process is represented by an arrow.
The milestones approach (A-CDM) main goal is to achieve common situational awareness by tracking the progress of a flight (definition of “timestamps” to enable close monitoring of significant events).
CHARACTERIZATION OF PROCESSES

1. BUSINESS PROCESS MODEL & A-CDM (AIRCRAFT FLOW MODEL)
2. FLOW CHARACTERIZATION (MILESTONES & PROCESSES)
3. SYSTEM'S SATURATION (INDEXES & INDICATORS)
4. CAUSAL ANALYSIS (INTERDEPENDENCIES AMONG FACTORS, PREDICTABILITY & LOCATION OF PREDICTORS)
Case study at Adolfo Suárez Madrid Barajas Airport (LEMD)

- **LEMD**: four runways (36L-18R, 36R-18L, 32L-14R, 32R-14L), two terminal areas (T123 and T4T4S) and 163 parking spaces (50,420,583 passengers and 378,150 aircraft movements in 2015) (*).
- Observation period: first week of July, which was the peak month in terms of traffic (2,997,408 passengers and 25,516 aircraft movements) (*).
- Two operational configurations (north and south).
- A collection of **1,500 turnaround operations** at LEMD is used to describe the aircraft flow characteristics (radar & airport data).

Source: LEMD AIP (ENAIRE, 2016).  
(*) Source: AENA, 2016.
### Top 20 Delay Affected Departure Airports

**Figure 21. All-Causes Delay. Top 20 Affected Departure Airports 2015**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Departure Airport</th>
<th>ICAO Code</th>
<th>Average delay per departure (mins)</th>
<th>Average delay per Flight Percentage Change</th>
<th>Average Delayed Departure</th>
<th>Percentage of Delayed Departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ROME FIUMICINO</td>
<td>LIRF</td>
<td>19.3</td>
<td>30%</td>
<td>28.8</td>
<td>60.9%</td>
</tr>
<tr>
<td>2</td>
<td>LONDON/GATWICK</td>
<td>EGKK</td>
<td>15.7</td>
<td>8%</td>
<td>28.0</td>
<td>54.4%</td>
</tr>
<tr>
<td>3</td>
<td>ISTANBUL-ATATURK</td>
<td>LTBA</td>
<td>13.5</td>
<td>11%</td>
<td>22.4</td>
<td>60.3%</td>
</tr>
<tr>
<td>4</td>
<td>LONDON/HEATHROW</td>
<td>EGLL</td>
<td>12.0</td>
<td>-2%</td>
<td>25.0</td>
<td>49.0%</td>
</tr>
<tr>
<td>5</td>
<td>BRUSSELS NATIONAL</td>
<td>EBBR</td>
<td>11.7</td>
<td>0%</td>
<td>24.4</td>
<td>47.9%</td>
</tr>
<tr>
<td>6</td>
<td>PARIS CH DE GAULLE</td>
<td>LFPG</td>
<td>11.3</td>
<td>-1%</td>
<td>23.6</td>
<td>47.9%</td>
</tr>
<tr>
<td>7</td>
<td>LIOBON</td>
<td>LPPT</td>
<td>11.3</td>
<td>-32%</td>
<td>26.0</td>
<td>43.4%</td>
</tr>
<tr>
<td>8</td>
<td>SCHIPHOL AMSTERDAM</td>
<td>EHAM</td>
<td>11.2</td>
<td>6%</td>
<td>24.5</td>
<td>45.7%</td>
</tr>
<tr>
<td>9</td>
<td>BARCELONA</td>
<td>LEBL</td>
<td>11.0</td>
<td>10%</td>
<td>28.0</td>
<td>38.7%</td>
</tr>
<tr>
<td>10</td>
<td>ZURICH</td>
<td>LSZH</td>
<td>10.8</td>
<td>6%</td>
<td>20.1</td>
<td>53.7%</td>
</tr>
<tr>
<td>11</td>
<td>DUSSELDORF</td>
<td>EDOL</td>
<td>10.4</td>
<td>27%</td>
<td>24.3</td>
<td>42.7%</td>
</tr>
<tr>
<td>12</td>
<td>FRANKFURT-MAIN</td>
<td>EDDF</td>
<td>10.3</td>
<td>11%</td>
<td>19.5</td>
<td>53.1%</td>
</tr>
<tr>
<td>13</td>
<td>MADRID BARAJAS</td>
<td>LEMD</td>
<td>10.1</td>
<td>10%</td>
<td>25.7</td>
<td>39.3%</td>
</tr>
<tr>
<td>14</td>
<td>DUBLIN</td>
<td>EIDW</td>
<td>9.5</td>
<td>12%</td>
<td>23.0</td>
<td>40.5%</td>
</tr>
<tr>
<td>15</td>
<td>TELEG-BERLIN</td>
<td>EDDT</td>
<td>9.2</td>
<td>11%</td>
<td>21.8</td>
<td>42.2%</td>
</tr>
<tr>
<td>16</td>
<td>PARIS ORLY</td>
<td>LFPO</td>
<td>8.2</td>
<td>-21%</td>
<td>21.9</td>
<td>37.4%</td>
</tr>
<tr>
<td>17</td>
<td>MUNICH</td>
<td>EDDM</td>
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<td>17%</td>
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<td>43.6%</td>
</tr>
<tr>
<td>18</td>
<td>STOCKHOLM-ARLANDA</td>
<td>ESSA</td>
<td>7.8</td>
<td>8%</td>
<td>21.8</td>
<td>36.0%</td>
</tr>
<tr>
<td>19</td>
<td>OSLO/GARDERMoen</td>
<td>ENGM</td>
<td>7.8</td>
<td>11%</td>
<td>24.1</td>
<td>32.5%</td>
</tr>
<tr>
<td>20</td>
<td>COPENHAGEN KASTRUP</td>
<td>EKCH</td>
<td>7.6</td>
<td>14%</td>
<td>24.6</td>
<td>31.0%</td>
</tr>
</tbody>
</table>

Source: CODA Digest (EUROCONTROL, 2016).
### Top 20 Delay Affected Arrival Airports

Figure 23. All-Causes Delay. Top 20 Affected Arrival Airports 2015

<table>
<thead>
<tr>
<th>Rank</th>
<th>Arrival Airport</th>
<th>ICAO Code</th>
<th>Average delay per Flight (mins)</th>
<th>Average Delay per Flight Percentage Change</th>
<th>Average Delay per Delayed Arrival</th>
<th>Percentage of Delayed Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ISTANBUL-ATATURK</td>
<td>LTBA</td>
<td>18.4</td>
<td>37%</td>
<td>33.1</td>
<td>55.6%</td>
</tr>
<tr>
<td>2</td>
<td>LONDON/GATWICK</td>
<td>EGKK</td>
<td>10.5</td>
<td>15%</td>
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<td>45.4%</td>
</tr>
<tr>
<td>3</td>
<td>LONDON/HEATHROW</td>
<td>EGLL</td>
<td>13.1</td>
<td>7%</td>
<td>30.5</td>
<td>43.1%</td>
</tr>
<tr>
<td>4</td>
<td>ROME FULVIMICO</td>
<td>LIRF</td>
<td>12.0</td>
<td>41%</td>
<td>31.6</td>
<td>38.0%</td>
</tr>
<tr>
<td>5</td>
<td>DUBLIN</td>
<td>EIDW</td>
<td>12.0</td>
<td>21%</td>
<td>28.4</td>
<td>42.2%</td>
</tr>
<tr>
<td>6</td>
<td>BARCELONA</td>
<td>LEBL</td>
<td>11.9</td>
<td>11%</td>
<td>31.7</td>
<td>37.6%</td>
</tr>
<tr>
<td>7</td>
<td>LISBON</td>
<td>LPPT</td>
<td>11.2</td>
<td>36%</td>
<td>28.2</td>
<td>39.5%</td>
</tr>
<tr>
<td>8</td>
<td>BRUSSELS NATIONAL</td>
<td>EBRB</td>
<td>11.0</td>
<td>7%</td>
<td>26.8</td>
<td>41.1%</td>
</tr>
<tr>
<td>9</td>
<td>DUSSELDORF</td>
<td>EDDL</td>
<td>10.1</td>
<td>25%</td>
<td>26.5</td>
<td>38.0%</td>
</tr>
<tr>
<td>10</td>
<td>MADRID BARAJAS</td>
<td>LEMD</td>
<td>9.6</td>
<td>10%</td>
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<td>35.3%</td>
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<td>SCHIPHOL AMSTERDAM</td>
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<td>22.7</td>
<td>40.0%</td>
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<td>FRANKFURT MAIN</td>
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<td>7.9</td>
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</tr>
<tr>
<td>18</td>
<td>COPENHAGEN KASTRUP</td>
<td>EKCH</td>
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<td>LFPO</td>
<td>7.1</td>
<td>-22%</td>
<td>23.4</td>
<td>30.1%</td>
</tr>
<tr>
<td>20</td>
<td>WIEN SCHWECHAT</td>
<td>LOWW</td>
<td>6.7</td>
<td>11%</td>
<td>23.2</td>
<td>28.7%</td>
</tr>
</tbody>
</table>

Source: CODA Digest (EUROCONTROL, 2016).
• **Demand profile** for the 1st of July 2015 (baseline day scenario) against the practical (declared) **capacity** of the airport.

• Accumulated hourly delay for arrival and departure operations against the demand profile (1st July 2015).

• Departure delay is defined by the sum of arrival upstream delay and the aggregated delay at the rotation stage. Delays can be positive or negative, as they are defined in relation to scheduled times.
Hourly number of turnaround operations against the airport total capacity and the hourly accumulated final departure delay (1st July 2015).

- Arrival delay increases and accumulates its impact over the day, due to the network effect.
- Departure delay does not follow this pattern, which implies that the airport-airspace system is somehow capable of absorbing a fraction of the arrival delay across the rotation stage.
- We analyze this aptitude by studying the different processes that were previously identified with the BPM and the milestone approach.
- We assess the system’s time efficiency performance and its level of saturation by evaluating three mutually exclusive stages: arrival (including Taxi-In), turnaround and Taxi-Out.
Total accumulated **ARRIVAL** delays (min)  
(related to number of turnaround operations)
• **Characterization of processes** is the baseline for evaluating the system’s level of saturation.

• **Time efficiency** performance is measured for each milestone (when scheduled and actual timestamps are available) or between two milestones (to assess the length of the process).
<table>
<thead>
<tr>
<th>Measure</th>
<th>Description</th>
<th>Statistical data (mean and standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIBT-SIBT. Arrival delay</td>
<td>It represents the upstream arrival delay (reactionary delay), by assessing if the In-Block operation (timestamp) is developed as scheduled, with delay or in advance.</td>
<td>$\mu = 9.8 \text{ min} \ (\sigma = 28.9 \text{ min})$</td>
</tr>
<tr>
<td>ALDT-AIBT</td>
<td>It represents the Taxi-In process length.</td>
<td>$\mu = 8.8 \text{ min} \ (\sigma = 16.7 \text{ min})$</td>
</tr>
<tr>
<td>Actual turnaround time (AIBT-AOBT) against Scheduled turnaround time (SIBT-SOBT). Turnaround delay.</td>
<td>It represents a measure for evaluating if the turnaround operation at the airport is developed as scheduled, with delay or better than expected (absorbing delay). It allows assessing the relationship among the arrival delay and the departure delay for the different operations, i.e. the ability of the airport to absorb the arrival delay.</td>
<td>$\mu = 4.7 \text{ min} \ (\sigma = 27.2 \text{ min})$</td>
</tr>
<tr>
<td>AIBT-AOBT</td>
<td>It represents the turnaround process duration.</td>
<td>$\mu = 151.9 \text{ min} \ (\sigma = 168.6 \text{ min})$</td>
</tr>
<tr>
<td>ASRT-ASAT</td>
<td>It allows assessing the difference in time between the aircraft operator request for start-up and the actual start-up approval permission by the Air Traffic Controller (ATC).</td>
<td>$\mu = -1.5 \text{ min} \ (\sigma = 6.7 \text{ min})$</td>
</tr>
<tr>
<td>ASAT-AOBT</td>
<td>It allows assessing the difference in time between the actual start-up approval permission by the Air Traffic Controller (ATC) and the Off-Block operation.</td>
<td>$\mu = -1.3 \text{ min} \ (\sigma = 40 \text{ min})$</td>
</tr>
<tr>
<td>TSAT-ASAT</td>
<td>It allows to understand if there is some delay between the target time for start-up and the actual one.</td>
<td>$\mu = 0.9 \text{ min} \ (\sigma = 33.1 \text{ min})$</td>
</tr>
<tr>
<td>AOBT-SOBT</td>
<td>It represents a measure for evaluating if the Off-Block operation (timestamp) is developed as scheduled, with delay or better than expected (absorbing delay).</td>
<td>$\mu = 14.7 \text{ min} \ (\sigma = 6.7 \text{ min})$</td>
</tr>
<tr>
<td>AOBT-ATOT</td>
<td>It represents the Taxi-Out process duration.</td>
<td>$\mu = 15.8 \text{ min} \ (\sigma = 25.5 \text{ min})$</td>
</tr>
<tr>
<td>Actual Taxi-Out duration (AOBT-ATOT) against Scheduled Taxi-Out duration (SOBT-STOT). Taxi-Out delay</td>
<td>It represents a measure for evaluating if the Taxi-Out operation at the airport is developed as scheduled, with delay or better than expected (absorbing delay).</td>
<td>$\mu = 9.9 \text{ min} \ (\sigma = 29.2 \text{ min})$</td>
</tr>
<tr>
<td>Departure delay</td>
<td>Departure delay = Arrival delay + Turnaround delay + Taxi-Out delay</td>
<td>$\mu = 18.5 \text{ min} \ (\sigma = 24.8 \text{ min})$</td>
</tr>
</tbody>
</table>
• The turnaround step is partially absorbing the arrival delay.

• Delay pattern for the **total delay** (sum of the accumulated delay in each of the stages) through the first 3 days of July 2015.

• Delay pattern for each **stage**: arrival (including Taxi-In), turnaround and Taxi-Out, through the first 3 days of July 2015.

• Accumulated hourly **delay for each of the stages** against the **number of operations** at the observed hour.
SATURATION ANALYSIS

1. BUSINESS PROCESS MODEL & A-CDM (AIRCRAFT FLOW MODEL)
2. FLOW CHARACTERIZATION (MILESTONES & PROCESSES)
3. SYSTEM’S SATURATION (INDEXES & INDICATORS)
4. CAUSAL ANALYSIS (INTERDEPENDENCIES AMONG FACTORS, PREDICTABILITY & LOCATION OF PREDICTORS)
1) Ki: delay evolution indicator (applied to the total and to each of the three partial stages).

\[ K_i = \frac{(\text{Delay for flight } i) - (\text{Average delay over the last 20 flights})}{|\text{(Average delay over the last 20 flights)}|} \times 100 \% \]

- Average total delay over the last 20 flights (01/07/2015).
- Ki (total) evolution throughout the day (01/07/2015).
2) $\alpha_i$: Hourly delay index based on the aircraft type (an application of the Herfindahl-Hirschman Index).

$$\alpha_1 \text{ (hourly)} = \frac{\sum (\beta_i \times D_i)}{N^o \text{ ops}} \left( \frac{\text{min}}{\text{op}} \right)$$

$$\alpha_2 \text{ (hourly)} = \frac{\sum (\beta_i \times D_i)}{N^o \text{ ops} \times <\text{hourly average delay}>} \left( \% \right)$$

3) $\delta_i$: Hourly performance indicator (total operations).

$$\delta_i = \frac{\text{Average delay (hour } i)}{\text{Daily average delay}} \left( \% \right)$$

4) $\Theta_{ij}$: Hourly performance indicator (contribution of each stage).

$$\theta_{ij} = \frac{\text{Average delay of the stage } i \text{ at hour } j}{\text{Average delay for hour } j} \left( \% \right)$$
5) $\eta_i$: **Global performance indicator** (an application of the Lerner Index).

$$\gamma_i = \frac{\text{No of operations at hour } i}{\text{No of daily operations}} \quad (\%)$$

$$\eta_1 = \sum_{1}^{24} \gamma_i \ast < AD_i > \quad (\text{min})$$

$$\eta_2 = \frac{\sum_{1}^{24} \gamma_i \ast < AD_i >}{< AD_t >} \quad (\%)$$

- $\gamma$ against hourly average delays throughout the day (01/07/2015).
- Evolution of the turnaround stage saturation throughout the day (01/07/2015).
- Contribution of each stage to the total delay throughout the day (01/07/2015).
CAUSAL ANALYSIS (PREDICTABILITY MODEL)
Bayesian Networks (BN)

- BN are **graphical probabilistic models** used for reasoning under uncertainty.

- A BN is a directed acyclic graph (DAG), in which **each node denotes a random variable**, and each **arc denotes a direct dependence between variables** (nodes that are not connected symbolize variables that are conditionally independent of each other).

- Each node is associated with a probability function that takes, as input, a particular set of values for the node's parent variables, and gives (as output) the probability (or probability distribution, if applicable) of the variable represented by the node.

\[
\text{Bayes Theorem: } P(A|B) = \frac{P(B|A) * P(A)}{P(B)}
\]

Joint probability density of all nodes: \( p(x) = p(x_1, \ldots, x_n) = \prod_{i=1}^{n} p(x_i | \pi(x_i)) \)

- \( X_2 \) and \( X_3 \) are parent nodes of \( X_4 \) (child node for \( X_2 \) and \( X_3 \)): the probability distribution of \( X_4 \) depends exclusively on the value of its parent variables (\( X_2 \) and \( X_3 \)).
• A BN can be **constructed** either manually, **based on knowledge and experience** acquired from previous studies and literature, **or automatically from data**.

• In this study, the selection of variables is constrained by the availability of data. We use the elements (timestamps, aircraft data and airport information/configuration) that have been analyzed.

• The first step is to generate the **correlation matrix** for the variables involved, in order to assess the correlation among pairs.

• Subsequently a data-driven process was applied to build the BN, following a **Bayesian Search Algorithm** (**GeNle Software**, BayesFusion LLC).

• The final network was determined by applying this algorithm (including variable discretization and validation) and refining it with previous knowledge (**combination of a data-driven process and practical adjustments**).

• We develop a **statistical significance** test on pairs of nodes connected by an arc in the BN: associations between the nodes were statistically significant at level 0.05 (p-value test).
<table>
<thead>
<tr>
<th>Node</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arrival delay for the operation</td>
</tr>
<tr>
<td>2</td>
<td>Turnaround delay for the operation</td>
</tr>
<tr>
<td>3</td>
<td>Taxi-Out delay for the operation</td>
</tr>
<tr>
<td>4</td>
<td>Total delay for the operation</td>
</tr>
<tr>
<td>5</td>
<td>Average total delay of the previous 20 flights</td>
</tr>
<tr>
<td>6</td>
<td>Delay indicator (Ki) for the operation</td>
</tr>
<tr>
<td>7</td>
<td>ALDT (Actual Landing Time)</td>
</tr>
<tr>
<td>8</td>
<td>Arrival Runway</td>
</tr>
<tr>
<td>9</td>
<td>Departure Runway</td>
</tr>
<tr>
<td>10</td>
<td>Route origin (national, UE Schengen, international)</td>
</tr>
<tr>
<td>11</td>
<td>Route destination (national, UE Schengen, international)</td>
</tr>
<tr>
<td>12</td>
<td>Terminal Area (T123, T4T4S)</td>
</tr>
<tr>
<td>13</td>
<td>Wake-turbulence category (H, M, L)</td>
</tr>
<tr>
<td>14</td>
<td>Aircraft size (narrow body, wide body)</td>
</tr>
<tr>
<td>15</td>
<td>Taxi-In process duration</td>
</tr>
<tr>
<td>16</td>
<td>Taxi-Out process duration (scheduled)</td>
</tr>
<tr>
<td>17</td>
<td>Taxi-Out process duration (actual)</td>
</tr>
<tr>
<td>18</td>
<td>SOBT-SIBT (scheduled turnaround)</td>
</tr>
<tr>
<td>19</td>
<td>AOBT-AIBT (actual turnaround)</td>
</tr>
<tr>
<td>20</td>
<td>ATOT (Actual Take Off Time)</td>
</tr>
<tr>
<td>21</td>
<td>TOAT (Taxi-Out Approval Time)</td>
</tr>
<tr>
<td>22</td>
<td>AOBT-SOBT (delay in the Off-Block process)</td>
</tr>
<tr>
<td>23</td>
<td>ASRT-AOBT</td>
</tr>
<tr>
<td>24</td>
<td>ASRT-ASAT</td>
</tr>
<tr>
<td>25</td>
<td>TSAT-ASAT</td>
</tr>
</tbody>
</table>

The thickness of an arc represents the strength of influence between two directly connected nodes.

\[
p(x) = p(x_1, \ldots, x_n) = \prod_{i=1}^{n} p(x_i | \pi(x_i))
\]
• **Scenario 1** (forward/inter-causal scenario). The model predicts departure delay & delay indicator (output-child node) by setting the probability of having certain configuration, i.e. by setting one or more parent-input nodes.

• **Scenario 2** (backward inference). The model delivers a particular configuration in the parent nodes by setting the delay node to a target value. It provides understanding on which are the main contributors to delay (if delay is settled to a high positive value) or what configuration optimizes operations (if delay is settled to a negative value).

• “**Strength of influence**” between two directly connected nodes enables us to develop a sensitivity analysis.

• A sub-sample of 90% of the observations was selected to build the model structure and to estimate parameters. The remaining 10% of the data was set aside to test the accuracy of the predictions made by the model.

• The scenarios tested provided promising results regarding the model’s ability to manage uncertainty (by explaining the system’s performance and predicting delay propagation). The test error ranged between 20% - 35%, and the average value was 27%.
**Scenario 1** (forward/inter-causal scenario)

- P (Route origin: international) $\sim 1$ (100%)
- P (Terminal area: T4) $\sim 1$ (100%)
- P (Arrival runway: 18R) $\sim 1$ (100%)
- P (Aircraft type: WB) $\sim 1$ (100%)
- P (Morning, 6:00-11:00) $\sim 1$ (100%)

Probability distribution for the node: departure delay

- Decision making tool for operational strategies and resource allocation.
- Variables of control. Can we “act” over all the parameters?
Scenario 2 (backward inference)

- Delay drivers & precursors (post-operational analysis for optimization).
- Is the “combination” of variables feasible?

- P (Departure delay: <0 min) ~ 0.5 (50%)
- P (Departure delay: 0-5 min) ~ 0.5 (50%)
- 47% Route origin: national
- 78% Terminal area: T4
- 83% Arrival runway: 18R
- 72% Aircraft type: WB
- 37% ALDT: Evening (13:00-20:00)
CONCLUSIONS, APPLICATIONS & FUTURE WORK
• Functional analysis of the aircraft flow through the airport-airspace system.
• Dynamic spatial boundary associated with the E-TMA concept, so a linkage between inbound and outbound flights can be proposed.
• Aircraft flow characterized by several temporal milestones related to the A-CDM method and structured by a hieratical task analysis, providing a BPM for the rotation stage.
• Statistical analysis of processes shows that arrival delay increases and accumulates its impact over the day, due to network effects.
• Departure delay does not follow this pattern, which implies that the airport-airspace system is somehow capable of absorbing a fraction of the arrival delay across the rotation stage.
• Evaluation of the system’s level of saturation is completed by the definition of indexes.
• Relationships among factors that influence the aircraft flow are evaluated to create a probabilistic graphical model, using a BN approach.
Main applications of the model:

- Achieve a comprehensive understanding of operations at the E-TMA (airport-airside integration).
- Detect possible incidents or irregularities that may occur during processes.
- Define the different operational actions that may correct the inefficiencies identified.
- Investigate the impact of changes in tactical decisions and policies on the management and propagation of delays in the E-TMA system.
- The propagation model and the proposed indicators may be used to ensure that all agents collaborate in reducing delays, ensuring some target levels of efficiency.
- Using “forward” analysis it is possible to estimate the final departure delay (settlement of buffer time and optimal rotation times).
- Using “backward” analysis it is possible to identify the main contributors (causes) to a final delay (locate inefficiencies).
• **Future work** needs to focus on:
  
  • Improve the **accuracy** of the model (more complete testing data and methodological improvements).
  
  • Assess whether or not the model is suitable for use in **other airports**.
  
  • Analyze potential **response strategies** (reduce delays, mitigate inefficiencies and optimize operations).
  
  • Apply the propagation model to **other types of incidents** (not just delays).
THANK YOU VERY MUCH FOR YOUR ATTENTION. ANY QUESTIONS?

ANALYSIS OF SATURATION AT THE AIRPORT-AIRSPACE INTEGRATED OPERATIONS

A case study regarding delay indicators and their predictability

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