Abstract— In this document, new capacity enhancement alternatives were studied for Lisbon’s airport. In order to do that, a network model representation of the airport was used to simulate the ground and airspace movements with the help of an airport fast-time simulation software: CAST Aircraft. Then, based on EUROCONTROL’s recommendations and analysing the baseline scenario results, 3 new scenarios are created: study of additional exits to one of the airport’s runways, the analysis of less-restrictive departure/departure separations and the combination of both alternatives. It was concluded that the airport’s capacity could be increased with small changes on the runway layout and, most important, with the introduction of less restrictive aircraft separation in the airport’s terminal manoeuvring area.

1. Introduction

The number of flights and passengers have been increasing within last decades and with it the demand for larger and better Airports [1]. The Humberto Delgado Airport, in Lisbon, was no exception.

At the time of writing, it was predicted that Lisbon’s main airport would be able to accommodate 267545 movements during 2016, with maximum 40 movements per hour (total of arrivals and departures) in the morning peak hour (0700 to 0900 UTC). Eurocontrol’s forecast 287255 movements in 2038 with the peak of 43 flights per hour [3]. In many cases, the runway slot load is already reaching the runway system capacity limits in one of the airport’s traffic peak hour.

With that in mind, the aim of this document is to take a small part on the constant development of the Lisbon’s main airport, while trying to answer some of the previously mentioned capacity issues.

2. Airport Capacity

For simplicity the main features of the capacity analysis is described for landings and take-offs on a single runway under Instrument Flight Rules (IFR). Typically, an arriving aircraft follows essentially a curved path from an arrival fix to the approach gate where different paths merge. It then follows the straight glide path defined by the radar beams of the Instrument Landing System (ILS), and touches down after passing over the threshold. After touch down the aircraft decelerates to a speed at which it can turn off at a suitable exit. A departing aircraft travels along the taxiways to a holding point near the runway threshold where it may have to wait before being given clearance to line up on the runway prior to departure. After receiving take-off clearance, the aircraft accelerates down the runway, lifts off and follows a common departure path for only a short distance before turning towards one of a number of departure fixes. The two major elements limiting the capacity of a single runway: separation requirements set by ATM and runway occupancy times [10]. These two elements, however, are influenced by many other variables. Basically, depending on the mix of operations, the capacity is influenced by aircraft separations and runway occupancy times in the following way:

- Arrival-Arrival: capacity depends only on the airspace separations between approaches, usually in NM.
- Arrival-Departure: the typical time interval of a runway operating in mixed mode, for each landing and takeoff cycle, consists of three factors:
  - Time needed to guarantee the minimum separation between an aircraft starting the takeoff roll and an approaching flight;
  - Runway Occupancy Time of Arrival (ROTA);
  - Runway Occupancy Time of Departure (ROTD).
- Departure-Departure: capacity depends mostly on the time-separations between departures.

With the need to increase the capacity of airports, several approaches can be taken. The main focus of this study has been on the two major capacity limiting factors mentioned before: minimization of aircraft separations and runway occupancy times.

3. Performance Assessment Modelling

Two of the major performance measures of ATM systems are capacity and delay. A large number of models have been developed over the years for these purposes. In fact, this is the oldest area of model development in the ATM field, with the first significant models dating back to the late 1950s. It is also the area where the most advanced modelling capabilities currently exist [21]. According to Odoni et al, usually, airport models are classified with respect to three aspects: level of
detail, methodology, and coverage [21]. According to the model coverage, airfield models can be grouped according to their main focus: models focused on the runway system, the taxiway system, the apron area, or integrated models (complete airfield). With respect to methodology, models can be divided into analytical and simulation models. Basically, analytical models consist of a set of simplified mathematical relations that represent the real world. Simulation models move individual objects through the system elements. Based on the parameters and flow intersections of each entity, the time which objects spend in each segment of the system is determined, and consequently system performance and the LOS.

Models may also be classified according to their level of detail as macroscopic or microscopic. The first, omit a great deal of detail, since their objective is to obtain approximate answers, with lower granularity. Airfield microscopic models use highly faithful representation of the various processes that take place at the airport. Typically, such models represent aircraft on an individual basis and move them through the ATM elements, which are represented by the model. They take into consideration each aircraft’s performance characteristics. Such detailed features as the airport’s taxiway and gate selection, pushback maneuvering, and so on, are generally included only in microscopic models.

In practice, according to Transport Research Board, depending on their applications, assumptions, the data, time and cost requirements, the model availability and the skill/training required for the operator, five levels of airfield modelling sophistication can be defined [16]:

- Table Lookup;
- Charts, Nomographs, and Spreadsheets;
- Analytical Capacity Models;
- Airfield Capacity Simulation Models and
- Aircraft Delay Simulation Models.

The main focus for this document is simulation modelling, discussed next.

### 3.1 Simulation Models

At first, airport simulation models were mostly used for final “what-if” scenario evaluations, but then simulation modeling and analysis were progressively integrated into the airport planning process rather than being simply used for final evaluations [22]. There are no regimentations about the standardized employment of capacity analysis and simulation. However, most research has been implementing the same methodologies, with small differences depending on several factors, such as the software used. As referred before, microscopic simulation models generate traffic flows through the airspace and airport segments. Observations from these flows allow appropriate measures of capacity and/or delay to be computed. Microscopic models, can be either node-link or 3-Dimensional (3-D). Node-link models such as the Airport and Airspace Simulation Model (SIMMOD) and the Airport Machine separate the airport and airspace into a number of nodes and links over which aircraft move. Conflict occurs when more than one aircraft tries to pass one node. 3-D models such as Total Aispace and Airport Modeller (TAAM) and Heuristic Runway Movement Event Simulation (HERMES), allow flight over random 3-Dimensional routes [21]. Most of the literature reviewed that used SIMMOD followed essentially the same steps to study maximum capacities for baseline and alternative scenarios [23] [24] [25]: Modeling of existing conditions and calibration with respect to hourly runway throughput and delay.

- Cloning using constant demand increments.
- Making curve estimation: carry out curve fitting test, significance test and parameter estimates.
- Summarizing and calculating average delays of each cloning scenario. Then, usually, the next step is to estimate at which rate of demand and under which scenario the service rate is exceeded, flights are delayed and the average delays increase above predefined LOS.

In the case of the literature found for TAAM, the authors analyzed three capacity measures for each scenario. This way, they compare the different scenarios in terms of: efficiency/design functionality; sensitivity to technological/procedural improvements and overall utilization of potential capacity. These are, essentially, saturation capacities of each layout constrained at varying levels [26] [27]:

- Fully constrained capacity ($\lambda_1$): Capacity as influenced by all constraints incumbent at an airport - ground as well as airspace constraints;
- Semi-constrained capacity ($\lambda_2$): Capacity under procedural and technological constraints - only Airspace constraints,
- Unconstrained capacity ($\lambda_3$): Capacity in an unconstrained environment considering only safety related constraints such as separation standards.

There are other methodologies to incorporate airside simulations into the capacity analysis. Theiss, for example, showed that the identification of the declared capacity of an airport can be supported through the methodology of capacity analysis according to Gilbo and the application of airside simulation [28]. Gilbo presented a capacity analysis approach incorporating a diagram which displays all actual movements on a runway system within a certain period of time. In this diagram a scatter plot represents all monitored traffic movements with reference to the ratio of departures and arrivals [29]. By embracing the scatter plot, an envelope can be generated. Theiss basically implemented a range of scenarios with various ratios of departures and arrivals as well as different traffic demands in the simulation. A simulation implying an adequately long period of time as well as a constant traffic demand can generate a constant traffic flow. The results of the individual simulation runs could then be transfused into a Gilbo diagram.

Recently, Böck and Hornung presented a new approach to establish robust capacity values based on fast-time simulation results [30]. Initially, an operational case is defined specifying a typical operational condition including the definition of a characteristic aircraft mix - a central determinant of airport capacity. They followed a similar approach to the one presented by Theiss where demand volume and arrival to departure ratios are systematically varied. The output of each simulation run is analyzed in sliding time intervals to generate the data points for the capacity curve diagram. Each data point contains information regarding the arrival rate, the departure rate, the average delay and the aircraft mix of all aircraft movements.
measured in the respective sliding time interval. In a following step the aggregated simulation data are then evaluated to reject those data points which do not sufficiently represent the aircraft mix specified in the operational case and which are identified as outliers and therefore would lead to a non-robust result when included in the capacity curve. To do that, and in order to improve the lack of practicability of the “frequency of occurrence” method to identify outliers proposed by Gilbo, the Local Outlier Factor (LOF) algorithm by Breunig et al. has been identified to overcome this limitation [31].

Selecting an appropriate level of modeling sophistication depends primarily on the purposes of the capacity analysis and the characteristics of the specific airport [16]. In the particular case of this document, as the main goal was to study different layout scenarios for the airport’s capacity, modelling the full airport system, including gates, apron and all types of taxiways (not only RETs and parallel taxiways) was imperative. For this to happen, a detailed layout scheme, using CAD software, for example, should be used as input. Another main objective was, through computer animation graphic, convince the stakeholders that the results of the study are valid and credible. All this could only be accomplished through simulation models. In addition, the development of a new computer tool or the use of generic ones like ARENA [32] or AnyLogic [33] were a priori excluded hypothesis so that the main focus could be the scenario analysis, not the development or adaptation of the software to the study purposes.

The software used in this document for simulation analysis is called Comprehensive Airport Simulation Tool (CAST) developed by Airport Research Center GmbH (ARC). CAST is a high-performance 2D/3D fast time PC-based simulation system for modelling and evaluating airport-systems, traffic and processes. CAST is based on multi-agent technology: every passenger, vehicle or aircraft is an individual agent and able to react to the given situation according its individual goals, intentions and characteristics.

### 4. Methodology

The methodology followed can be divided in two stages. In the first stage, based on the available data, the baseline airport model is created and tested. In the second stage, alternatives are tested and the results are compared to the reference scenario.

![Figure 3.2 - Testing new layout for Lisbon’s airport in CAST.](image)

Besides the airport layout, the main inputs for the model are: the aircraft separation requirements, the aircraft fleet mix and the runway exits usage distribution. The separation between aircraft is based on ICAO’s critical values, i.e. those that lead to maximum runway capacity. In terms of aircraft fleet mix, a compromise is obviously required between a very precise categorization of aircraft types and the need to keep the number of movement types down to manageable levels for modelling purposes. Two characteristics of aircraft which have an important effect on times are weight and speed. Weight is the dominant factor and acts via the wake turbulence separation. For the purpose of specifying the wake turbulence separations, aircraft are usually divided into three main weight classes. Speed determines the runway occupancy times as well as the travel times over certain specified separation distances on the approach and departure paths. An independent division of aircraft according to both weight and speed could lead to a large number of types. For civilian aircraft, a rough correlation between weight and speed can be made: the heavier aircraft tend to be faster. This way, for the capacity analysis it is sufficient to distinguish heavy, medium and light aircraft and to adopt typical mean speed and accelerations for each class [34]. The arrival aircraft are then distributed by the runway exits according to their type. Both aircraft fleet mix and the exits usage distribution are entered as fixed probabilities which will result in different outputs since CAST uses a (pseudo)random seed to produce different distributions of those shares over the simulation time.

In the simulations, besides the daily and hourly movements for the runway, the taxi-times, ROTs, taxi delays, departure queue delays and queue length were selected as outputs. For the departing aircraft, the taxi times are defined as the difference between the gate out time and the runway entry time. For the arriving aircraft, the taxi times are calculated as the difference between the runway exit (tail clearance) time and the gate in time. As referred before, the ROTDs are estimated as the duration between the runway entry time and the runway threshold exit time. In a similar way, for arrivals, the ROT is equal to the duration between the runway threshold entry time and the runway exit time. Taxi delay times correspond to the sum of ground holding times along the paths during the taxi movements of aircraft. Departure queue delays are the ground holding times spent at the departure queues and are estimated separately from the taxi delays. The maximum and average departure queue lengths are estimated according to the number of aircraft queueing during the time-intervals defined.

### 4.1 Fast-time Simulations - CAST

#### 4.1.1 Model Structure

As mentioned before, one advantage of the chosen simulation software is the ability to import the layout from a Drawing Exchange Format (DXF) file to create the airport’s model structure. This way it is much easier to create the model than creating the structure inside the simulation software. The DXF file was based on a scale drawing chart of the airport in PDF format. This chart is part of the AIP provided by the local Air Traffic Control company – NAV. Similar charts were used to obtain other specific layout configuration characteristics, such as the stand locations. In cases where the charts didn’t provide enough information for a clear model creation, Google Earth was used to get the objects disposition and sometimes, in
very few cases, some distances were obtained using its internal measurement tool by scaling according to foreknown 2D distances.

### 4.1.2 Model Configuration

In CAST it is possible to define the maximum time a moving aircraft can be delayed by an aircraft performing its pushback or the maximum off-block delay admitted for an aircraft requesting for pushback approval. In this study, the default time values were used in both cases:

- Maximum pushback on taxi intrusion delay: 2 minutes.
- Maximum pushback delay: 4 minutes.

At first and after the pushback, without any movement restrictions in the model, aircraft in CAST will always choose the fastest available path between their source and their destination automatically according to the default taxiing times entered. In this document those values were obtained with the help of the airport experts:

- Default Taxi-in Time: 3min30sec;
- Default Taxi-out Time: 6mins.

By default, in CAST Aircraft, each guideline can be used by each aircraft. But one can define passages restrictions, defining which type of aircraft is allowed to use one particular guideline. In this study, besides some closing some paths completely, only two types of passage restrictions were applied to guidelines, according to:

- Flight Direction: first, in runway entrance taxiways, it was necessary to restrict the passage to arrival aircraft. For runway exit taxiways, the opposite was applied: departure aircraft cannot use the taxiway guideline.
- Airport Operating Mode: restrict the routing of the aircraft according to the operating mode of the airport, i.e. it was assumed that, during the simulation time, the airport is operating with a single runway and that the aircraft should follow the routing concepts defined in the Aerodrome Ground Movements Charts. To do that, a property was created on the airport, with the following parameters:
  - Name: “Operation Mode”;
  - Value Kind: “String”;

In LPPT’s model, the ground dynamics were defined independently of the aircraft type. The maximum linear and radial accelerations and speeds are presented below. The same applies to the vehicle interaction: all vehicles must respect the same distance/time separations independently of the leading/trailing aircraft:

- Accelerations:
  - Max. Acceleration: 1.5 m/s²
  - Max. Deceleration: −1.5 m/s²
  - Max. Radial Acceleration: 1.3 m/s²
- Speeds:
  - Taxiway Max. Speed: 10.3 m/s
  - Aircraft Max. Pushback Speed: 2 m/s
  - Aircraft Max. Towing Speed: 8 m/s
  - Aircraft Max. Speed: 236.1 m/s

To control and sequence a traffic flow and specially to define passage constraints, it is important to insert “Flow Management Waypoints” that pose those passage constraints. Aircraft may only pass such a flow management waypoint once the respective constraints are fulfilled. These can be distance-based separation time-based separation or upstream-distance flow separation constraints. In this study, there are distance and time separations constraints and there are also flow constraints related to sectors occupancy. Each runway has one departure sector with Departure Holding Transition (DHT) and the Arrival Threshold Transition (ATT) acting as entries and an additional transition named as Sector Exit Transition (SET) serving as exit to that sector. This exit corresponds to the departure line-up location for RWY entrance P. Each runway has also an Arrival Flow Management Transition (AFMT) where the approach separations are defined and there is also another transition named Departure Line-up Transition (DLT) that serve as the reference line-up location for departures.

<table>
<thead>
<tr>
<th>Vehicle Interaction</th>
<th>Conflict Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Spacing</td>
<td>Time Headway</td>
</tr>
<tr>
<td>50m</td>
<td>3sec</td>
</tr>
</tbody>
</table>

It was decided to locate AFMT 8NM upstream from DTT because that is where LPPT’s APP transfer control to TWR on ILS approach [3]. Table 4-2 describes the flow management points and the respective passage constraints.

Then, basically, when planning its path to execute a flight from one airport to another (remote) airport, an aircraft will try to incorporate one waypoint of each of the abovementioned types in its path, respecting the passage restrictions referred before, namely the operating mode of the airport, in order to replicate the typical ground movement. Basically, each aircraft will try to incorporate these waypoints:

- On its destination airport: Arrival Threshold – Runway Exit

![Figure 4-1 - RWY03 Departure Sector.](image-url)
In this study, two TFGs were used. For the outbound traffic generator all local stands were used as sources and the single stand on the remote airport as destination. The opposite was done for the inbound traffic generator. In addition, one NSA is created starting at the remote airport and ending at the transition representing the final approach for inbound traffic, and another NSA is created for outbound traffic using the aircraft stands as entries and the departure end of runway transition as the single exit for the sector. The aircraft prototypes used were the Airbus A330-300, Airbus A320-200 and Cessna Citation Mustang 510 for the Heavy, Medium and Light wake turbulence category, respectively.

With the aim of generating typical daily traffic in each simulation, there is also the need to replicate the hourly peaks usually observed. In order to do that, the traffic generation process differentiate periods of time in which the maximum number of aircraft allowed inside the NSAs is greater. Those periods correspond to the previous mentioned: 0800-0900 UTC, 1400-1500 UTC and 2000-2100 UTC. Several values were tested until the movements generated would resemble to the typical daily traffic of LPPT and when it was reasonable to assume the continuous generation of traffic during the traffic peaks (to test both Ultimate and Practical Capacity). After testing all combinations possible with range of values from 1-10 for each variable, the best values found to reproduce the typical high demand traffic were 3 for 0800-0900 UTC, 2 for 1400-1500 UTC, and 1 for the rest of the day.

4.1.4 Stand allocation

In the particular case of this document, the integrated stand allocation module was not used and the stand allocation complex rules were replaced by a much simpler method of entering different probabilities of using a specific aircraft stand as source/destination for the flight generated by the TFG. This was due to three main reasons:

- The main focus of the study is the airport’s runway system. As long as there is a constant traffic to and from the stands, the aircraft routing on the rest of the manoeuvring area, just need to have reasonable taxiing times (with small deviations from what are considered the typical times for the airport, i.e. the default times).
- The routing of the aircraft generated by TFG, will not consider any flight property related guideline restrictions, since the aircraft’s movement is not related to a flight, but only to a simple origin-destination relation. This means that, by using TFG, the stand allocation is much less complex and it is usually replaced by adjustments in aircraft stand usage probabilities.
- For safety reasons, the access to official data on typical aircraft stand allocation (from previous flight schedules) was denied by the airport’s company (ANA).

The solution was to get basic information and take notes on the current aircraft stand allocation rules and get reasonable values for the probabilities of using a specific aircraft stand as source/destination for the flight. After some discussion with the airport’s experts, it was found that for the particular case of this study, it was also interesting to study as much origin/destination stand allocation combinations as possible in order to test the model in several different potential cases. In practice, the solution was to assign the same probability of using any of the 82 stands, i.e. the stand allocation is a random process in each different run.

4.2 Data Logging

Within CAST, there is no central logging module. Every object, which is capable of logging data, is responsible for
logging the data it has access to. Besides, logging within CAST is essentially event-based. This means that retrieving current data out of the scene object and storing it for further analysis is performed every time a certain event (a so-called “log event”) occurs. The actual and detailed analysis of the simulation results takes place subsequent to the actual simulation run and will be processed via the “Log Analyser”. This tool provides comprehensive evaluation templates, i.e. predefined calculation algorithms, usable to generate customizable tables and diagrams, considering CAST specific object properties.

The objects used to directly aggregate and analyze data were:
- Network Sector Analyser: the sector to analyse is defined by sector transitions, which serve as entries or exits. This way, this object detects all vehicles in the area of interest, their time in the sector as well as their entry and exit. It is used in the RWY system for analysis of specified areas concerning daily RWY throughput using 10 minute steps: o Number of Arrival, departure and total movements; o Number of Movements per aircraft type; o Number of Movements per RWY exit; o ROTs.
- Ground Controller: as referred before, the Ground Controller is the NSA equivalent for the entire infrastructure on the ground.
- Queue Detector: determines the number of aircraft in a queue, the queue length and the queuing times. During the simulation, the Queue Detector also draws a frame around all aircraft it has detected to be in the queue, helping to visualise the main taxiway bottlenecks. Both Ground controller and queue detector are used to calculate:
  o Average dwell times; o TOP 90 percentile analysis; o Maximum dwell times.

The only data that is not retrieved directly from the Log Analyzer is related with the mix of operations observed during the simulations. As logging within CAST is basically event-based, in order to obtain that values, a simple test was performed with the data retrieved from the TFG: using 1-minute step (the smallest possible), the traffic per dispatching center (remote stand for arrivals and local stands for departures) was calculated and every time a difference in the traffic between two time intervals is verified, it is assumed that there was an arrival or departure. This way, with the correspondent sequence, it is possible to make a rough estimate on the proportion of sequences during the simulation. Consequently, the ADA sequence is divided into DA and AD sequences.

5. Case Study

As mentioned before, the average ROTA on RWY 03 is above 50 seconds for all types of aircraft In order to reduce that time, among the ACE report’s recommendations, a change in the layout is recommended: the construction of an additional RET for RWY 03. In fact, the report’s group believe that this would bring significant capacity benefits (RWY 03 is the most used runway - high return on investment) as traffic levels grow and especially now that 3NM radar separation is implemented [67].

As mentioned before, on DD sequence, the two-minute separation parameter is due to the need of providing 5NM for the departing traffic as the initial path is common for all SID’s. In case of being able to create alternate SIDs with the minimum divergence of 45º between the tracks, one could operate departures with one-minute separation. In fact, in ACE’s report there is also a reference to the need for further analysis on different DD separation parameters.

That being said, the baseline scenario of this study is based on the current airport’s layout and will serve to validate the simulation model. The remaining scenarios were based on the ACE report’s recommendations and other prospective cases. Table 5-1 presents the list of scenarios that will be studied and their main characteristics.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Layout</th>
<th>Rules</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPPT_A</td>
<td>AIP</td>
<td>AIP + ACE Report</td>
<td>Reproduce the current situation and model calibration.</td>
</tr>
<tr>
<td>LPPT_B</td>
<td>AIP + New RWY03 Exit</td>
<td>AIP + ACE Report</td>
<td>Analyze eventual benefits of the new exit.</td>
</tr>
<tr>
<td>LPPT_C</td>
<td>AIP</td>
<td>AIP + ACE Report with new departure/departure separations</td>
<td>Evaluate the impact of the introduction of new SIDs.</td>
</tr>
<tr>
<td>LPPT_D</td>
<td>AIP + New RWY03 Exit</td>
<td>AIP + ACE Report with new departure/departure separations</td>
<td>Calculate the impact of a combination of LPPT_B and LPPT_C scenarios.</td>
</tr>
</tbody>
</table>

5.1 Results and Discussion

The reproduction and calibration of the reference scenario resulted in realistic simulations with consistent performance data compared to the historical data. The visualization of the aircraft movements and interaction during the simulations also contributed to confirm the reliability of the model:
- Correct pushback and parking maneuvering;
- No excessive vehicle interaction or congestion problems were verified;
- The airport’s operating mode was plainly respected;
- Realistic ROTs (Table );
- Realistic taxi-in and taxi-out times (Table 5-3);
- Reasonable departure queue delay and lengths.

In what concerns ROTS, the results for the baseline scenario were satisfactory will small deviations from the historical values. The results for ROTAs are close to the observed in ACE’s report for HN and RWY 17 exits: 2 seconds difference in both cases. S1 exit ROTA is equal to the observed in the exercise. In the case of U5 the 62 seconds result was found
suitable according to the typical values. The ROTD corresponds to the interval between the line-up position and the end of the runway, i.e. it is the sum of the ATC take-off clearance time (TOCD), the flight crew reaction to line-up clearance (FRLC) and the take-off roll time (TOFT), assuming, in this case, that both TOCD and FRLC are included in the TOFT. There is a difference of 3.2 seconds between the model’s ROTD and the observed 49.8 seconds (4.1 + 14.3 + 31.4) total departure time after the aircraft has been lined up. Considering the exits usage distribution and the ROTAs obtained for each exit, the average ROTA for this reference scenario is 54.3 seconds, which is very close to the historical value of 54.1 seconds.

In terms of airside operations durations and delay, the values presented in Table correspond to the complete ground maneuvering, i.e. for the outbound traffic the departure delay in queue and the delay during pushback are included in those values, for example. The ROTs are also included in the taxing durations for both directions. The average durations found with the fast-time simulations were slightly below the historical values. Two reasons may be responsible for these differences:

- **Speeds:** In the simulations, only maximum fixed ground speeds for aircraft could be used because the simulation did not allow momentary speed changes. This could be done, for example, as in real world situations, depending on the current traffic congestion. In practice, controllers can influence the speeds of aircraft with specific commands for each flight, such as to expedite taxi or slow down. In addition, in the real world, the aircraft are subjected to variations in their accelerations/velocities, which means that, in most cases, the aircraft will not follow its path as quick as the airport taxiway layout and the aircraft characteristics would allow.

- **Path-related factors:** In the simulations, aircraft preferred using the path with the shortest distance to reach the waiting point at the beginning of the runway, providing that the standard ground movement paths for the operating mode of the airport were followed. This could lead to routes of aircraft intersecting, or, contrariwise, as it turned out to be the case of this document, to too optimistic cases where no aircraft path intersects the path of another, i.e. the delay caused by the airport is insignificant. That is the case of inbound traffic (Table ). In that sense, these simulations neglect the human factors inherent to the ATC path planning. In addition, there are also factors related to other vehicles movements and interaction that were also not included in the simulations model. In fact, the only significant delay observed in the airport movement was detected in the outbound traffic, where the main reason for the delay had to do with the vehicle interaction during pushback. Besides that, the delay observed for the outbound is mainly caused by the queue created at the holding positions for departure, as explained next.

### Table 5-2 - Simulations RWY3 ROTs per exit

<table>
<thead>
<tr>
<th>Exit</th>
<th>RWY 03</th>
<th>RWY 17</th>
<th>Departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROT(secs)</td>
<td>HG</td>
<td>S1</td>
<td>U5</td>
</tr>
</tbody>
</table>

In respect to the departure queue data, the maximum number of aircraft in a departure queue during the traffic peaks was 6, which is equal to the historical maximum number during those hours. According to the airport experts, both average and top 90th percentile departure delay values are realistic and, in fact, could increase without any operational efficiency concerns. However, these values do not give provide much information on the departure delay for the hourly traffic peaks, which is the focus of this study. In fact, regarding the maximum departure delay matching the traffic peaks hours, the results obtained were also influenced by the fact that, during the simulations, the aircraft would follow the paths assigned in the moment of the flight creation, i.e. before they leave the source stand, with predefined speeds. On the other hand, in the real world, depending on several factors, such as the number of aircraft approaching the airport, the controllers would adapt the ground speed and the path to the departure holding position accordingly.

In the fast-time simulations it was not possible to intervene in the paths assignment and aircraft speed on the ground, neither on the approach aircraft sequence, enabling the reduction of the waiting times in the departure queue, and, therefore, maximum values for the departure delay may not be considered realistic. However, since the method used did not change between alternatives, the three values for the departure delay were considered reasonable for scenario comparison.

### Table 5-3 - Ground movements duration and delay per direction for LPPT_A with 40 replications sample

<table>
<thead>
<tr>
<th>Direction of Traffic</th>
<th>Duration (mins)</th>
<th>Delay (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Top 90th Percentile</td>
</tr>
<tr>
<td>Inbound</td>
<td>3.9</td>
<td>4.12</td>
</tr>
<tr>
<td>Outbound</td>
<td>9.3</td>
<td>13.67</td>
</tr>
</tbody>
</table>

In the fast-time simulations it was not possible to intervene in the paths assignment and aircraft speed on the ground, neither on the approach aircraft sequence, enabling the reduction of the waiting times in the departure queue, and, therefore, maximum values for the departure delay may not be considered realistic. However, since the method used did not change between alternatives, the three values for the departure delay were considered reasonable for scenario comparison.

![Figure 5-1 - LPPT_A average daily movements and departure delay (hh:mm:ss) - 40 replications sample, 10-minutes steps.](image-url)
In terms of scenario comparison, although there is an improvement of 1 movement in the traffic peak hours and almost a 4 movements increase in the daily average traffic, a direct conclusion can be drawn when comparing the outputs resulting from the introduction of the new RWY exit (LPPT_A to LPPT_B); with the model used and with the methodology followed, the reduction in the ROTAs did not have the impact that was expected in terms of RWY maximum capacity, and consequently on the airport daily capacity (Table 5-4). In fact, despite there is almost a 4-minute reduction of the maximum departure delay in queue and on the maximum queue length and a reduction in the ground movement duration for the inbound traffic, due to the aircraft stand proximity to the new exit, the 9 seconds reduction in the average ROTA, which corresponds to a reduction of about 17% from the previous value, did not result in significant capacity enhancement, neither in departure delay improvement, suggesting that the delay is mainly caused by the separations between takeoffs and landings and not because of the RWY occupancy times.

As referred before three factors can influence the RWY capacity when analyzing AD sequences: ROTA, ROTD and the time needed to guarantee the minimum separation between an aircraft starting the takeoff roll and an approaching flight. Since ROTD did not change between the scenarios, and since the mix of operations did not change significantly from LPPT_A to LPPT_B, one can define the last factor as the major capacity factor for this type of sequence. This means that a reduction in the minimum upstream distance from the arrival threshold required for a new departure flight to enter in the runway (4.2NM in this document), is mandatory in order to obtain better results in this types of sequences.

In AD sequences, the time needed to ensure correct separation has also to take into account the departure/departure appropriate separation, i.e. the DD separation needs to be respected first in order to consider the aircraft entrance on the RWY and the AD separation. Therefore, studying the introduction of less restrictive departure separations becomes more relevant for AD sequence, in which, with the traffic generation method used, the departure waiting time turned out to be mostly due to the need of providing the 2-minute separation between departure aircraft, instead of the time needed for RWY vacancy. In fact, the study of LPPT_C is of great importance not only for AD but also for DD sequences, which means that it could, according to the mix of operations obtained from the simulations, potentially benefit the RWY capacity in more than 65% of the total operations. The 1-minute reduction of the departure/departure separation studied in LPPT_C, which corresponds to a 50% reduction compared to the time separation used in baseline scenario, resulted in more significant consequences on the capacity and delay for departures. In terms of delay, the results are significantly improved compared to the previous scenarios.

In fact, as presented in Table 5-4, the maximum and top 90th analysis revealed a reduction in the daily average departure delay of around 30% compared to the reference scenario, proving that, most of the times, the aircraft queuing in the departure holding position need to wait, not only to allow the RWY vacancy, but mainly to respect the time-separation to the last departure aircraft. RWY throughput was also significantly improved. The RWY maximum number of movements increased from 40 to 48, which is an important result since it matches the maximum RWY throughput value predicted by EUROCONTROL in their recent study for the airport’s capacity enhancement, while considering new departure-departure separations [4].

![Figure 5-2 - LPPT_B average daily movements and departure delay (hh:mm:ss) - 30 replications sample, 10-minutes steps.](image)

![Figure 5-3 - LPPT_C average daily movements and departure delay (hh:mm:ss) - 40 replications sample, 10-minutes steps.](image)
When considering the combination of the two alternatives (LPPT_B and LPPT_C), there are improvements in all outputs, comparing to the reference scenario. Considering LPPT_D the “final design” or the “best alternative” scenario, it was proved, through the simulations, that it is possible to substantial improve the RWY maximum hourly capacity (+8 movements) and also the daily average movements (+36 movements), maintaining the operational efficiency of the airport regarding the departure delay and taxi times, while considering random flight schedules and stand allocation. On the other hand, and as expected, the improvements are not as significant as the previous scenario, comparing both with the reference case, for the same reasons mentioned for LPPT_B.

![Figure 5-4 - LPPT_D average daily movements and departure delay - 30 replications sample, 10-minutes steps.](image)

Table 5-4 - Departure queue data comparison.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average (mins)</th>
<th>% Change</th>
<th>Top 90th (mins)</th>
<th>% Change</th>
<th>Maximum (mins)</th>
<th>% Change</th>
<th>Maximum</th>
<th>% Change</th>
<th>Average</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPPT_A</td>
<td>1.40</td>
<td></td>
<td>4.43</td>
<td></td>
<td>18.65</td>
<td></td>
<td>6</td>
<td>1.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPPT_B</td>
<td>1.37</td>
<td>-2.4</td>
<td>4.40</td>
<td>-0.8</td>
<td>14.72</td>
<td>-21.1</td>
<td>6</td>
<td>0.0</td>
<td>1.08</td>
<td>-1.3</td>
</tr>
<tr>
<td>LPPT_C</td>
<td>0.98</td>
<td>-30</td>
<td>3.18</td>
<td>-28.2</td>
<td>12.27</td>
<td>-34.2</td>
<td>5</td>
<td>-16.7</td>
<td>0.94</td>
<td>-14.5</td>
</tr>
<tr>
<td>LPPT_D</td>
<td>0.97</td>
<td>-31</td>
<td>3.00</td>
<td>-32.2</td>
<td>12.52</td>
<td>-33</td>
<td>5</td>
<td>-16.7</td>
<td>0.93</td>
<td>-15.4</td>
</tr>
</tbody>
</table>

6. Conclusions

Regarding EUROCONTROL’s “Humberto Delgado + Montijo” solution for the urgent Lisbon’s airport capacity issues and since it is the local air navigation expert’s belief that, in order to increase the airport’s capacity, it is imperative to reduce the waiting time for arrivals and departures by reducing the runway occupancy times and implementing less restrictive departure air space separations, these document focused on the maneuvering area and on the departure procedures.

Firstly, airport capacity concepts were studied. Since Lisbon’s airport is having capacity issues mainly on the major traffic hours, Ultimate Capacity concept was found to be the most suitable for these purposes. This way, by entering a continuous demand for both arrivals and departures flights, it was possible to study the extreme hypothetic situation where there is always an aircraft waiting to land or to take off. Since the main focus was on the airport’s maneuvering area and on the departure operations, the departure delay (on ground) was another major data analysis.

Secondly, the major capacity enhancement approaches were analyzed. Most of the literature reviewed stated that the major approaches are restricted to two major groups, coinciding with the approaches initially suggested by the local air navigation experts for Humberto Delgado: minimization of aircraft separations and runway occupancy times. With the lack of available area for construction around the airport, at first, a previous EUROCONTROL recommendation was studied: study of a new RET to RWY 03. Then, with the separations between aircraft in mind and, with some expertise advise, another solution was studied: reducing the departure-departure time separation by half, as in ICAO’s regulations.

In order to study the alternatives, the different airport modelling approaches were reviewed. This study helped to evidence the viability of using fast-time simulations in airport capacity analysis with reliable results. A network model for the airport was created and, this way, it was possible to visualize the aircraft movements after introducing the modifications in the airport, which helped in the tradeoff analysis between capacity improvements and ground operations trustworthiness. The software chosen was also suitable for this type of research. CAST was the right choice since it provided a user-friendly interface and efficient tools which facilitated not only the airport models creation but also the output analysis.

The technical approach followed was adequate. Based on the available data with the adaptation of some inputs, the model was correctly structured and configured. The traffic generation method and the stand allocation resulted in typical airport operations during low and high demand hours. In fact, the baseline scenario was properly calibrated regarding the declared capacity of the airport the typical taxi times and the delay data.

The results obtained with the simulations were consistent and, after comparing the scenarios, it can be concluded that the airport’s capacity could be increased with the introduction of
the new runway exit and, most important, with the introduction of less restrictive aircraft separation in the airport’s terminal maneuvering area for departures in RWY 03. The introduction of the new exit resulted in a statistical significant increase of 1 hourly movement during the traffic peaks and in an increase of 4 movements in the daily mean. Better results were obtained with the 1-minute reduction in the departure time separations: an increase of 7 movements during the traffic peaks and 33 movements increase of the daily traffic. As expected, the best results were obtained with the combination of the other two alternatives: increase of 7 movements during the peak hours and 36 daily movements. In the three alternative scenarios the mean results for the time spent by the aircraft in queue and the queue length were reduced proving also the benefits in terms of ground movement bottlenecks.

In this document, as inherent to the process of modelling, some simplifications were done. Despite this, the adaptations were only applied to the model providing that those would not affect it directly in terms of respecting the real world regulations and deviating from typical operational procedures of the airport. Nevertheless, there is room for further research:

• In the future, inputting different ground dynamics per aircraft type and per replication may result in interesting conclusions that could then be compared to the three aircraft categorization used in this document. This could be done, for example, by means of distributions in the inputs, or by entering more types of aircraft with different acceleration profiles and air/ground behavior.

• In this document, the airspace segments serve as entrance or exit to the model, with the restrictions applied to airspace movements being the separation between aircraft according to their type and to whether there are departure aircraft waiting in a queue or not. In the future, as the runway capacity is directly affected by the airport terminal airspace, one development could be the introduction of more complex airspace models. In addition to the inherent simplification of the airspace surrounding the airport’s model, alongside one of the alternatives of this study, there is also the need to study what would have to be the new airspace configurations in order to achieve the requirements for less restrictive departure separations. In order to do that, another airspace specific software, such as RAMS, could be used, since the core focus of CAST is on the airport airside and terminal topics.

• The method for the generation of traffic and the stand allocation rules were modified due mainly to the need of assessing the capacity of the runway in as many scenarios as possible. Despite the satisfactory results, testing the model with real flight schedules is something to consider in the future.

• Although the runway system capacity is usually recognized as the major airport capacity limiting factor, other infrastructure elements should not be neglected a priori. In the particular case of the taxiway system, despite some local constraints due to taxiway locations or configurations, especially in the areas of taxiway intersections, the taxiway system it is most often designed to provide capacity which exceeds the capacity of the runway system and should not be analyzed as the factor limiting its capacity [12]. However, the development of the Lisbon’s airport taxiway system is something to consider in the future and a similar study, with a similar fast-time simulation software, could be used for that purpose.

REFERENCES