Integrated Multimodal Airport Operations for Efficient Passenger Flow Management – Two Case studies

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***Abstract* — Predictive models and decision support tools allow information sharing, common situational awareness and real-time collaborative decision-making between airports and ground transport stakeholders. To support this general goal, IMHOTEP has developed a set of models able to anticipate the evolution of an airport's passenger flows within the day of operations. This is to assess the operational impact of different management measures on the airport processes and the ground transport system. Two models covering the passenger flows inside the terminal and of passengers accessing and egressing the airport have been integrated to provide a holistic view of the passenger journey from door-to-gate and vice versa.**

This paper describes IMHOTEP's application at two case study airports, Palma de Mallorca (PMI) and London City (LCY), at Proof of Concept (PoC-level) assessing impact and service improvements for passengers, airport operators and other key stakeholders.For the first time one measurable process is created to open up opportunities for better communication across all associated stakeholders. Ultimately the successful implementation will lead to a reduction of the carbon footprint of the passenger journey by better use of existing facilities and surface transport services, and the delay or omission of additional airport facility capacities.

Keywords -Airport-CDM; multimodality; passenger journey; real-time decision-making; disruption management

I. Introduction

In its vision for Europe in 2050, the European Commission (EC) establishes the goal that "90% of travelers within Europe are able to complete their journey door-to-door within 4 hours" [1]. Aligned to this vision, the EC depicts a passenger-centric system that takes travelers from their origin to their destination in a seamless, efficient, predictable, environmentally-friendly and resilient manner [2]. Achieving this vision calls for enhanced modal integration not only in terms of physical infrastructure, but also of business models, operational processes and information systems. Airport Collaborative Decision-Making (A-CDM) [4, 5, 6] is intended to enhance the efficiency of airport operations due to information sharing and common situational awareness of all airports stakeholders. The extension of the A-CDM process to the ground transport system, as presented in this paper, has been suggested as an enabler for improved intermodal integration.

II. Objectives

1. Propose a concept of operations (ConOps) for the extension of A-CDM to ground transport stakeholders.
2. Develop new data collection, analysis and fusion methods able to provide a comprehensive view of the door-to-gate passenger journey in both directions.
3. Develop predictive models and decision support tools able to anticipate the evolution of an airport's passenger flow at the day of operation, and assess the operational impact on both airport processes and the ground transportion system.
4. Validate the ConOps and the newly developed methods and tools through a set of case studies conducted in collaboration with airports, local transport authorities and transport operators.

Concept of Operations

The IMHOTEP ConOps is aiming to include surface transport stakeholders, local transport authorities, traffic agencies, transport operators and mobility service providers in the A-CDM. It represents a transition from a flight-centric to a passenger-centric approach using the concept of a Passenger Airport Travel Diary (ATD). As such, the ConOps establishes the A-CDM_extended system comprising five functions that define where the data is collected from, and how it is used in simulation models to create and update the ATD (see Figure 1).

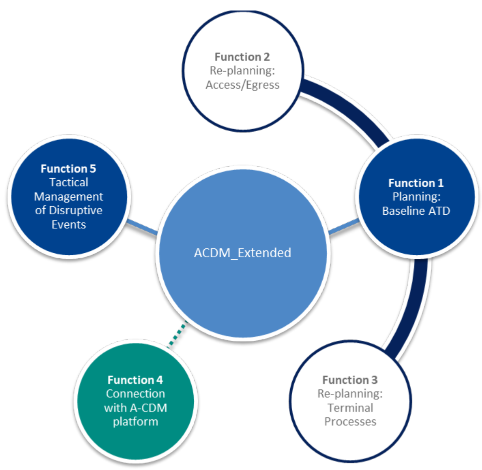

Figure 1: Schematic representation of the A-CDM-_eExtended functions.

Function #1 creates a baseline ATD based on forecasted information. As such, it provides an initial picture of the flows of departing, connecting and arriving passengers at one particular airport prior to the day of operations, which is then continuously updated as more information becomes available during the day of operations, so that the latest update is always available from the A-CDM_extended system. This would allow different stakeholders (e.g., ground transport operators, airport operators, airlines, ground handlers) to allocate their resources more efficiently.

Function #2 updates the access/egress model with real-time data on the actual state of transport networks and services. In the case of passengers accessing the airport, the updates on the passenger arrival to the airport will trigger Function #3 in order to update the section of the Passenger ATD that concerns the terminal processes. In the case of arriving passengers, the information regarding the passengers egressing from the airport will be used as an input for Function #2 to forecast the passengers' egress leg accordingly. Updates use real-time data collected during the day of operations.

One of the premises of the A-CDM_extended concept is that it should be implemented in both CDM and non-CDM airports alike. Therefore, instead of envisioning this new platform as an extension of the current Airport CDM Information Sharing Platform (ACISP), it has been defined as an independent platform supporting Multimodal Collaborative Decision Making which can be used by any airport without the need of having an ACISP previously implemented. Nevertheless, for A-CDM-enabled airports, Function #4 connects the ACISP with the A-CDM_extended concept so that both platforms can exchange information.

Finally, Function #5 is defined for the tactical management of disruptive events by triggering alarms when a deviation from normal operations is identified, further described in IIC. The objective of this function is to support the collaborative management of disruptions that could appear during the day of operations. The disruption management process will be initiated through Function #5. The deviation is assessed through the KPIs that have been defined in the development of the case studies, and the management process is triggered by stakeholders made aware by the decision support tool that visualises the KPIs in real time.

Definition of case studies

Two case studies, airports with heterogeneous characteristics, were defined in order to demonstrate the maturity of the IMHOTEP tools and concepts, evaluate their benefits and assess the appropriateness of the transition to SESAR Industrial Research.

London City (LCY) is an urban airport, initially focused on business travel but with leisure travel gaining increased attention offers a wealth of airport surface transport options. In contrast, Palma de Mallorca (PMI) has a substantial majority of leisure traffic, with high seasonality, and surface access is restricted to the main motorway connecting to the city of Palma and the rest of the island of Mallorca by public transport buses (EMT operated), airport transfer (tour operators), taxi or ride-hailing and car hire or private car/vehicle.

The two case studies aim to shed light on how information sharing and real-time coordinated decision-making between air transport and ground transport modes can benefit airports with very different characteristics and operational challenges.

a) *Main characteristics of PMI*

- Main gateway to the Balearic Islands and the third largest airport in Spain (just behind Madrid-Barajas and Barcelona-El Prat) with almost 30 MAP in 2019.
- The majority of the passengers travel for leisure purposes, leading to traffic peaks in the holiday season and much lower traffic during the rest of the year.
- PMI is a CDM airport.
- Current surface airport access alternatives are only by road, (bus and car).

b) *Main characteristics of LCY*

- LCY is located next to the financial district, attracting a larger proportion of business travel.
- The majority of passengers use public transport, crucial contribution of the airport surface access to CO_2 neutrality
- LCY's customer proposition "20 minutes from check in to departure lounge, 15 minutes from plane to forecourt, and rapid transport links to Central London".
- LCY is not a CDM airport but it uses the RATT system to aid performance management of turnarounds. Ground handling agents use remote/mobile devices to capture turnaround milestones of the aircraft.
- Due to its inner-city location, most surface access transport systems operate independently from the airport, potential congestions/disruption of the passenger journeys to and from the airport are unrelated to the operation of the airport.

Surface access/egress alternatives include the Docklands Light Railway (DLR), London Underground connecting to long-distance rail and high-speed train, two bus lines, Riverboat and Cable car.

III. Methodology

A. *Airport terminal process simulation*

It is current industry standard that individual parts of the passenger journey are assessed separately (check-in, security, immigration, boarding etc.) using different methods commonly based on the IATA Airport Design Reference Manual (ADRM) as KPI, and at some airports supported by the application of sensor-based technology (e.g., XOVIS people counting sensors). IMHOTEP seeks to predict , delays and disruptions throughout the entire passenger journey including airport access and egress. CAST software (ARC, 2022) was chosen to simulate the passenger flow through the passenger terminals.

B. *Airport access and egress simulations*

Whilst the modelling of airport processes is based on real passenger air tickets, surface transport has to consider passengers sharing vehicles with a wider travelling community. Not only that, but even the same vehicle type has different behaviours (boarding site, travel time, etc). Furthermore, whilst aircraft depart and arrive at the airport with a batch of passengers at the same time, those same passengers will access/egress the airport with a variety of modal and temporal characteristics.

Aimsun Next (a traffic simulation software tool) was used to simulate airport access and egress to replicate different vehicle types in the transport networks of each airport's catchment area. Data collection included trip demand data, network geography, traffic control features, public transport operational characteristics and network performance. Once created, the models were calibrated using actual traffic counts but also with information extracted from the innovative use of of airport users ATD's. These were created from existing flight schedules, public transport schedules, passenger surveys and passenger terminal presentation characteristics (from boarding card reader data at security). In addition, the novel use of anonymised mobile telephone data gave antenna use locations and sociodemographic data for a sample of passengers using the airports.

C. *Refinement of case study definition*

The demonstration and evaluation process includes three steps:
Revision and refinement: Develop an iterative and participative approach to integrate the relevant stakeholders to define specifications of the most relevant simulation scenarios, in response to the characteristics of each airport, along with the management actions that can be implemented and the KPIs to measure the effectiveness of the actions intended to mitigate the effects of the disruptions. A detailed specification of three simulation scenarios was validated with the modelling partners.

Execution of simulation scenarios: Implement the access/egress and terminal simulation models to validate their predictive capabilities and provide outcomes for the next step.

Impact assessment: Evaluate the performance impact of the proposed concepts, management actions and tools by comparing and contrasting the results of the KPIs derived from the simulation experiments.

The initial conceptualisation to define potential use cases to build scenarios consider the occurrence of disruptions that alter the normal course of operations. This is intended to be generic and applicable to any airport. The boundary of the surface access and egress models, and the terminal processes models define the realm in which the use cases are defined (see Figure 2): *Air-realm* refers to events affecting flights or airport terminal processes; while *ground-realm* refers to events affecting surface transport systems or passengers before they arrive at the airport forecourt or after they leave the airport premises upon arrival.

Figure 2: Definition of the "air-realm" and "ground-realm" where events affecting air or surface transport operations can happen.

Given the differences in the specific characteristics of airports, including their integration with surface transport networks, four generic events or combinations of events have been defined to be modelled as use cases (see below). These generic definitions can be adapted to specific airport contexts by defining narratives that summarise concrete events and their implications for airport and surface related stakeholders:

- airport exit delay
- airport departure delay
- airport arrival delay
- airport early arrival

Air-realm

Airport exit delay

Airport exit delay refers to arriving passengers experiencing longer than expected travel times due to events happening before they step out of the airport terminal's landside.

Airport departure delay

An *airport departure delay* refers to departing passengers experiencing longer than expected travel times due to events happening within the airport terminal before they board the departing aircraft. The reason for the delay is associated to stakeholders in the air-realm and the main consequence, without any action taken, will be an increase in the number of passengers in the terminal space with a subsequent disruption to capacity and resource allocation. If passengers are aware of these delays, they could delay their journey to the airport, posing challenges to surface transport potentially changing the expected pattern of use of transport infrastructure and services.

Ground-realm

Airport arrival delay

An *airport arrival delay* (also to be considered as a *city exit delay*) refers to departing passengers experiencing longer travel times due to events happening before they reach the airport terminal. This can also impact staff commuting to the airport with a knock-on effect for the passenger operation.

Airport early arrival

Departing passengers arriving too early at the terminal can be disruptive for an airport. They have luggage to check in and tend to linger around the departure concourse where retail or entertainment options may be limited, and where they could strain limited resources or capacity of the airport terminal.

Airports where traffic is heavily driven by seasonal inbound tourism (PMI) can be inconvenienced with large groups brought in early by tour operators. Airports with a comparatively small terminal footprint (LCY), may suffer congestion from passengers arriving well in advance of their flights.

Major weather event (delay of arriving flights, also called Airport exit delay from the arriving passenger perspective)
A major weather event delays a substantial proportion of arriving flights for a significant amount of time. For instance, a storm may significantly reduce the capacity of the airport under consideration because separation at approach or runway use times are higher than usual, or wind conditions induce aborted landings. As a result, a substantial proportion of passengers is expected to be in the terminal later than originally planned, disrupting capacity and staff allocation plans, especially if a large number of flights are cleared to land once the weather event has subsided. The delay may impact surface transport stakeholders and passengers in two main ways: for passengers, public transport alternatives (or rental car facilities) may not be available once they actually make their way through airport arrivals; for public transport operators, services that were originally planned to run with a particular occupancy may run emptier, whereas later services, if available, may be running at capacity or may not provide enough capacity for the accumulated number of passengers; for taxi or ride hailing operators there may also be a change in the expected loads.

D. *Validation simulation scenarios*

Three scenarios were considered as the most relevant for the two case studies, selected by the two case study airports PMI and LCY as the most impactful disruptive events:

1. Delay of arriving flights
2. Delay of departing flights (Tour operator at PMI was seen as a special case of the same scenario)
3. Road disruption (Public transport disruption was considered as a special case of the same scenario)
4. The following subsections summarise the specific definition of the validated simulation scenarios in terms of the parameters to be used in the models for each case study, based on historical data both airports have provided.

1) *Delay of arrivals*

TABLE 1. SIMULATION PARAMETERS FOR "DELAY OF ARRIVALS'.

Parameter	PMI	LCY
Time of disruption Period to which the delays are to be applied (out of the base model day)	04:00 to 08:00 (UTC) 06:00 to 10:00 (Local)	15:30 - 17:30 (Local) Arriving flights delays coinciding with the departure peak hour (16:00 - 17:00) is critical due to limited stand capacity
Share of delayed flights Percentage of flights arriving during the time of disruption that are delayed Random selection of the flights that are delayed	20% of Schengen 25% of non-Schengen	20% of all arriving flights The model does not consider stand allocation explicitly, so this is an estimate of a disruption that would put a strain on stand capacity
Delay duration A delayed flight is delayed a random duration following a triangular distribution	Mean = 40 min Minimum = 20 min Maximum = 60 min	Mean = 40 min Minimum = 20 min Maximum = 60 min

Although the simulation models only consider delayed flights for this scenario, both airports have highlighted how early arrivals could also be problematic (that is, flights arriving earlier than expected, as opposed to passengers arriving too early to the airport as discussed above). However, it is a relatively minor disruption that does not seem to extend to surface egress. This is mostly because scheduled block times do not differ substantially from actual block times, thus there is a natural limit to how early an early arriving flight can get to the airport.

2) *Delay of departures*

Most relevant delays of departures at LCY have been recorded in the afternoon (see

Figure 3 for an example).


DEPARTURES
2 of 2
London City Airport
Airline
Destination
Time
Flight
Gate
Status
DUSSELDORF 15:25 BA3275 Delayed 17:00
AMSTERDAM 15:30 BA8455 Delayed 16:00
DUBLIN 15:30 AF3138 Gate Shown 30min...
EDINBURGH 15:40 AB5224 Delayed 16:10
BELFAST 15:40 BE1356 Gate Shown 30min...
ZURICH 15:50 AB5099 ...before Departure
MADRID 15:55 IB7465 Gate Shown 30min...
LUXEMBOURG 15:55 LG4596 ...before Departure
GLASGOW 16:05 AB5182 Gate Shown 30min...
14:23

Figure 3: Departures Delay at London City Airport (photo Henrik Rothe, taken 1st February 2017)

TABLE 2. SIMULATION PARAMETERS FOR "DELAY OF DEPARTURES".

Parameter	PMI	LCY
Time of disruption Period to which the delays are to be applied (out of the base model day)	04:00 to 06:00 (UTC) 06:00 to 08:00 (Local)	16:00 - 18:00 (Local)
Share of delayed flights Percentage of flights departing during the time of disruption that are delayed Random selection of the flights that are delayed	30% of Schengen 30% of non-Schengen	80% of all departing flights
Delay duration A delayed flight is delayed a random duration following a triangular distribution	Mean = 90 min Minimum = 30 min Maximum = 150 min	Mean = 60 min Minimum = 30 min Maximum = 90 min

3) *Disruption in surface access transport*

Given the different nature of access mode alternatives in both case studies, this scenario implies a different specific disruption in each airport. For PMI, it affects the main motorway in the direction towards the airport, for LCY only a disruption to the London Underground, with potential knock-on effects on DLR services is considered.

TABLE 3. SIMULATION PARAMETERS FOR "DISRUPTION IN SURFACE ACCESS TRANSPORTATION" AT PALMA DE MALLORCA AIRPORT.

Parameter	Value for PMI	Notes
Location of the disruption	Closure (and then partial closure) of the Ma-19 motorway eastbound carriageway (city to airport direction) between junctions 6 and 7a	Implemented in the surface access model
Time of disruption	05:00 to 06:00 (UTC) 07:00 to 08:00 (Local)	Full closure for half an hour, reopen one lane for another half hour before fully opening.
Travel time	As determined by the model (Travel times are affected by re-routing and congestion)	Passengers affected may miss their flights and this is measured in the terminal model

TABLE 4. SIMULATION POARAMETERS "DISRUPTION IN SURFACE ACCESS TRANSPORTATION" AT LONDON CITY AIRPOPRT.

Parameter	Value for LCY	Notes
Location of the disruption	4 Trains in a row carry 50% of the expected passengers The following 4 trains carry 50% more passengers than expected Arrival pattern covers about half an hour	DLR pattern of arrivals changes due to a planned disruption in the TfL network (i.e., a strike). This pattern of arrivals is implemented where DLR passengers are held before entering the terminal
Time of disruption	15:00 - 17:00 (Local)	To coincide with the time passengers of the afternoon departing peak flights should be coming to the airport
Airport surface access Modal share	-10% fewer passengers on DLR +10% additional passengers to assign to other models	The airport does not notice substantial change in modal choice during disruption, this may differ depending on the type of passenger (i.e., locals vs. tourists)

E. Management action plan

Management actions for those three scenarios were discussed following the triggering questions and aligned with KPIs. Not all management actions would lead to different simulation models as some may be implemented in the current decision rules of the models. Whereas other management actions can be considered in combination to define "action plans" to create simulations to be compared with the baseline simulation for each scenario. The baseline corresponds to the simulation considering the definition of the associated disruption, but with no management action plan implemented.

TABLE 5 summarises the parameters to be implemented in the simulation models to emulate real-time decision making by the relevant stakeholders highlighted in each case.

TABLE 5. SIMULATION PARAMETERS FOR MANAGEMENT ACTION PLAN.

Delay of arrivals	Delay of Departure	Disrupted surface access
Open more manual passport control lanes (if possible, i.e., if not all are open already) avoiding congestions	Delay departure time of surface access leg	Open Hartmann Road access to the East for taxis only (LCY only)
Change frequency of public transport (PMI only)	Change transport mode for surface access leg	Anticipate departure time of surface access leg
Open Hartmann Road access to the East for taxis only (LCY only)	Change frequency of public transport (PMI only)	Delayed passengers can "fast-track" security (i.e., skip the queue)
	Delayed passengers can "fast-track" security (i.e., skip the queue)	Delay flight

F. Visualisation tool

A visualisation tool is implemented as a web-based platform accessing a results database that emulates real-time information. The results are presented using interactive graphs based on visualisation and data analytics provided within the Plotly.js Java Script and Plotly.py Python implementation. The first version of the platform is intended to be used by decision makers within the air-realm and the ground-realm. Future work is expected to introduce the possibility of passenger interaction, both as consumers and generators of real-time data and decision making.

At least two KPIs are to be visible at the same time: one for a "current status" view and another for a "trend" view. Likewise, a fixed message could be included to signal the time stamp for the KPIs that depict a "current status" view and, potentially, to introduce "alarm" messages when the KPIs show a substantial deviation from previous trends. Nevertheless, given time constraints in the project, these recommendations remain potential future work to be addressed after its completion.

The current version of the visualisation tool presents the three simulation scenarios independently by choosing from the "scenario" drop-down menu. For each scenario, there are two dashboards representing the two main sets of KPIs for both models. These are referred to as "views" and include "Access/Egress" and "Terminal" options in the corresponding drop-down menu. In each view under every scenario, the visualisations for the KPIs represent the results obtained in the "Baseline" implementation, which refers to the results of the simulation considering the disruptions defined in each of the three scenarios; next to the "Management plan" implementation, which refers to the results of the simulation considering the mitigating actions once the disruptions defined in each scenario have occurred.

IV. ASSESSMENT OF THE SIMULATION SCENARIOS

The three simulation scenarios presented in III.G were run to emulate real-time decision making by the relevant stakeholders. The assessment of each scenario, therefore, consists of a comparison of the results of the baseline situation, where the disruption occurs and no actions are taken, with the results of the implementation of a management action plan as the disruption unfolds. The underlying assumption is that the management action plan is enabled by the existence of tools that provide situational awareness of aspects that were not previously considered in the context of airport and air traffic management collaborative decision making. IMHOTEP considers passengers to play a crucial role in this process if timely information is made available.

The assessment also engages with the complexity of the modelling process of the journey to and from the airport and the passenger process in the terminal whereby events can be gradually increased and therefore trigger additional impact (e.g., a delay of additional 30 minutes offers the passenger as user and the airport operator a different choice of action, which will influence the impact of the IMHOTEP tool). Once the tool has been established passengers and airport operators will consciously include into their day-to-day routine and accelerate the positive impact or mitigate the negative effects.

A. Delay of arrivals

TABLE 6. SYNTHETIC DESCRIPTION OF THE "DELAY OF ARRIVING FLIGHTS" SCENARIO.

	PMI	LCY
Disruption	Affects noon arrivals peak (20% of Schengen flights delayed and 25% of non-Schengen flights delayed)	Affects arrivals that would combine and thus exacerbate afternoon departures peak (20% of all flights delayed)
Management action	Additional passport control desks are opened and Public Ttansport frequency is increased	Additional passport control desks are opened and an additional access to the terminal is opened

PMI

Analysing the travel times, the management action performed on the terminal (opening of additional passport control desks) reduces the terminal travel time for non-Schengen passengers (Figure 4). Without management action nearly 400 passengers are to spend 40-50 minutes in the terminal, while mitigating management action reduces this to about 200 passengers and near zero passengers longer than 50 minutes. Passenger peaks of 20 to 40 minutes, increases from 360 to 1,000 passengers, and from 750 to 1,000 passengers, respectively.

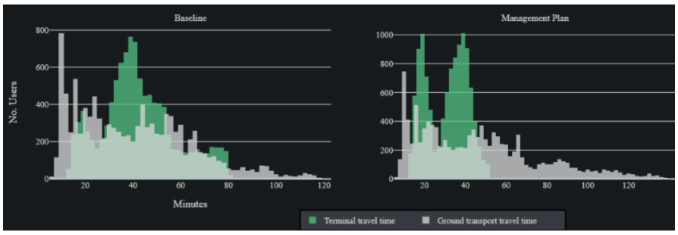

Figure 4: Travel time in baseline and management plan for delayed arrivals at PMI.

Analysing queue times and throughput at the manual passport control (Figure 4), opening more passport control lanes drastically reduced the queue time from more than 50 to just 13 minutes, and increased the number of processed passengers from maximum 500 to more than 800 passengers every 15 minutes, significantly reducing the impact on passengers.

Figure 5: Queueing time in baseline and management plan for delayed arrivals at PMI.

Additionally, the increase on the public transport frequency caused a reduction on the passenger waiting times. In Figure 6, it is presented how, before applying the management action, there are 138 passengers waiting between 30 to 40 minutes for the bus, while this has been reduced to 81 once the management action is applied.

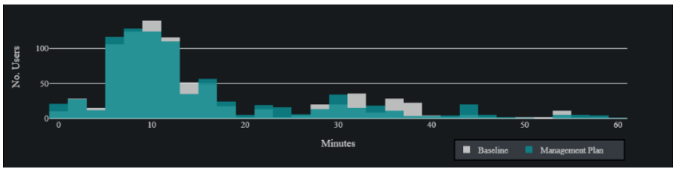

Figure 6: Waiting time in baseline and management plan for delayed arrivals at PMI.

LCY

The opening of additional immigration control desks also reduced the queue time as presented in Figure 7. Applying the management action reduces the waiting time to almost zero.

Figure 7: Queueing time in baseline and management plan for delayed arrivals at LCY.

In this case, the management action on the surface consisted of opening additional access to the terminal to minimise possible congestion due to the unexpected late arrival of passengers. This action does not have a special effect on the travel time as, due to the small number of passengers at LCY, the congestion produced is not significant. However, the congestion reduces CO_2 emissions by 1.5% from 151.9 to a 149.6 kg/h

B. *Delay of departures*

For quick reference, this summary is a synthetic description of the simulation scenario concerning the delay of departing flights:

TABLE 7. SYNTHETIC DESCRIPTION OF THE "DELAY OF DEPARTURE FLIGHTS".

Summary	Substantial delay to a significant proportion of flights departing from the airport	
Disruption	PMI	LCY
	Affects morning departures peak (30% of flights delayed, applied independently to Schengen and non-Schengen departures)	Affects afternoon departures peak (80% of all flights delayed)
Management action	Passengers are advised to delay their arrival at the airport (50% take the advice and start their journey 45 minutes later and 10% change to PT modes) and PT frequency is increased.	

PMI

The management actions performed slightly reduced the travel times of passengers whose flights have been delayed. Although the reduction is not clearly appreciable, passengers with longer travel times in the airport terminal have been reduced and, additionally, the peak of passengers with longer travel times in ground transport modes have likewise been reduced, possibly due to a more graduated arrival of passengers to the airport, avoiding the rush moments and thus contributing to a reduction in the congestion at the airport.

The modal share is slightly modified due to the change of some of the delayed passengers to public transport modes, this is translated in the model as an increase of 2% for public bus share (see Figure 8). The transfer of some of the passengers to public transport modes reduced the environmental footprint, however, the increase in the number of public buses due to the modification of the public transport frequency counteract this effect. Therefore, the CO_2 emissions are reduced from 2,800.64 kg/h in the baseline to 2,799.60 kg/h once the management action is applied. Once IMHOTEP will be implemented data will be available to assess benefits of varying bus sizes and service frequencies.

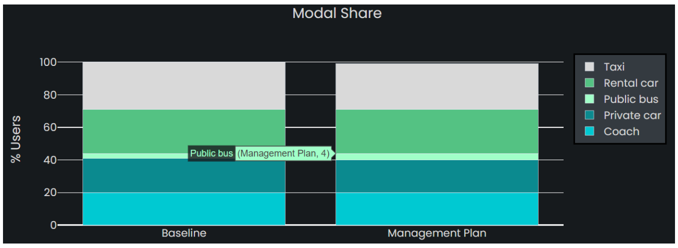

Figure 8: Baseline Modal modal share in baseline and management plan for delayed departures. at PMI.

The increase of the use of PT alternatives can be displayed during the times affected by the delayed flights. Additionally, due to the increase of the PT frequency, there is a marked reduction in public transport waiting times (Figure 9).

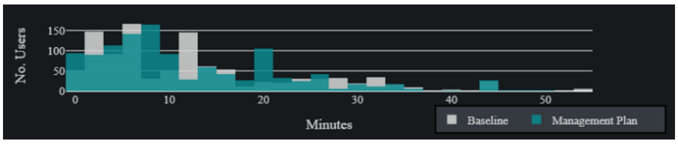

Figure 9: Waiting time for public transport alternatives in baseline and management plan for delayed departures at PMI.

Regarding the terminal, the delay of passenger starting time to the airport, contributes to the reduction of flights missed by passengers. Figure 10, shows the number of passengers missing flights drops from 399 to 258, this reduction is more evident in the flights missed at check-in (arriving late to the check-in desk) as none of the passengers missed their flight at the check-in when applying the management actions.

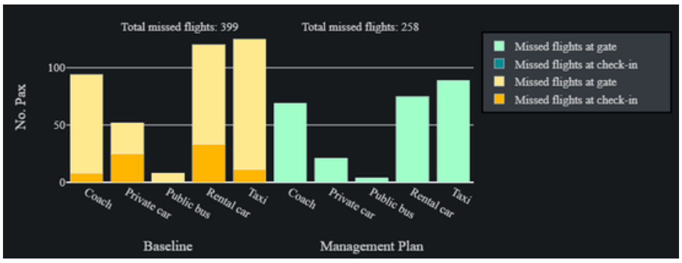

Figure 10: Missed flights in baseline and management plan for delayed departures at PMI.

When analysing the queueing time at security (Figure 11) a reduction is appreciated between 07:30 and 08:30 as some passengers (now aware of the delayed departure of their flight) arrive later at the airport, avoiding this busy hour. Additionally, the waiting time peak decreases from 19 to 16 minutes as passengers dropping in dispersed over a longer period of time reducing overlap with passengers of subsequent flights.

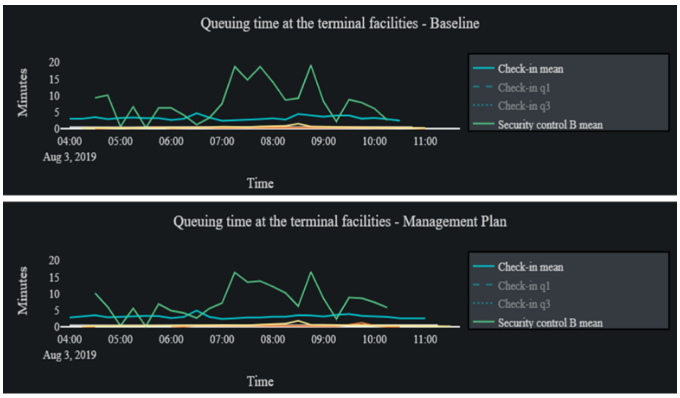

Figure 11: Queueing time in baseline and management plan for delayed departures at PMI.

LCY

The results present similar behaviours as at PMI. The share of DLR increases from 47% to 49%, and a subsequent reduction of CO_2 emissions. As the public transport modes (DLR) are not modelled, just includes private traffic emissions (private car and taxi), appreciating a 3% reduction, from 207 to 200 kg/h. Emissions are much lower than in the PMI case study because the LCY surface model just includes the surroundings of the airport, while the PMI model includes a wider area of the road network.

Inside the terminal, security throughput presents a steadier flow of passengers than before applying the management actions (especially noticeable between 15.30 and 16.30) where the flow of passengers was more irregular (see Figure 12). This is beneficial to the airport as it facilitates the management of resources allocated to security.

The effect of delaying the passenger arrival, impacts the airside dwelling time, a reduction from 107 to 101 minutes, as well as the Q1 and Q3 quartiles, from 140 to 136 minutes, and from 28 minutes to 24, respectively.

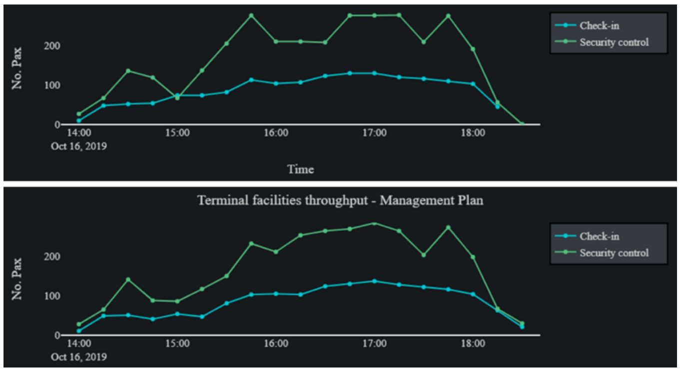

Figure 12: Throughput in baseline and management plan for delayed departures at LCY.

C. *Disruption in surface access transport*

Table 8. SYNTHETIC DESCRIPTION OF THE "DISRUPTION IN THE SURFACE ACCESS" SCENARIO.

Disruption	Closure (followed by partial closure) of the main motorway in the direction from the city to the airport.	Unbalanced distribution of passengers arriving by DLR due to a planned disruption in the London Underground network (i.e., a strike)
	Coincides with the morning peak of departures	Coincides with the time passengers of the afternoon departing peak flights should arrive to the airport
Management action	Passengers are advised to anticipate its arrival to the airport (25% of passengers take notice of the advice and start their trip to the airport 45 minutes earlier) and "fast-track" lane to security is allocated for delayed passengers	Passengers are advised to anticipate its arrival to the airport (25% of passengers take notice of the advice and start their trip to the airport 45 minutes earlier) and an additional access to the terminal is opened

PMI

Providing information to users so they can adapt the current status of the road enables users to depart earlier and, as a result, the airport access congestion is reduced. This slightly reduces the travel time, as well as CO_2 emissions. The travel time is presented in Figure 13, with the number of passengers spending more than 100 minutes in the access notably reduced, while thepassengers peaks around 20-25 minutes and 45-55 minutes have increased.

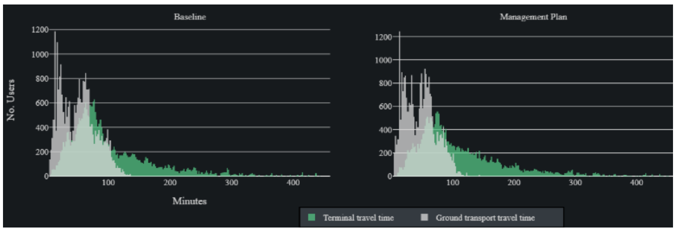

Figure 13: Travel time in baseline and management plan for disruption in surface access at PMI.

CO_2 emissions have been reduced from 3,264.6 to 3,192.6 kg/h, a 2.2% of reduction.

The management actions performed contributed to notably reducing the total number of missed flights from 321 to 209. The number of passengers missing their flight at check-in reduced from 53 to 17 due to a reduction on their access time. Additionally, management actions on the surface and the terminal reduced the initial 268 passengers that lost their flight at the gate, to 192.

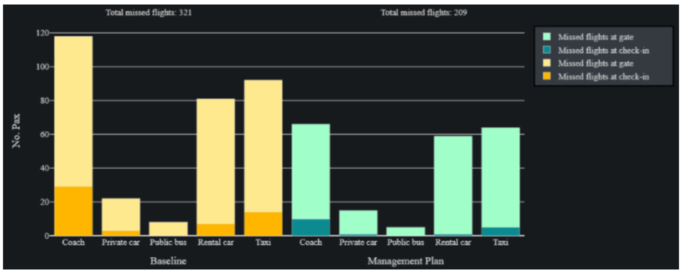

Figure 14: Missed flightsin baseline and management plan for disruption in surface access at PMI.

Part of this reduction in the number of passengers who lost their flight is caused by the management action applied at the terminal which allows delayed passengers to skip part of the security control queue using the 'fast-track' lane. The security control queuing time early 07:00 peak is reduced from 19 to 14 minutes, and at the later peak at 10:00 from 16 minutes to 9 minutes.

Finally, the earlier arrival of passengers to the airport produces an increase of the passenger stay times at the airport, thus promoting the use of shops, restaurants and other services which have an economic impact on the non-aeronautical revenues for the airport. Figure 15 presents a comparison of the airport occupancy, where the increase on the different airport modules and terminal occupancy is detailed.

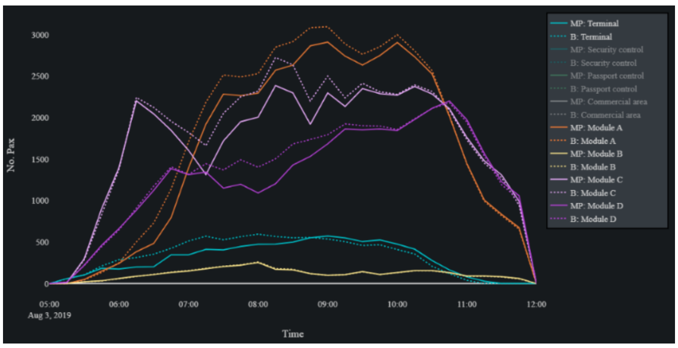

Figure 15: Occupancy of airport facilities in baseline and management plan for disruption in surface access at PMI.

LCY

The action for reducing the congestion is opening an additional access, aimed at reducing the traffic on the rest of the entries. Due to the reduced geographical scope of the LCY model, there is no significant decrease in the travel times. However, the level of CO_2 emissions is reduced from 188.2 to 186.9 kg/h.

At the terminal, the queue time at security is also remarkably reduced. Management action keeps the queue time at 6 minutes, while before, peaks reached 10 minutes of waiting time.

Similarly, as at PMI, the occupancy on the airside is increased due to an earlier arrival of passengers to the airport (see Figure 16). Promoting the use of shops, restaurants and other services has an economic impact on the non-aeronautical revenues.

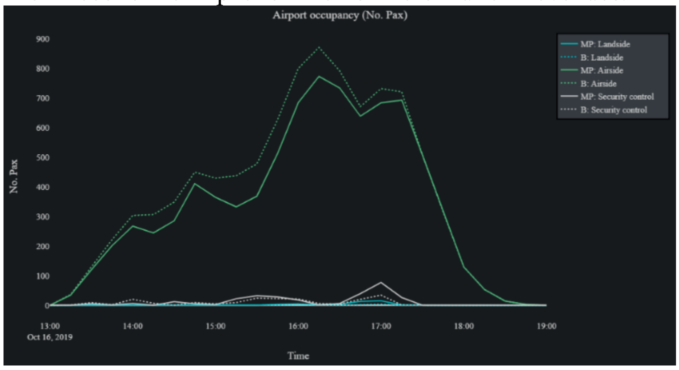

Figure 16: Occupancy of airport facilities in baseline and management plan for disruption in surface access at LCY.

V. Conclusions

IMHOTEP brought together key stakeholders, along with different datasets, in a way that has not been attempted before. Modal share, travel times, CO_2 emissions, PT alternatives occupancy, productivity of the ground transportation, and waiting time (bus only), all sought to assess access/egress in a way that increased efficiencies. Meanwhile, the terminal view was underpinned by the KPIs of waiting times (queuing time) at check-in, security and immigration. This view was also linked to the KPIs of occupancy, and of dwelling times (both at airport defined areas); and finally, the KPI missed flights indicator. Ultimately, closely linking ground to air realm generates greater efficiencies, especially when dealing with major delays and disruptions.

This project has clearly revealed that meaningful and actionable management responses with a real chance to mitigate these, are possible when a holistic view of the situation is mirrored in a multi-stakeholder approach. In this context, information from all key stakeholders is crucial; however, not just at the data sharing level, but also wide input at the decision-making level as well. The 'not my problem to solve' mentality does more to negatively affect all key stakeholders in the longer-term, than it does to protect and shield individual stakeholders in the short-term. It only takes one issue at a single stakeholder to impact the entire aviation system; while conversely, it takes all key stakeholders to limit the extent of that same issue.

The vision for the IMHOTEP project came into place following a conversation between the Cranfield Urban Turbine Research Project (www.urbanturbine.org) and Nommon, based on an ambition to explore opportunities for better allocating and managing resources by sharing facilities between airports and municipalities. Innovative territory-transgressing communication is one first step in achieving this vision.

The air and ground realm definitions established in this project, overcome traditional narrower defined 'air- and landside', encouraging a wider overlap, reflective of a flexible zone than of a rigid border.

Another measurable success of the project is the intention disclosed by LCY to join the A-CDM, as benefits of a collaborative environment have been identified. These benefits also apply to other airports with a similar scale of operations to LCY. Further, potential applications of the IMHOTEP project relate to the physical implementation of the visualisation tool into new airport infrastructure, such as OTC's.

VI. Future Orientation

In continuation of the IMHOTEP project beyond POC, the granularity of the KPIs can be increased while other key stakeholders (i.e. airlines) can be integrated to extend its benefits. Airport operators could be engaged in a holistic discussion about new forms of passenger services. For example, LCY was obviously impressed with IMHOTEP as they stated that staff would be better prepared to handle peak hour flows if they had clearer visibility and knowledge about delays or disruptions of the ground transport system.

Similarly, we assessed, right at the final stage of IMHOTEP, the potential for such better preparation to handle peak demand for the airport's airside including the aircraft turnaround (Figure 17). The early and robust information on disruptions along these processes show the potential benefits from a broader approach to A-CDM, the interdependencies between the ATM, and the airport terminal. Realms were studied in several case studies. As a lesson learnt, there are terminal processes that can either be affected by disruptions in the turnaround, or could be used proactively as management actions. Figure 16 shows the application of the simulation model developed for LCY for a combined scenario of late or delayed boarding and a last minute change of the departure gate. A better understanding of the interactions of these elements could enable a substantial integration between stakeholders involved in the provision of the entire door-to-door journey.

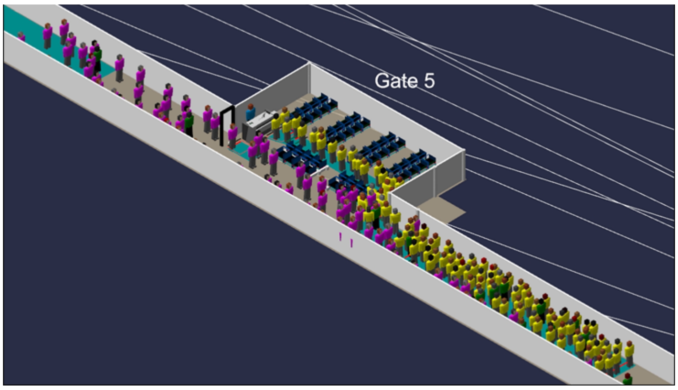

Figure 17: Effects of late or delayed boarding and a last minute change of the departure gate at LCY, IMHOTEP airside simulation.

Though many airports are presently undergoing a fundamental transformation towards greater flexibility through digitalisation of the airport management, potential management actions to balance delays and disruptions are still related to traditional or less flexible processes. By connecting so far disconnected data, along with key stakeholders who typically have not met each other (certainly not in any significant manner before), IMHOTEP has been able to demonstrate the clear and valuable benefits of its innovative approach, model and visualisation tool. The future prospects for what IMHOTEP has thus far uncovered are substantial, including the project's wider applicability, and its ability to positively challenge the status quo.

The reduction of the carbon footprint including the optimisation of facility utilisation and enabling passengers to benefit from new airport processing technology are key drivers of airport development in coming decades. Airports with high seasonality would benefit from delayed investment into larger terminals, tour operators can better predict travel times from hotels and resorts to the airport.

The IMHOTEP platform can easily include new transport operators e.g., Flexibus in improving regional connectivity and reducing unnecessary congestion.

IMHOTEP demonstrates that fundamental challenges can be transformed into achievable opportunities, overcoming a fragmented and siloed passenger journey. Subsequently commercial services along the journey will be impacted by advanced seamlessness. A sensivity analysis will explain how robust such service implementation is. For example, the shape of the delay duration distribution and the percentage of Schengen and non-Schenghen flights.

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