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IMHOTEP

INTEGRATED MULTIMODAL AIRPORT OPERATIONS FOR EFFICIENT PASSENGER FLOW MANAGEMENT

This document is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 891287 under European Union's Horizon 2020 research and innovation programme.

Abstract

The goal of IMHOTEP is to develop a concept of operations and a set of data analysis methods, simulation models and decision support tools that enable information sharing, common situational awareness and real-time collaborative decision-making between airports and ground transport stakeholders.

Passenger terminal and airport access/egress flows have traditionally been considered separately. IMHOTEP brings both together into one measurable flow and provides models and tools to assess the operational impact of different management measures on both the terminal airport processes and the ground transport system, in order to facilitate coordinated decision making across stakeholders. This leads to a better use of existing facilities and surface transport services, delaying or removing the need for additional terminal capacity or other airport facilities, and ultimately improving the efficiency and environmental sustainability of airport operations and the passenger experience.

This document describes the application of the IMHOTEP's concept and toolset at two case study airports, namely Palma de Mallorca (PMI) and London City (LCY), at Proof of Concept (PoC) level, with the aim of assessing the benefits of the new proposed concept for passengers, airports, ground transport operators, and other relevant stakeholders.

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List of Acronyms

Acronym	Meaning
A-CDM	Airport Collaborative Decision-Making
ACISP	Airport CDM Information Sharing Platform
ADRM	Airport Design Reference Manual
ARC	Airport Research Company GmbH
ANSP	Air Navigation Service Provider
AU	Airspace User
ATD	Activity Travel Diary
ATM	Air Traffic Management
BHS	Baggage Handling System
CAST	Comprehensive Airport Simulation Technology
CDM	Collaborative Decision-Making
ConOps	Concept of Operations
DLR	Docklands Light Railway
EMT	Empresa Municipal de Transportes (Palma de Mallorca municipal transport company)
IATA	International Air Transport Association
IT	Information Technology
KPI	Key Performance Indicator
LCY	London City Airport
MaaS	Mobility as a Service
OTC	Onward Travel Centre
PMI	Palma de Mallorca International Airport
PoC	Proof of Concept

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Acronym	Meaning
PT	Public Transport
PRM	Passenger with Reduced Mobility
RATT	Real-time Aircraft Turnaround Tool
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaking
TAM	Total Airport Management
TfL	Transport for London
UK	United Kingdom
WP	Work Package

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Executive summary

The IMHOTEP project is focused on the development of a concept of operations and a set of data analysis methods, simulation models and decision support tools that enable information sharing, common situational awareness and real-time collaborative decision-making between airports and ground transport stakeholders. Passenger terminal and airport access/egress flows have traditionally been considered separately. IMHOTEP brings both together through a holistic view of the whole door-to-gate and gate-to-door passenger journey and provides tools and mechanisms to assess the operational impact of different management measures on both the terminal airport processes and the ground transport system, in order to facilitate collaborative decision-making across airport and ground transport stakeholders.

With the aim of evaluating the performance of the proposed concept and the developed tools, two case studies have been conducted in airports with considerably different operational characteristics, Palma de Mallorca (PMI) and London City (LCY) airports. To this end, a set of validation exercises have been defined in close collaboration with the partner airports based on different stakeholder working sessions. Across these working sessions, both PMI and LCY airports:

- provided airport-specific reoccurring disruptions in their daily schedule;
- proposed relevant key performance indicators (KPIs) aimed at assessing the performance of the complete transport system (including both the airport and the ground transport system) and quantifying the impact of such disruptions.
- proposed potential management actions that can be applied in order to mitigate the impact of the disruptions on the passengers and the involved stakeholders.

After the discussion, a final set of scenarios, KPIs and management actions were selected for its analysis and study within the project. The three disruption scenarios selected for the validation exercises are the following:

1. Delay of departure flights: substantial delay affecting a significant proportion of the flights departing from the airport.
2. Delay of arrivals: substantial delay affecting a significant proportion of the flights arriving to the airport.
3. Disruption in the surface access: critical disruption of the ground transport system used to access the airport caused by a major incident on the road network, a reduction in public transport services (e.g., due to a strike), etc.

Each scenario has been fine-tuned according to the specificities of each airport. For example, the delayed departures scenarios were defined to account for the fact that PMI tends to experience issues surrounding the morning departure peak, while LCY is more affected by the afternoon departures peak.

The three simulated scenarios presented different management challenges for the airport and ground transport stakeholders. Despite these differences, each scenario demonstrated that the holistic view of the passenger flows and the coordination between the airport and the ground transport modes contributed to the improvement of the conditions of the whole transport network, bringing significant benefits to the involved stakeholders (airport and ground transport operators) as well as to the passengers and the environment which can be summarised as:

- **Shortening of passenger waiting times** in both the access and egress legs (waiting time for the public transport and reduction of surface network congestion) and the airport terminal (waiting time at the different airport facilities such as security control or passport control) and overall **travel times** for passengers, which would translate into an enhancement of the passenger experience.
- **Reduction in the number of flights missed** by passengers due to potential airport and access disruptions, which is directly translated into a better passenger experience.
- **Reduction of the congestion** on the access and egress from the airport, which not only leads to an improvement of the passenger experience, but also to the **reduction of the CO_2** emissions, thus improving the airport environmental footprint.
- **Better predictability** of the passenger flows and the overall transport network performance, which gives the involved stakeholders the possibility to better allocate their resources (human resources in the case of airport operators, and vehicle fleet in the case of ground transport operators). This is in turn translated into a potential improvement of the **Operational Efficiency**, a reduction of costs (**Cost-Efficiency**), an increase of **Capacity** and, ultimately, an improvement of the service provided to the passengers.

Although the project has mainly focused on the benefits that the proposed solution can bring to the stakeholders directly involved in the project (airport and ground transport operators), the proposed concept has also the potential of bringing significant benefits to other stakeholders such as ANSPs and AUs, due to higher predictability on the passenger flows, as well as to the passengers themselves.

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1 Introduction

1.1 Scope

The IMHOTEP project is primarily focused on the development of a Solution consisting of a concept of operations and a set of data analysis methods, simulation models and decision support tools that enable information sharing, common situational awareness and real-time collaborative decision-making between airports and ground transport stakeholders.

This report presents the assessment and validation of the IMHOTEP Solution, with the aim of evaluating their benefits and guide future work to enhance the door-to-door passenger journey and enable seamless intermodal trips involving air transport services. To this end, the IMHOTEP Solution is applied to a set of validation exercises defined in collaboration with IMHOTEP's case study airports, London City and Palma de Mallorca, and other relevant stakeholders.

1.2 Intended readership

The intended readership of the current document includes:

- SESAR JU
- European Commission
- Airports
- AUs
- ANSPs
- Network Manager
- Ground transport stakeholders
- Relevant SESAR IR projects (e.g., PJ04 TAM)
- Relevant SESAR ER projects (e.g., TRANSIT, MODUS, X-TEAM D2D projects)
- Scientific community

1.3 Reference and applicable documents

- Grant Agreement No 891287 IMHOTEP – Annex 1 Description of the Action.
- IMHOTEP-D1.1 Project Management Plan v01.03.00, June 2021.
- IMHOTEP D2.1 IMHOTEP ConOps, v0.01.00, February 2021.
- IMHOTEP D2.2 Specification of Case Studies, v01.01.00, March 2021.
- IMHOTEP-D3.1 Data Management Plan v01.01.00, March 2021.
- IMHOTEP D4.1 Passenger Terminal Process Simulation, v0.01.00, December 2021.
- IMHOTEP D5.1 Airport Access-Egress Simulation, v0.01.00, December 2021.
- IMHOTEP D6.1 Airport Access-Egress Simulation, v0.01.00, June 2022.

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1.4 Structure of the document

The document is structured as follows:

- Chapter 2 summarises the previous developments of the IMHOTEP project for quick reference, allowing this report to be fully comprehensive as a stand-alone document.
- Chapter 3 describes the process that has been followed to specify and develop the two validation case studies, from their conceptualisation to the refinement and final definition of the scenarios, the management actions and the KPIs considered in the validation exercises.
- Chapter 4 presents the main results of the validation experiments.
- Chapter 5 discusses the validation of the IMHOTEP ConOps and the possibilities to extend the proposed concept to other airports.
- Chapter 6 presents the main conclusions of the project, including the future orientation and potential next stages in the development and implementation of the IMHOTEP Solution.

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2 Background

Airport Collaborative Decision-Making (A-CDM) enables air transport stakeholders affected by a certain decision to share information and agree on a decision-making approach that improves the overall system performance, while balancing against their individual performance needs (Eurocontrol, 2017). A-CDM has delivered a variety of benefits, including time and fuel savings, reduction in delays, improved resource utilisation, better management of adverse conditions, and more accurate prediction of aircraft take-off time (EUROCONTROL, 2016). Total Airport Management (TAM) is being developed to improve the integration of airports into the Air Traffic Management network relying on real-time information sharing (EUROCONTROL, n.d.). Yet, both applications are confined to airside airport operations and stakeholders, reducing the potential to impact the whole door-to-door journey and improve passenger experience.

The tools developed for the IMHOTEP project are based on the concept of the passenger activity-travel diary (ATD), which collects information on individual door-to-door journeys for air transport passengers. The aggregation of such information and, crucially, its update in real time, would enable the extension of current A-CDM to incorporate surface access and egress legs. This extension, in turn, would enable real-time collaboration between relevant stakeholders to ensure common situational awareness and prompt response to disruptions beyond the air traffic management scope, therefore responding better to the needs of passengers with the ultimate goal of ensuring a seamless multi-modal journey.

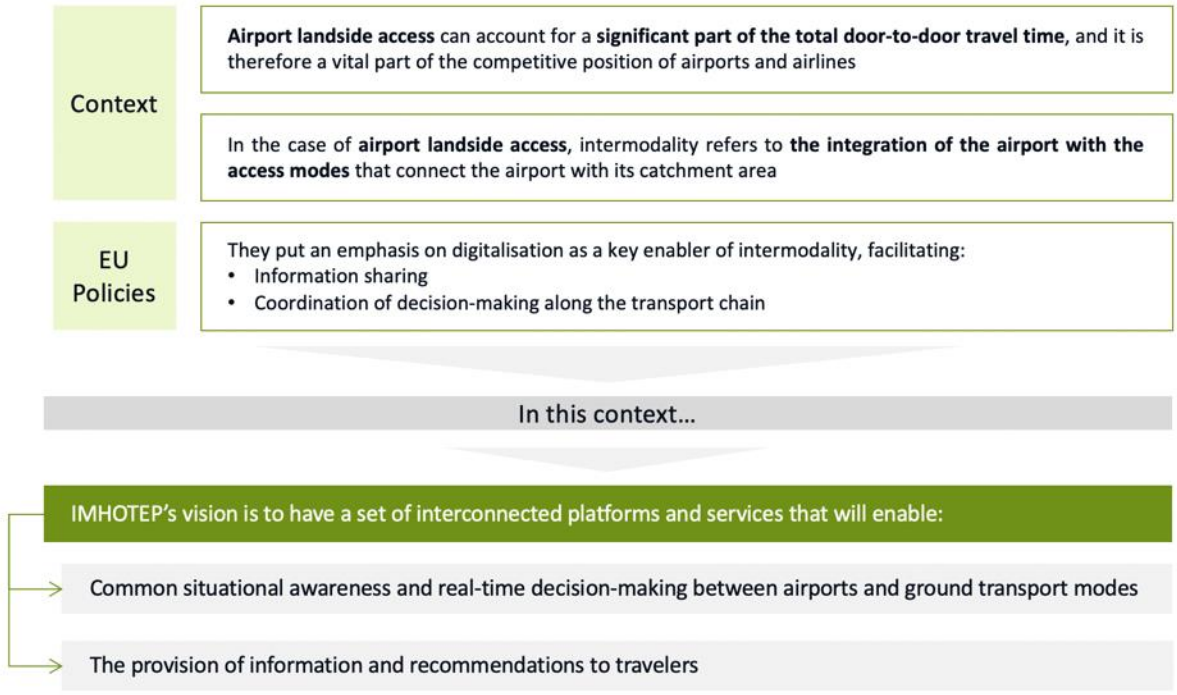

Figure 1: IMHOTEP background and motivation.

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2.1 IMHOTEP Concept of Operations

As one of the key objectives of IMHOTEP is to close the gap in information sharing between airport and surface transport operations, in particular about passenger flows, different methods of data collection and processing had to be brought together. This allows linking passenger data related to flights with passenger data related to local transport on the ground. This is precisely the role of the IMHOTEP Concept of Operations (ConOps), which has been developed with the aim of including the surface transport stakeholders into the collaborative decision-making process, including local transport authorities, traffic agencies, transport operators and mobility service providers. The IMHOTEP ConOps represents a transition from a flight-centric to a passenger-centric approach that considers the entire door-to-door journey as the central element of information, relying on the passenger ATD concept.

The ConOps establishes the 'Multimodal Collaborative Decision Making based on Advanced Passenger Flow Prediction' system, which comprises five functions that define how the data is collected and processed to create and continuously update the ATD (see Figure 2).

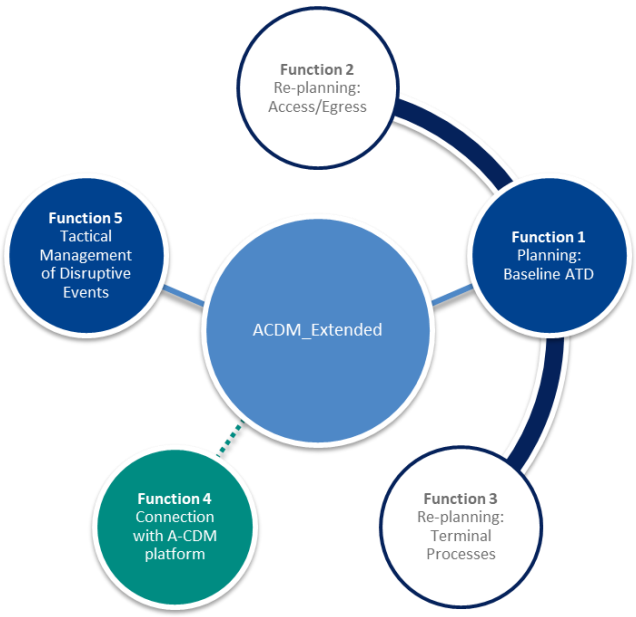

Figure 2: Schematic representation of the Multimodal Collaborative Decision Making functions.

Function 1 creates a baseline ATD from 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 Multimodal Collaborative Decision Making 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 passenger arrival at 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

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passengers egressing from the airport will be used as an input for Function 2 in order to forecast the passengers' egress leg accordingly. Updates use real-time data collected during the day of operations.

One of the premises of the Multimodal Collaborative Decision Making concept is that it should enable its implementation into both CDM and non-CDM airports. 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 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 Multimodal Collaborative Decision Making so that both platforms can exchange information.

Finally, Function 5 is defined for the tactical management of disruptive events by triggering alarms when any deviation from normal operations is identified. The objective of this function is to support the collaborative management of disruptions that could appear during the day of operations. When the deviation from normal operations is greater than a certain threshold previously established by the stakeholders involved in the system, the disruption management process will be initiated through Function 5. The deviation is assessed through a set of KPIs, which have been defined as part of 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.

2.2 Definition of case studies

Two case studies 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. The case studies cover two airports with heterogeneous characteristics which serve different markets: Palma de Mallorca (PMI) and London City (LCY).

LCY is an urban airport, initially focused on business travel but with leisure travel gaining increased attention, especially in the aftermath of Covid-19 related restrictions. It has not implemented A-CDM and it offers a wealth of surface transport options for airport access and egress thanks to its location. In contrast, 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. The analysis of these two airports, with markedly different typologies, operations and business models, reflects different characteristics and passenger behaviours when considering the intermodal character of their journeys. The two case studies are therefore different, with the aim to shed light on how information sharing and real-time coordinated decision-making between air transport and ground transport modes can be of benefit for airports with very different characteristics and operational challenges (including implementation of A-CDM). Similarly, the range of outcomes sheds light on potential learnings for other airports too.

The initial definition of the case studies (as stipulated in Deliverable 2.2) considered the analysis of a base-case for each airport that focuses on a representative day in 2019 to account for operations under usual circumstances before the Covid-19 pandemic. Then, the effectiveness and potential benefits of the IMHOTEP Solution is tested through use cases that reflect operations under disruptive events. Disruptions affecting both the air and surface transport operations are taken into account.

2.2.1 Main characteristics of PMI to be considered

The main features which have to be considered when defining the case study are:

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- Palma de Mallorca Airport is the main gateway to the Balearic Islands and the third largest airport in Spain (just behind Adolfo Suárez Madrid-Barajas and Barcelona-El Prat) with almost 30 million passengers in 2019.
- The majority of passengers travel for leisure purposes. Therefore, Palma de Mallorca Airport presents a high seasonality, with relevant traffic peaks in the summer and holiday seasons and lower traffic during the rest of the year.
- Palma de Mallorca Airport is a CDM airport.
- Current alternatives at PMI for access and egress to/from the airport are only by road, with bus and car as the main options. The complete list of alternatives comprises:
  - Palma de Mallorca public transport buses (EMT buses).
  - Airport transfer (tour operators).
  - Taxi or ride-hailing.
  - Car hire or private car/vehicle.

2.2.2 Main characteristics of LCY to be considered

London City Airport's (LCY) principal features which have to be considered when defining the case study, as a consequence of the operational business model and sustainability policy of the airport, are the following:

- Surface access and egress is essential to deliver LCY's customer proposition of "20 minutes from check in to departure lounge, 15 minutes from plane to forecourt, and rapid transport links to Central London".
- The majority of the passengers travelling to and from the airport use public transport, hence contribution of the airport surface access and egress to CO_2 neutrality is crucial.
- LCY is located next to the financial district, attracting a proportion of business travel that is larger than in most airports.
- LCY is not a CDM-enabled 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 beneficial inner-city location, most surface access and egress transport systems operate independently from the airport and potential congestions/disruption to the passenger journeys to and from the airport are unrelated to the operation of the airport.
- Due to its closeness to the city centre, there is a large number of surface access/egress alternatives, such as:
  - Docklands Light Railway (DLR): the London City Airport station provides connections to London Underground, suburban rail, long-distance rail and high-speed train.
  - London buses: 473 and 474.
  - Taxi (black cab), minicab, ride-hail, car hire, private car, motorcycle.
  - Walking.
  - Cycling.
  - Other minority access and egress alternatives nearby: Riverboat or Cable car.

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2.3 Reconstruction of Activity-Travel Diaries

Prior to the development of the predictive models, a set of data analysis tasks have been performed in order to extract historical passenger ATDs. The objective of this step is twofold: first, to use the data extracted from the ATD for the validation of the models by comparing the outputs extracted from both sources; and second, to feed the models with the actual airport demand. Reconstructing the actual characteristics of individual inter-modal trips in the ATD involves a sequential process that relies on a novel combination of several data sources (see Figure 3).

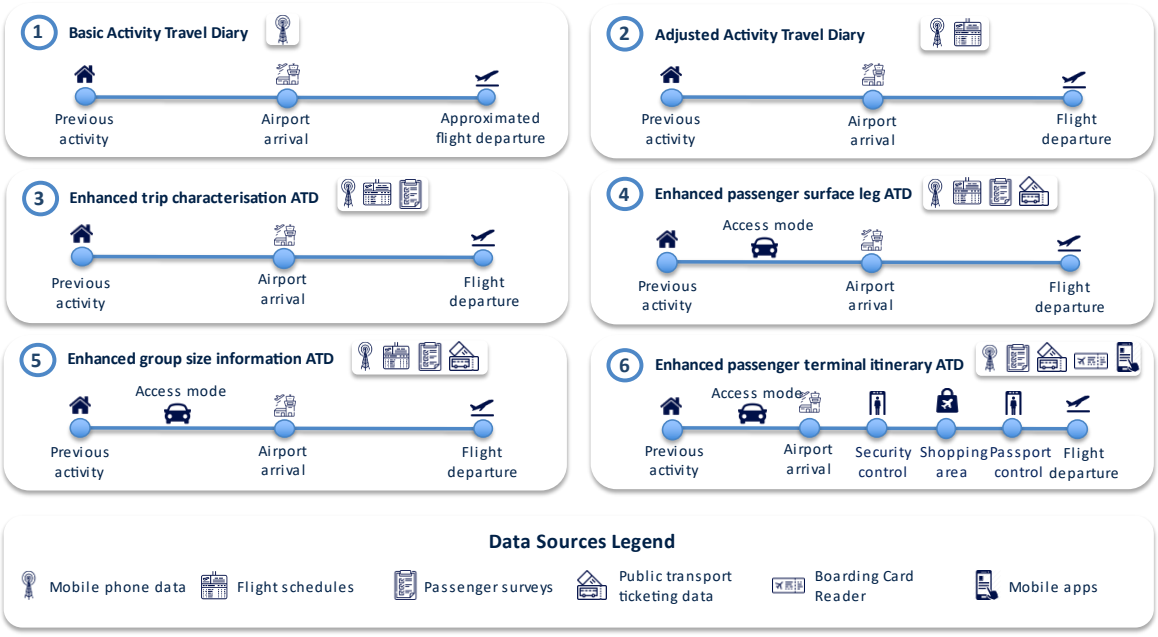

Figure 3: Integration of data and models in the reconstruction of the passenger ATD.

First, a basic ATD is identified from mobile phone data records. This stage defines the main characteristics of the trip (origin-destination, duration of stay, outbound/inbound, arrival/departure) and passenger profile (age, gender, nationality, passenger/worker/professional driver, etc.). In the second stage, airport flight schedules are used to adjust the number of trips detected using mobile phone data to ensure agreement with the expected number of total passengers. This stage also adds information about the specific origin/destination airport, flight number, specific departure/arrival time and terminal gate. The third stage enhances trip characterisation by identifying the passengers' trip purpose (business/leisure) using machine learning techniques fed by passenger surveys data and mobile phone data. Stage 4 enhances the surface access/egress leg by assigning the passengers' surface transport mode using a mixed approach between machine learning methods fed by passenger surveys and mobile phone data and further adjustment with public transport ticketing information. Stage 5 extracts potential groups of passengers travelling together based on mobile network data and assigning the final group size distribution using the distributions observed in the passenger surveys. Finally, Stage 6 updates the passenger itinerary within the terminal by considering data from the use of airport terminal facilities (such as passenger registers at the boarding card readers located before gaining access to security control) and mobile apps geolocated information. All records are anonymised and do not allow for the identification of individuals. For further information on the data analysis tasks performed and the reconstruction of the ATD please refer to deliverables 'D4.1 Passenger Terminal Processes Simulation Module' and 'D5.1 Access and Egress Simulation Module'.

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The combination of different data sources has proven valuable to identify milestones and attributes in the passenger journey that are traditionally out of reach of any data owner in the air transport context. Hence the continued development of the IMHOTEP tools has the potential to impact not only the operations of airports under normal and disrupted circumstances, but also to enable innovative solutions for passengers, metaphorically breaking the rigid fences of the airport boundaries.

2.4 Airport terminal processes simulation

The flow of passengers through the airport and in particular through the passenger terminal is a complex process. Currently the de facto industry standard is that individual parts of the passenger journey are measured separately (check-in, security, immigration, boarding etc.) using different methods commonly based on the IATA ADRM as KPI and the application of sensor-based technology in the terminal building (e.g., people counting sensors). This method is useful to assess the efficiency of particular processes of the terminal operation only. IMHOTEP seeks to monitor delays and disruptions throughout the entire passenger journey including airport access and egress.

CAST, one of the globally leading software for airfield and terminal aircraft and passenger simulation (ARC, 2022), was chosen for this project to simulate the passenger flow through the passenger terminals at PMI and LCY. This scalable and modular aviation software solution comprises simulation, allocation and optimisation systems for pedestrian, vehicle and aircraft traffic, as well as process models of landside, terminal, airside and airspace. The purpose of using CAST is to reduce cost for investments and operations, speed up decision making and planning processes, and support smooth, safe and punctual operations. CAST solutions seamlessly cover strategic and tactical planning, as well as operational and real-time optimisation. Figure 4 presents an example of the PMI airport terminal implemented in CAST Software.

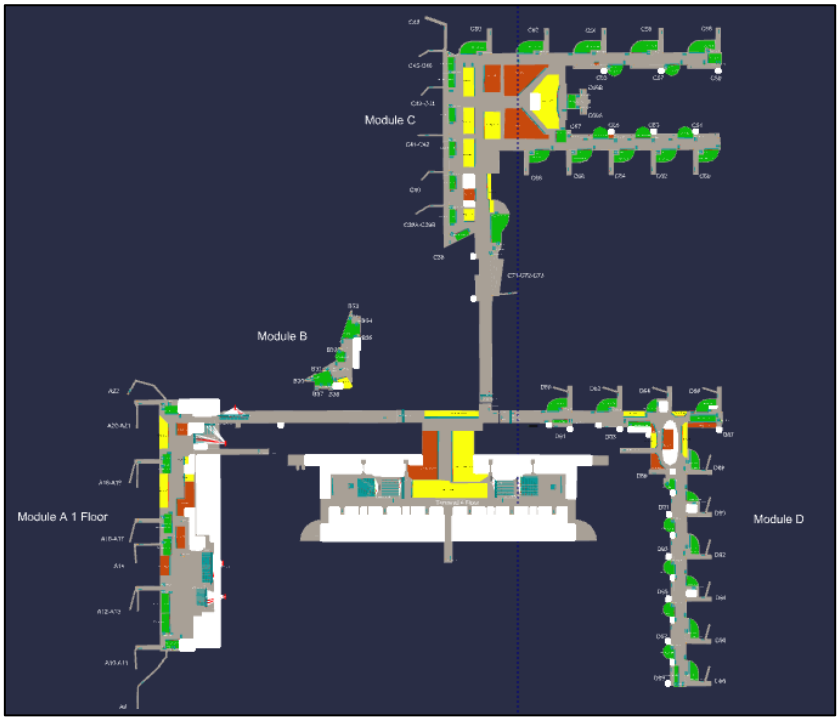

Figure 4. Top view of the PMI airport terminal simulation model implemented in CAST.

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The models have been calibrated and validated using the data extracted from the ATDs. This process consisted of the comparison of results from both the models and the ATD, in order to assure that both sources are coherent. Figure 5 presents an example of the validations.

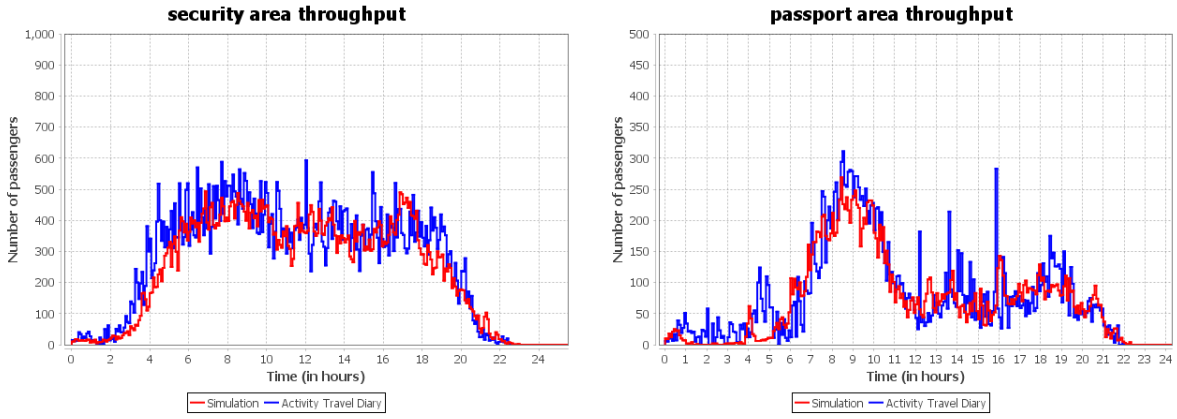

Figure 5. Example of validation results in the PMI terminal model

For further information on the development, calibration and validation of the airport terminal models in Palma and London City, please refer to deliverable 'D4.1 Passenger Terminal Processes Simulation Module'.

2.5 Airport access and egress simulation

Whilst the modelling of airport processes is based on real passenger air tickets for specific flights, surface transport has to be modelled in a different way. This is because the vehicles that move passengers, like cars and buses, can have different behaviours in terms of boarding site, travel time, etc. For instance, cars can be privately owned, rented or taxis. 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.

Airport access and egress simulation models were created for Palma de Mallorca and London City airports. Aimsun Next traffic simulation software was used to replicate different vehicle types in the transport networks of each airport's catchment area. Extensive data collection was employed to create these models. This 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 ATDs of airport users.

These calibrations validated the chosen methodology and showed that the airport access and egress performance of the models was satisfactory. The results thus allow the computation of arrival time at the airport for departing air passengers, and arrival time at the final destination for arriving air passengers.

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Figure 6: Validation results of the LCY surface network implemented in Aimsun Next.

For further information on the development, calibration and validation of the access and egress models in Palma and London City, refer to deliverable 'D5.1 Access and Egress Simulation Module'.

2.6 Model integration and decision support tool

An integration process was developed in order to allow each model to take as input the output of the other. The integration of the models allows the door-to-gate and gate-to-door simulation of the passenger flows, thus enabling the evaluation of the different scenarios. The results of the simulations are presented to the final user via a visualisation tool which aims at facilitating situational awareness and the decision-making process of the relevant stakeholders, as well as enabling the assessment of mitigating actions by comparing the impact of different management plan vs a do-nothing scenario (see Figure 7).

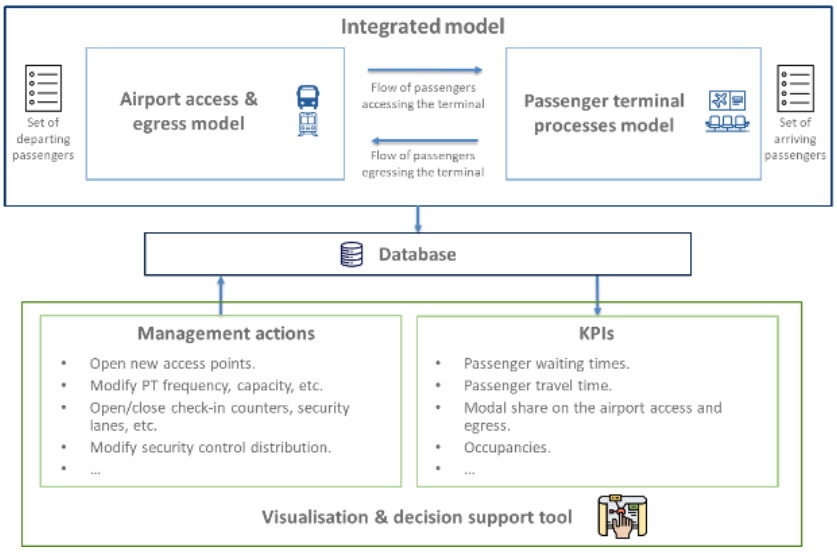

Figure 7. Model integration and decision support tool development approach.

The visualisation tool has been implemented as a web-based platform accessing a database with pre-computed results that emulate real-time information. The results are presented using interactive graphs developed using the Plotly.js Java Script and Plotly.py Python implementation.

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For further information on the development of the visualisation and decision support tool, please refer to deliverable 'D6.1 IMHOTEP Simulation and Decision Support Toolset'.

2.7 The challenge IMHOTEP addresses

As mentioned before, the key objective of IMHOTEP is to establish a holistic approach to the management of passenger and other airport users' movements to/from and through airports by merging and processing different data sources, including:

1. Flight-based data related to specific actors in the air transport system (i.e., flight schedules and passenger surveys),
2. Surface transport data collected directly from users via anonymised mobile phone records, public transport ticketing, traffic counts and mobile apps usage, and
3. In-airport terminal passenger flow information derived from aggregated boarding card reader data, anonymised mobile phone records, mobile apps usage, and other airport sensors.

Airport operations currently focus exclusively on the terminal, and to a lesser extent on passenger and employee access and egress, but not on the integration of passenger and other airport users flows inside and outside the airport. The result is that both processes, terminal operation and airport access/egress, are considered independently, leaving a gap of responsibility and missing communication between airport operators and ground transport system operators. This leads to an inefficient use of resources because facilities must be designed to cope with peak loads and to a looming likelihood of disrupted operations due to events outside the direct responsibility of specific stakeholders (see Figure 8). It is thus a logical consequence to close the gap between the airport and ground transport system operators by providing coordinated information to the passenger in the interest of a seamless and shorter journey as well as for the airport avoiding over-dimensioned, overcrowded or underused physical infrastructure.

Figure 8: Canary Wharf underground and PMI check-in hall. Photo H. Rothe

This challenge is growing with the increasing variety of ground transport system operators (bus, metro, train, taxi and on-demand services). At the same time, airports may compete by providing a better offer of ground transport services. Recently, some airports have introduced onward travel centres (OTC, see Figure 9) offering passengers space in the landside arrivals concourse to orientate, see transport schedules and buy tickets. Besides informing passengers 'on-the-go' via their mobile devices, the IMHOTEP Solution can feed data to such OTC's as potentially new public spaces inside the airport and in the city.

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Figure 9: Onward travel centre consolidating surface transport alternatives for airport egress at London Luton Airport. Photo H. Rothe

2.8 Key considerations on stakeholder decision making

Substantial impact on the decision-making process of airport development and operation is triggered by ownership and airport stakeholder considerations. Privately owned airports are usually under a higher pressure to produce revenues than publicly owned airports, which are typically guided by a long-term perspective and not short-term profits or shareholder returns. In particular, urban airports like LCY aim to reduce their physical terminal footprint by outsourcing airport services (e.g., baggage collection and delivery), which automatically leads to new passenger services and reaches out to other airport-service stakeholders. This has been a strong motivation for LCY to join and benefit from IMHOTEP. Further airport stakeholders are ground handlers (check-in and handling), security and border control. From a daily operational perspective, and potentially relevant for some of the scenarios assessed in IMHOTEP, are terminal control, Passengers with Reduced Mobility (PRM) service providers, baggage trolley/cart operations, emergency services, porter contractor and cleaning contractors. However, passengers remain the key stakeholder.

2.8.1 Palma de Mallorca Airport

Key stakeholders at Palma de Mallorca Airport are the airport owner and operator, AENA, of which the Spanish Government is a major shareholder (in contrast to LCY, which is 100% privately owned), the local transport operator (EMT Palma), and the airlines, tour operators and passengers. The airport is served by airlines predominantly flying in tourists from the UK and Germany whereby a large number of passengers are travelling to PMI on trips organised by tour operators.

At the moment PMI is experiencing increasing passenger numbers and is expanding to new destinations as travellers seek out safe and accessible holiday locations as Covid-19 restrictions ease, and many airports all over Europe still struggle to serve all passengers they could due to both their own staff shortages and those of major airlines and ground handlers, keeping passenger volumes still behind 2019-levels.

- The contemporary competitive landscape across much of the Mediterranean means that PMI needs to ensure that growing pains do not restrict or negatively impact this current growth trajectory.

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- A geographically dispersed and expanding international network of destinations helps to spread the risk of a sudden downturn in traffic at any one location (a new Covid variant to one side); however, human resource shortages across the sector mean that efficiently and consistently processing passengers remains a challenge likely only to increase.

The objectives identified for the two key stakeholders involved in the project, the airport itself and the public transport operator (EMT), were the following:

- For the airport, the objective was to **improve the predictability of passenger flows** for all stakeholders in order to make better decisions and apply more efficient management measures. This will allow the airport to take an active role in managing its resources by considering the incoming passenger volumes in the expected arrival times (e.g., by using smart check-in desk allocation).
- For EMT Palma, the objective was to **better match the public transport supply and real-time demand curves**, especially at the arrival's terminal, as well as to better understand passengers' actual origin and destination points on the island and have a better knowledge of user profiles for both passengers and airport workers.

As a result, PMI passengers (predominantly tourists) would benefit from a better experience of a stress-free and seamless journey from plane to their final destination and vice versa, feeling more comfortable, empowered and in control of their holiday trip. Another benefit derived from the objectives of the stakeholders would be a reduction on the environmental footprint, especially on the airport access, due to a higher predictability of the passenger flows, which would enable a better allocation of resources and services and a more adequate balance between passengers' demand and capacity.

2.8.2 London City Airport

Key stakeholders at London City Airport are the airport owner, currently a consortium of private organisations, made up of AIMCo, OMERS, Ontario Teachers' Pension Plan (OTPP) and Wren House Infrastructure Management. Airlines operating from LCY include British Airways, KLM, Alitalia, Lufthansa, CityJet, Luxair, Sky Work Airlines, Swiss International Airlines, VLM, Sun Air of Scandinavia and Aer Arann.

A specific LCY stakeholder is NATS, the ANSP since LCY first opened in 1987. NATS is now operating LCY from their Air Traffic Control Centre in Hampshire as the airport is the first commercial airport in the UK switching to digital ATC management. In the future, NATS will operate further airports from here, leading to a more effective mitigation of air traffic disruptions at different airports and ultimately supporting the operation of the IMHOTEP concept.

The initial objectives identified for the key stakeholders involved at LCY were the following:

- LCY's Global Vision is to remove any sense of psychological barrier between the airport and the final destination of the passengers.
- LCY is to become carbon-neutral in 2030.
- LCY is seeking to extend its market share and to increasingly attract leisure passengers, this will lead to new travel patterns with passengers arriving at the airport in groups and with more baggage to check-in.

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- LCY needs to expand, but uncertainties in the aftermath of Covid-19 and increasing environmental challenges are forcing a rethink on the size of the new passenger terminal and the consideration of outsourcing services away from the terminal and away from the airport campus.
- The airport has leveraged from the construction of the DLR and substantially improved access to public transport leaving LCY as one of the best-connected airports to public transport globally. However, the opening of the Elizabeth Line could change these dynamics as connecting times from Canary Wharf to London Heathrow have been cut in half to 45min. Excellent multimodal transport network connectivity and hyper-efficient airport operation are vital for the continued success of LCY.

Achieving these results entails better coordination between the airport and the ground transport modes, as well as a more detailed characterisation of the LCY passengers and their actual surface point of origin/destination. This will lead to a more seamless integrated transport chain and, as a result, to higher benefits for the LCY passengers, such as reduced travel times and waiting times.

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3 Refinement of case study definition

The main aim of this report is to demonstrate and evaluate the concepts and tools developed for the IMHOTEP Project through their application to the Palma de Mallorca Airport and London City Airport case studies. The demonstration and evaluation process includes three steps, as presented in Figure 10:

1. Revision and refinement of the case studies. This step develops an iterative and participative approach to integrate the relevant stakeholders and the project partners in order to define the specification of the most interesting simulation scenarios, given the characteristics and circumstances of the airports in the case studies, along with the management actions that can be implemented in each scenario and the KPIs to measure the effectiveness of the actions intended to mitigate the effects of the disruptions included in the scenarios.
2. Execution of simulation scenarios. Once the specification of the parameters that define different simulation scenarios is completed, these are implemented in the access/egress and terminal simulation models to validate their predictive capabilities and provide the outcomes for the next step.
3. Impact assessment. This step evaluates 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.

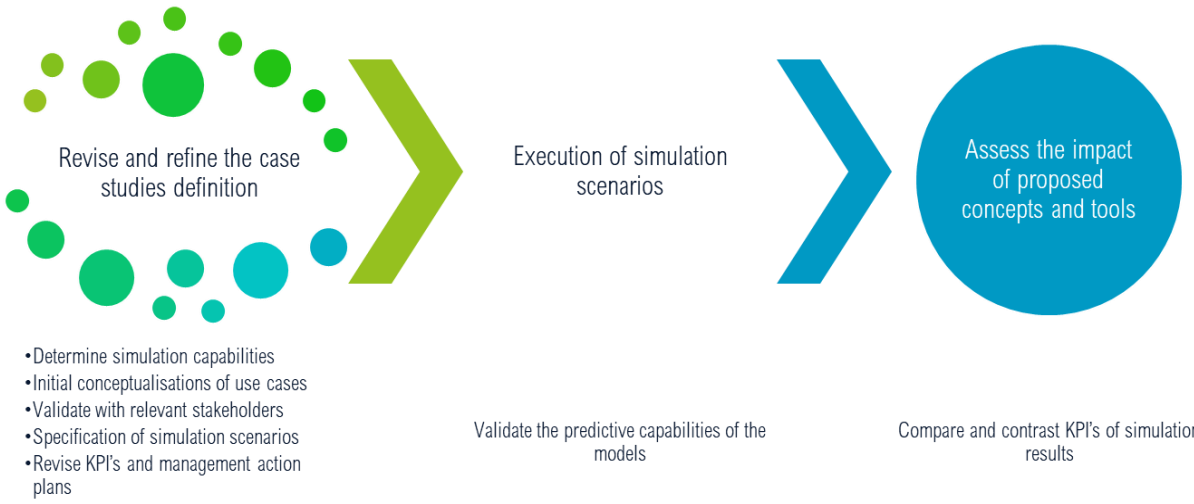

Figure 10: Schematic representation of the methodological approach for the assessment of the IMHOTEP concepts and tools

The revision and refinement of the case studies involved extensive discussion with both the project partners and key stakeholders in the two case study airports. This was done following three main activities (see Figure 11). First, a conceptualisation of the case studies was completed by the project partners in charge of Work Package 7 (Cranfield University and ISDEFE) after consultation with the modelling partners (Amsterdam University of Applied Sciences, Technical University of Dresden, Aimsun and Nommon) to fully grasp the capabilities of the models developed in Work Packages 4, 5 and 6. Then, two workshops to validate the initial conceptualisation of case studies were conducted at

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each of the airports involved, first in Palma de Mallorca and then in London City. The purpose of these workshops was to incorporate the perspective of the potential users of the tools developed in the project and to develop scenarios that reflected the actual considerations and concerns of the stakeholders in each context, with emphasis on the airports and surface transport providers. Finally, the partners coordinating WP7 defined a detailed specification of three simulation scenarios that was again validated with the modelling partners.

Figure 11: Process for validation of final simulation scenarios.

3.1 Initial conceptualisation of use cases

The initial conceptualisation to define potential use cases to build scenarios considered 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 12): *Air-realm* refers to events affecting flights or airport terminal processes; *ground-realm* refers to events affecting surface transport systems or passengers before they arrive to the airport forecourt or after they leave the airport premises upon arrival.

Figure 12: 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 different airports, both physically and in their operations, and their integration with surface transport networks, four generic events or combinations of events have been defined to be modelled as use cases (see Figure 12 and Table 1). These generic

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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.

Table 1. Generic definition of use cases that consider disruptive events affecting air or surface transport operations.

Air-realm	Ground-realm
Airport exit delay	**Airport arrival delay**
An airport exit delay refers to passengers experiencing travel times that are longer than expected due to events happening before they step out of the airport terminal.	An airport arrival delay (which could be considered as a city exit delay too, depending on the perspective) refers to passengers experiencing longer travel times due to events happening before they reach the airport terminal. These events are largely ignored in current air traffic management and airport operations, mostly because of the lack of tools that enable situational awareness and collaboration between relevant stakeholders. Crucially, disruption to surface access alternatives can greatly impact staff commuting to the airport to fulfil their roles, and therefore have a knock-on effect on other operations.
Airport departure delay	**Airport early arrival**
An airport departure delay refers to passengers experiencing travel times that are longer than expected due to events happening within the airport terminal before they board the departing aircraft. In this case, 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 make the decision to delay their journey to the airport, but this may pose a challenge to surface transport stakeholders because it will change the expected pattern of use of transport infrastructure and services.	Passengers arriving too early to the terminal can also be disruptive for an airport, especially if they do so in large groups. For the most part, because departing processes are normally started with check-in or bag-drop, which only open a fixed time before the scheduled flight departure (although some airports may allow for earlier check-in or bag-drop, this tends to be limited to major hub carriers at their hub airports). If passengers arrive too early and they have luggage to check in the aircraft hold, they will tend to mingle 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.

It is worth noting that, although the scenarios presented consider just one direction of passenger flow, they have an indirect impact on the flow of passengers in the opposite direction, as they can alter the number of passengers, vehicles and staff in areas used by both arriving and departing passengers. However, in order to allow the terminal and surface transport models to run sequentially and hence reduce the complexity of their integration, in this study arrivals and departures are considered at as two independent processes.

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Similarly, with the increase of online or otherwise automated check-in options, it seems like early arrivals should not be as disruptive in the near future, and the airport may actually benefit by increasing the opportunity of offering revenue-generating activities or services. However, airports where traffic is heavily driven by seasonal inbound tourism (such as Palma de Mallorca) can still be inconvenienced when early arrivals happen in large groups and not as a result of passenger preference but rather the decision of a third-party stakeholder, such as a tour operator. Whereas airports with a comparatively small footprint in the terminal (such as London City), may suffer unnecessary congestion if too many passengers arrive well in advance of their flights.

3.2 Use case validation workshops

The generic use cases defined in Table 1 were presented to a group of stakeholders in two validation workshops at each of the case study airports in order to define how exactly to implement the use cases as simulation scenarios in the models already developed. In addition, each workshop also covered the validation of the KPIs used to assess the impact of the mitigation actions that the management teams of the stakeholders could implement as a response to the disruptive events and the visualisation tool that presents the outcomes of the simulations to aid stakeholders in their situational awareness and decision making. The workshop facilitators (Cranfield University and ISDEFE) prepared material in advance to collect the most relevant inputs from all stakeholders and modify the use cases as the workshop developed. This material is collated in Appendix A and Appendix B.

The validation workshop for the Palma de Mallorca case study was conducted on the 19th and 20th May 2022 (see Figure 13) with representatives of Cranfield University and ISDEFE as facilitators; Amsterdam University of Applied Sciences and Nommon as modellers and developers of the visualisation tool; AENA as airport operator (and on behalf of ANSPs, airspace users and other airport users, such as tour operators); and EMT Palma as surface transport provider. The participating stakeholders were split into three groups for an initial discussion on the generic use cases and they were reorganised into two groups for the subsequent discussions on mitigating actions. Finally, the whole group jointly discussed the aspects concerning the visualisation tool. This arrangement was found to be the best way to collect individual feedback and group consensus at the same time.

This workshop was further enriched by a guided visit to Palma de Mallorca airport covering the forecourt of the airport to analyse user interactions for different transport modes used in accessing and egressing the terminal, and the terminal processes landside, both in the public and restricted areas. The visit was scheduled after an initial discussion on the conceptual use case definition so that more elements could be considered by all stakeholders in the subsequent discussions.

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Figure 13: Use case validation workshop at PMI. Collage H. Rothe

The validation workshop for the London City case study was conducted on 6th July 2022 (see Figure 14) and followed a similar structure to the one developed in PMI. However, because there had been substantial progress in the refinement of the use cases, the workshop in LCY was limited to the most relevant scenarios prioritised in the Palma workshop and focused more on identifying the specific circumstances and implications given the context of London City Airport (Figure 15). This workshop included representatives from Cranfield University as facilitators; Technical University of Dresden and Nommon as modellers and developers of the visualisation tool; London City Airport as airport operator (and on behalf of airspace users, ANSPs and passengers); and Transport for London as surface transport provider. A detailed visit to the facilities at LCY, both landside and airside, had already been conducted on the 11th November 2021, and thus the workshop focused on the discussion with the stakeholders about the simulation scenarios and management action plan.

Figure 14: Use case validation workshop at LCY. Photo H. Rothe

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Figure 15: London City Airport. Photo LCY Surface Access strategy 2017-2025

In order to facilitate the discussion around specific considerations for the simulation models, starting scenarios (see Table 2 to Table 4) were presented as exemplar narratives of disruptive events that align with the conceptual use cases defined in the previous section. All seven scenarios were presented in the PMI validation workshop and each of three groups conducted a ranking exercise to select four scenarios for further detailed discussion. All commonalities and differences between the selected scenarios were discussed with open questions from the facilitators to the entire assembled group.

Table 2. Exemplar narrative of disruptive events representing "Airport exit delay".

Airport exit delay
A major weather event (Delay of arriving flights)
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. Moreover, 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 be as well a change in the expected loads.
A major failure in the airport's baggage handling system
A major failure in the airport's baggage handling system (BHS) increases waiting time for a large proportion of arriving passengers. Arriving baggage is currently delivered to passengers via reclaim belts in the airside part of the airport terminal (the baggage reclaim area), usually just before customs control and the exit to onward transport alternatives. A failure in the BHS would accumulate passengers in an area of the terminal that is normally not prepared to hold large numbers of people for very long periods. In addition, this may increase the number of undelivered bags and subsequently alter passengers' plans for surface transport, as the absence of large pieces of hold luggage may open up other opportunities not previously considered. Moreover, as before,

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the unexpected delay poses a challenge for passengers and public transport stakeholders as the expected loads will not happen.
In the short term, the tools developed by IMHOTEP will help all relevant stakeholders to adjust to the situation and get back to normal operations quickly. In the future, however, the baggage handling process can be diversified offering passengers' alternative options, such as to have the baggage delivered to their final destination in the airport hinterland. This option would reduce the impact of potential delays at the airport but is not considered in this study explicitly.

Table 3. Exemplar narrative of disruptive events representing "Airport departure delay".

Airport departure delay
Major IT failure (Delay or cancellation of departure flights)
The information technology (IT) infrastructure of one of the main airlines at the airport, or one of the main ground handlers, experiences a major failure, forcing substantial delays to a substantial number of departing flights, or the cancellation of a substantial proportion of departing flights. *Flight delays* that occur at the airport are particularly challenging for airport stakeholders as they may be more demanding in terms of resource allocation. For instance, the aircraft may be ready to depart at the stand but it cannot do so because passengers have not been processed. This means the stand cannot be used for another flight in the meantime. However, if passengers and surface transport stakeholders can be informed of this eventuality, they can adjust their plans accordingly, especially in the case of *cancellations* that would otherwise require two additional trips (out of the airport and back) for some passengers.
Aircraft late arrivals (Delay of departing flights)
Departure delays due to accumulated delays affecting an aircraft rotation can be significant for a particular flight, yet it is rare that they are experienced by a substantial proportion of departing flights at the same time. For the air-realm stakeholders, however, late arriving aircraft can strain their resource allocation (especially because it affects both arriving and departing passengers); whereas for departing passengers this can present an opportunity to better adapt their journey to the airport; and arriving passengers, along with surface transport stakeholders, can be disrupted in the same ways as described for airport exit delays (Table 1). In fact, this condition can be considered as covered by both airport exit and airport departure delays, and thus it will not be modelled explicitly. Nonetheless, it represents a particularly relevant potential application of IMHOTEP tools.

Events affecting the door-to-door passenger journey outside of the airport premises, and outside of the control of air-realm-related stakeholders, are classed as *ground-realm* in the definition of the use cases. The tools developed for IMHOTEP are expected to have a positive impact in these type of situations as they are enabled by extending information sharing beyond the traditional air traffic management stakeholders. In order to have generic instances that could be replicated for any airport, ground-realm events have been grouped into airport arrival delays and airport early arrivals. The scenarios representing arrival delays are presented in Table 4. Early arrivals were initially considered when the number of departing passengers within a one-hour time window substantially exceeds the normal passenger presentation profile for the day and time under simulation. This was considered only relevant for PMI when tour operators deliver departing passengers too long in advance before their flights.

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Table 4. Exemplar narrative of disruptive events representing "Airport arrival delay".

Airport arrival delay
The two airports considered in the case studies heavily rely on very specific surface transport systems to carry a substantial majority of their passengers and staff: the Docklands Light Rail (DLR) for London City Airport (LCY) and the Autopista de Llevant motorway for Palma de Mallorca Airport (PMI). Yet this configuration is far from unique as many airports are serviced by few trunk roads or rail lines. Therefore, a major incident affecting the infrastructure or services to reach the airport can cause significant levels of delay to a substantial proportion of passengers. Moreover, local (outbound) and visitor (inbound) passengers will have uneven levels of knowledge about the occurrences and the existence of alternative ways to access the airport. There are different ways in which these incidents can occur, such as: - For PMI, an accident in the Llevant motorway, especially if it happens between junctions 7 and 10, can block most traffic or induce long detours to reach the airport. Moreover, public transport services provided by EMT may be affected more strongly as the flexibility to find new routes may be reduced. In addition, the relative high frequency of the A1 service to/from Palma city centre increases the chances of bus bunching and, therefore, of minor incidents affecting the remaining services for a longer period of time. - For LCY, severe delays and line or station closures in the DLR service, especially the lines to Woolwich Arsenal, would impact a sizeable proportion of passengers. Moreover, incidents in the rest of the Transport for London network, including key transfer stations en-route to the airport such as Bank or Stratford, may be less obvious for airport stakeholders but equally impactful. Similarly, traffic congestion in the roads around the LCY terminal can lead to delays for passengers using private cars, buses, black cabs or other on-demand taxis. Citizen protests, particularly those more concerned with environmental aspects, may target airports in their demonstrations and block passengers from reaching the terminal on time for their flights. This can be either by blocking access roads or by directly blocking airport terminal access. In all these cases, the expectation is that a substantial proportion of departing passengers will face a significant delay in arriving to the airport.

3.3 Validated simulation scenarios

The seven scenarios proposed in the validation workshop at PMI were coded as follows:

- Air-realm
  - S1. Delay of arriving flights
  - S2. Delay at baggage reclaim
  - S3.1 Delay of departing flights
  - S3.2 Cancellation of departing flights
- Ground-realm
  - S4.1 Road disruption
  - S4.2 Public transport disruption
  - S5. Tour operator early arrival at PMI

Participant groups (three groups, as mentioned above) were invited to rank the four most relevant scenarios and then a numerical score was assigned to each depending on the importance given by the group: 4 points to the most important, 3 to the second, and so on. This allowed for a weighted total score to be calculated for each scenario to define a consensus. After two rounds of open discussion

with all the participants, only three scenarios were considered as the most relevant for the two case studies:

- S1. Delay of arriving flights
- S3.1. Delay of departing flights (S5. Tour operator at PMI was seen as a special case of the same scenario)
- S4.1. Road disruption (S4.2. Public transport disruption was considered as a special case of the same scenario)

Given that for PMI road transport is the only mode to access/egress the airport, a disruption to the main motorway would affect both users of private vehicles and public transport alternatives. However, for LCY most passengers use the DLR, hence a disruption to public transport would be more relevant but still the focus in the discussion was geared towards airport access as more relevant than airport egress. Then, the last scenario was renamed 'disruption in surface access transport'. The original codes were disregarded to ensure coherence in the final presentation of the results.

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.

3.3.1 Delay of arrivals

Table 5. 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

It is worth noting that 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.

3.3.2 Delay of departures

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Table 6. 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

3.3.3 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, whereas for LCY only a disruption to the London Underground, with potential knock-on effects on DLR services is considered.

Table 7. Simulation parameters for "Disruption in surface access transport" 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 and then reopen one lane for another half an hour before it fully opens again.
Travel time	As determined by the model (Travel times are affected by the effect of re-routing and congestion)	Passengers affected may miss their flights and this is measured in the terminal model

Table 8. Simulation parameters for "Disruption in surface access transport" at London City Airport.

Parameter	Value for LCY	Notes

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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 This 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 a substantial change in modal choice when disruption happens but this may differ depending on the type of passenger consider (i.e., locals vs. tourists)

3.4 Management action plan

Management actions aimed at mitigating the disrupted situations of each of the selected scenarios were discussed in each workshop (following the triggering questions suggested in Table 9) and were validated in close collaboration with the stakeholders involved (airport and ground transport operators). “Action plans” were then defined as a combination of individual management actions in order to compare the baseline scenario (scenario considering the definition of the associated disruption but with no management action plan implemented) and the scenario applying the management action plan in order to mitigate the impact of the disruption.

Table 9. Triggering questions to facilitate the discussion around the management actions to mitigate the effects of the disruptions defined in the simulation scenarios.

Feasible action?	Useful action?	Implementation
Is it possible to implement in reality? By which stakeholder? How long in advance should they know about the situation to trigger the action?	Would there be a real benefit after implementing the action? Which stakeholder would benefit? Which stakeholder may be inconvenienced by the action?	Does each management action lead to a different simulation scenario? Is each management action implemented at a single level (i.e., a change in bus frequency from 1/30 min to 1/15 min) or to different levels (i.e., a change in bus frequency from 1/30 min to 1/20 min to 1/15 min to 1/10 min)?

Table 10 to Table 12 summarise the parameters to be implemented in the simulation models to emulate real-time decision making by the relevant stakeholders highlighted in each case.

Table 10. Simulation parameters for management action plan considering the “Delay of arrivals” scenario.

Action	Notes

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Open more manual passport control lanes (if possible, i.e., if not all are open already)	Technically the authority that handles border control would make this decision, but it is assumed it is the airport for modelling purposes.
Change frequency of public transport (PMI only)	Increase one bus on each line (A1 and A2) leaving the airport on each hour after one hour from the start of the disruption (i.e., two more services on each line between 12:00 and 14:00 local time). The new service should try to spread the frequency evenly (i.e., if there's one bus every 30 min before the disruption (2 buses/hour), then it should be 1 every 20 min now (3 buses/hour)). * DLR frequency for LCY is high enough to absorb the delays, and DLR final service is late enough to capture LCY service closure for the day. Hence no changes proposed for LCY.
Open Hartmann Road access to the East for taxis only (LCY only)	In light of possible congestion, the airport can decide to open the additional access to LCY in order to lighten the traffic in the rest of the exits.

Table 11. Simulation parameters for management action plan considering the "Delay of departures" scenario.

Action	Notes
Delay departure time of surface access leg	50% of the delayed passengers can start their journey as if the delayed departure was the scheduled departure (i.e., later than originally planned).
Change transport mode for surface access leg	10% of the delayed passengers that originally travelled by taxi can travel by public transport now and start their journey at the same time they would do it before The action is based on the assumption that, due to extra time to arrive to the airport caused by the delay, passengers have the possibility to take a PT option (which was not previously available due to time restrictions).
Change frequency of public transport (PMI only)	Increase one bus on each line (A1 and A2) towards the airport on each hour after one hour from the start of the disruption (i.e., two more services on each line between 07:00 and 09:00 local time). The new service should try to spread the frequency evenly (i.e., if there's one bus every 30 min before the disruption (2 buses/hour), then it should be 1 every 20 min now (3 buses/hour). DLR frequency for LCY is high enough to absorb the delays.
Delayed passengers can "fast-track" security (i.e., skip the queue)	Applicable to PMI fast-track security lanes. LCY does not provide fast-track security.

Table 12. Simulation parameters for management action plan considering the "Disruption in surface access transport" scenario.

Action	Notes

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Open Hartmann Road access to the East for taxis only (LCY only)	This should reduce travel time by taxi and thus increase the probability of passengers using it.
Anticipate departure time of surface access leg	25% of passengers (randomly selected) due to travel during "time of disruption" can start their journey: - 30 min before (LCY) - 45 min before (PMI) than originally planned.
Delayed passengers can "fast-track" security (i.e., skip the queue)	Applicable to PMI fast-track security lanes. LCY does not provide fast-track security.

3.5 Key Performance Indicators

The KPIs had already been redefined in previous meetings taking Deliverables 2.1 and 2.2 as a starting point, particularly in the discussion of the project meeting held in Barcelona on February 7th to 8th, 2022, and were re-evaluated during the validation workshop in Palma de Mallorca where small variations were suggested. Finally, after analysing the feedback received during the workshop and in light of the simulation results obtained, the KPIs presented in Table 13 were considered appropriate for the objectives of the project and the stakeholders involved.

Table 13. KPIs defined for the validation experiments.

KPI	How to measure it?	Aggregation	Segmentation	Visualisation
Access/egress model				
Modal share	Percentage of users choosing each transport mode.	Total time window	- Passengers/Staff - Business/Leisure - Residents/Non resident	Stacked bar plot
Travel times	Probability distribution of the door-to-gate/gate-to door travel times broken down by terminal and access/egress.	Total time window	- Destination/Airline - Flight time	Histogram (bar plot)
CO_2 emissions	Total CO_2 emissions per unit of time	Total time window	N/A	Bar plot
Occupancy on the PT alternatives	Number of users in the PT vehicles every hour.	Hourly	- Passengers/Staff - Business/Leisure - Resident/Non resident	Bar plot
Productivity of the ground side transportation	Simulation totals of the passengers-km travelled by mode.	Mode of transport	- Passenger/Staff - Business/Leisure - Resident/Non resident	Bar plot
Waiting time (PT options only)	Probability distribution of the waiting time for the PT alternatives.	Total time window	N/A	Histogram (bar plot)

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KPI	How to measure it?	Aggregation	Segmentation	Visualisation
Terminal model				
Queuing time at the terminal facilities	Evolution of the passenger waiting time at the airport facilities.	15 minutes	- Destination - Airline	Line plot
Facilities throughput	Evolution of the passenger throughput at the airport facilities.	15 minutes	N/A	Line plot
Occupancy at airport areas	Evolution of the occupancy in the different airport areas. Occupancy is defined as: $\sum_{p=0}^{n_pax} \frac{time\ spend\ in\ the\ area_p}{time\ interval}$ where *n_pax* is total number of passengers (*p*)	15 minutes	- Destination - Business/Leisure	Line plot and heatmap
Dwelling times at the airport areas	Evolution of the dwelling time in the different airport areas	15 minutes	- Destination - Business/Leisure	Line chart including percentiles
Missed flights	Number of passengers that missed their flights	Transport mode	- Cause (flight lost at check-in or at gate) - Flight number/Airline	Bar plot

The final set of KPIs are focused on reflecting the needs and expectations of the stakeholders involved in the project (airport and ground transport operators). Although AU or ANSP representatives are not involved in the project, the developed tools enable the possibility of allowing airlines, as one of the key ATM stakeholders, to make decisions in response to the enhanced situational awareness and based on some of the KPIs developed, such as delaying flights if a given proportion of passengers were known to be too late to the departure gate. Therefore, the 'missed flights' indicator could be considered as an ATM-related KPI; however, potential airline actions have finally not been modelled due to the absence of any airline representative within the project.

This kind of action should be considered in further development steps as other relevant stakeholders become involved in the development of the concept, such as AUs or ANSPs. The involvement of such stakeholders could also extend the initial set of KPIs proposed in light of new requirements and expectations of these new actors.

3.6 Visualisation tool

The validation workshops performed in Palma and London City allowed the collection of valuable feedback from the airport and ground transport stakeholders involved in the project. The feedback received was collected in deliverable 'D6.1 IMHOTEP Simulation and Decision Support Toolset'. Nevertheless, given time constraints in the project, while some of the feedback received has been implemented within the current prototype of the visualisation tool, some of these recommendations remain potential future work to be addressed in further concept development steps.

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It is worth noting that the visualisation and decision support tool developed within the project is an initial prototype whose aim is to show the potential of the implementation of the proposed concept as well as to demonstrate the feasibility to extract relevant KPIs for the involved stakeholders based on a holistic view of the passenger flows. In future implementations, these visualisations should be integrated into the existing platforms of the airport (A-CDM platform in case of CDM airports, but also already existing monitoring platforms in non-CDM airports), or deployed as an extension of the current tools already in place in the airport, according to the standards and regulations established on the implementation airport.

The current version of the visualisation tool is presented in Figure 16. It 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, as defined in Table 13. 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 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.

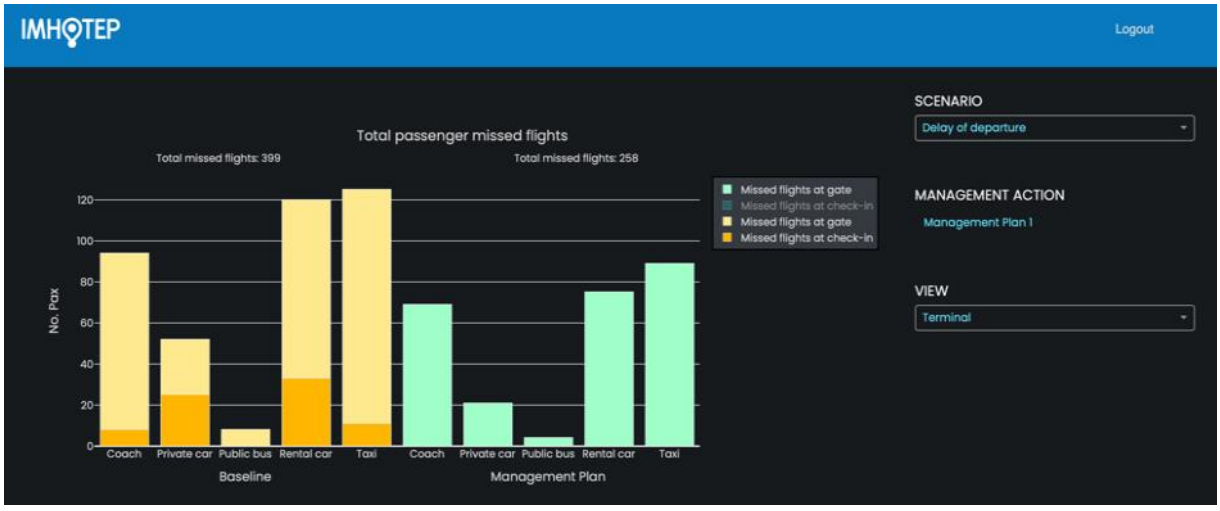

Figure 16: Snapshot of the web-based IMHOTEP KPI visualisation tool.

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4 Assessment of the simulation results

As explained in chapter 3, three simulation scenarios 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. Crucially, IMHOTEP considers that passengers play a crucial role in this process if timely information is made available.

The following sub-sections discuss the specific results of the comparative assessment for the two case studies. Given the depth and breadth of the KPIs considered, including the level of detail gained by segmenting some of the KPIs, the assessment is not exhaustive but rather attempts to capture the most interesting and relevant results.

The assessment also navigates around 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 an 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 it into their day-to-day routine and accelerate the positive impact or mitigate the negative effects.

4.1 Simulation results

4.1.1 Delay of arrivals

For quick reference, below is a synthetic description of the simulation scenario concerning the delay of arriving flights:

Table 14: Synthetic description of the 'Delay of arriving flights' scenario

	PMI	LCY
Summary	Substantial delay in a significant proportion of flights arriving to the airport	
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 PT frequency is increased	Additional passport control desks are opened and an additional access to the terminal is opened

4.1.1.1 Palma de Mallorca

Analysing the travel times, the management action performed on the terminal (opening of additional passport control desks) causes a reduction of the terminal travel time for non-Schengen passengers, as presented in Figure 17 (green graph). The mitigation management action remarkably increases the

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peaks of passengers that spend around 20 minutes and 40 minutes in the terminal, while the passengers that spend more than 40 minutes are notably reduced. This is particularly notable for the number of passengers that spend more than 50 minutes within the airport terminal, which is reduced to almost zero. Additionally, the actions performed on the ground transport systems also contribute to reducing the passenger travel times on the egress (white graph).

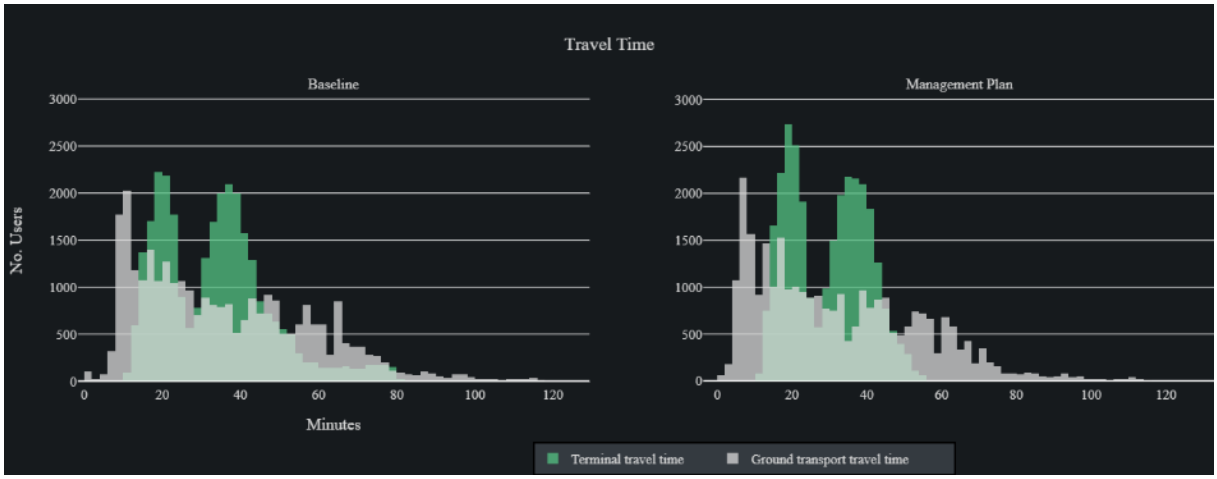

Figure 17. Reduction of travel times when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

When analysing the passenger throughput (i.e., number of incoming passengers), queue times and occupancy at the manual passport control (Figure 18, Figure 19 and Figure 20, respectively), it can be appreciated how opening more passport control lanes drastically reduced the queue time from more than 50 minutes to just 13 minutes, increased the number of processed passengers from a maximum of 500 to more the 800 passengers every 15 minutes and acutely reduced the occupancy on the passport area from a peak of more than 2,000 passengers to just half of the occupancy, thus contributing to a significant reduction of the impact on the passengers.

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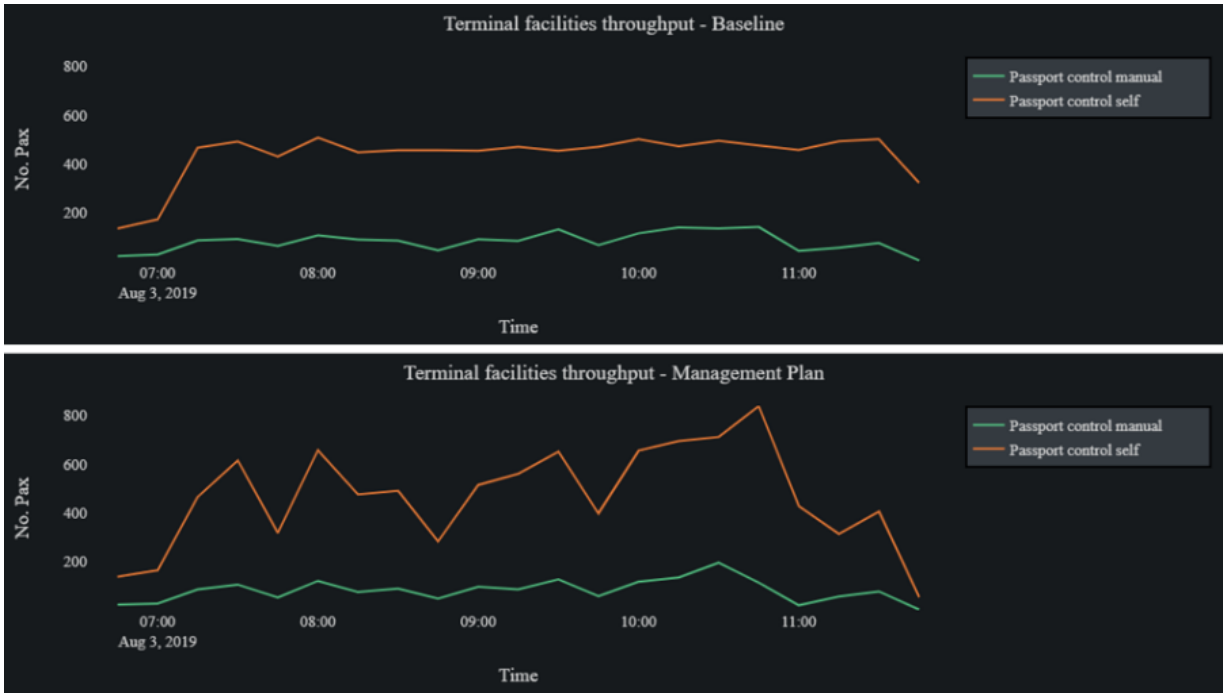

Figure 18. Increase of the throughput at the passport control when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

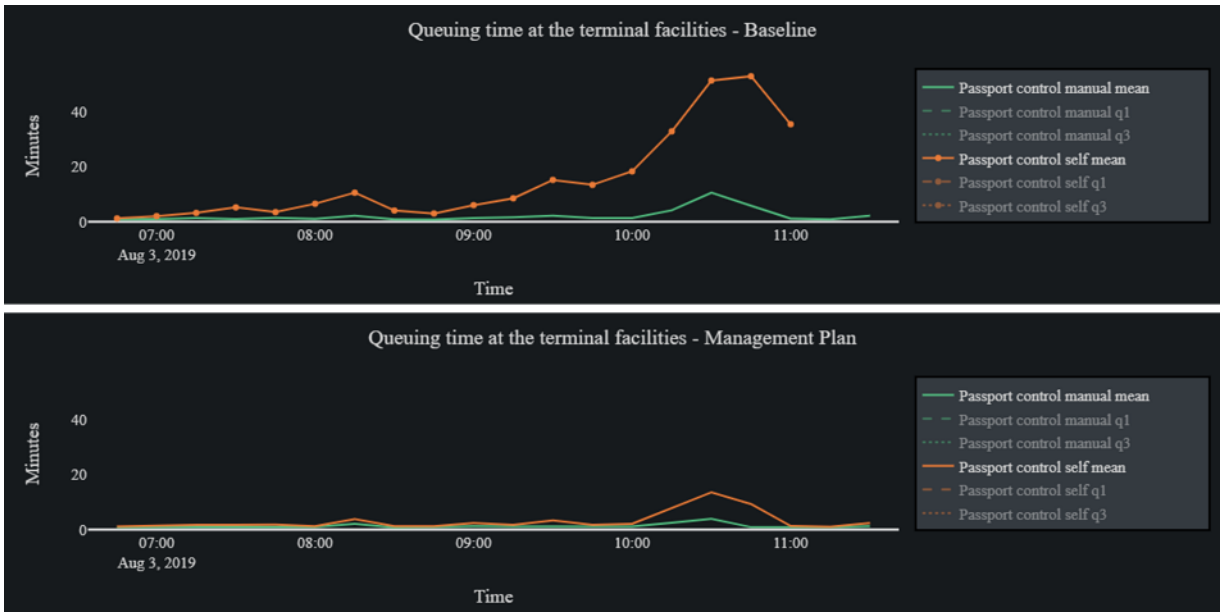

Figure 19. Reduction of passport control queueing time when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

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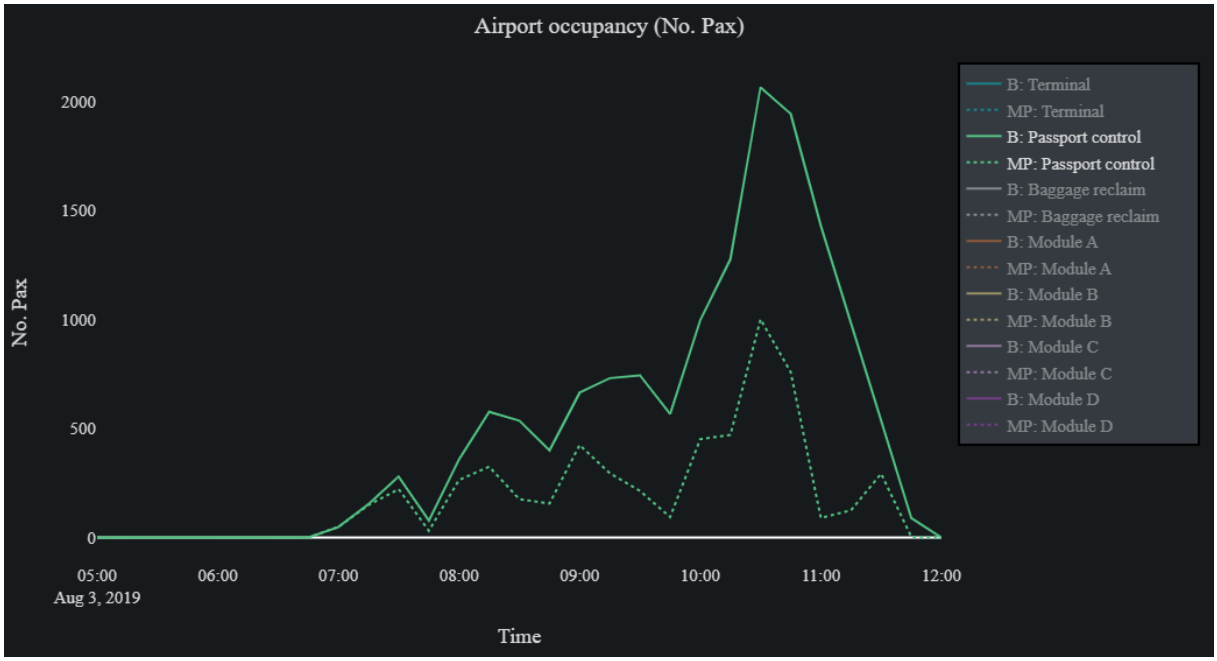

Figure 20. Reduction of the passport control area occupancy when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

Additionally, the increase in the public transport frequency allows a higher number of passengers to use the PT modes due to a reduction of the waiting times. Figure 21 shows that, before applying the management action, the number of PT users waiting less than 8 minutes for the PT alternative increases notably when comparing with the baseline scenario. This increase of the PT users leads to an increase of the PT modal share from less than 2% to more than 4%, as presented in Figure 22. This has an impact on CO_2 emissions, as presented in Figure 23.

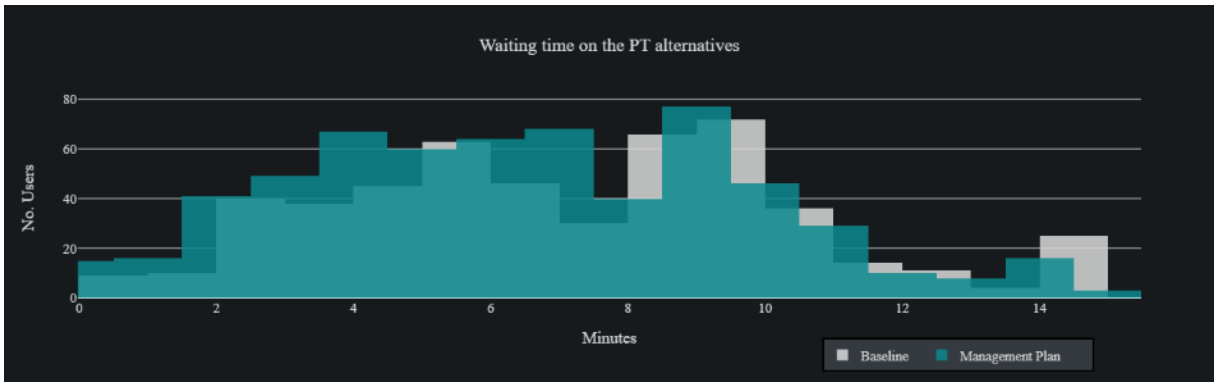

Figure 21. Reduction of passenger waiting times for PT alternatives when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

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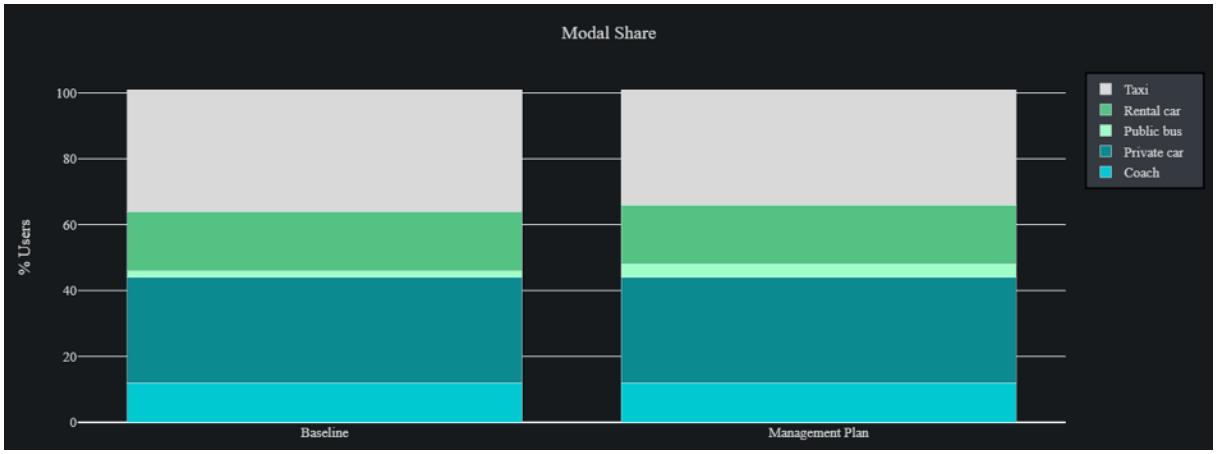

Figure 22. Increase on the PT modal share when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

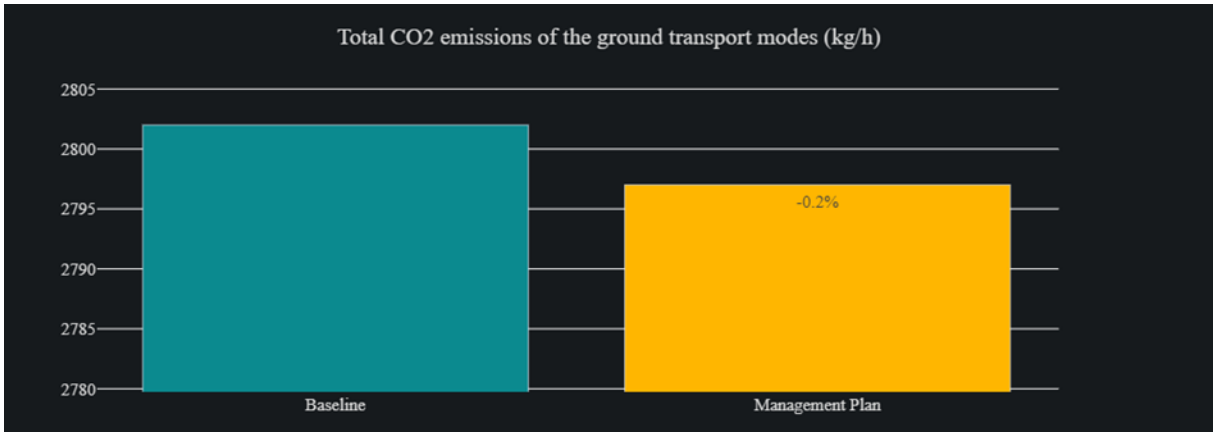

Figure 23. Reduction of CO_2 emissions when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at PMI.

4.1.1.2 London City

At London City, the opening of additional immigration control desks also reduced the queue time as presented in Figure 24. As the number of passengers attending the immigration control is not massive, the application of the management action reduced the waiting time to almost 0. Similarly, in Figure 25 a clear reduction of the occupancy in the immigration control area is appreciated due to a more agile processing of the passengers.

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Figure 24. Reduction of immigration control passenger queuing time when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at LCY.

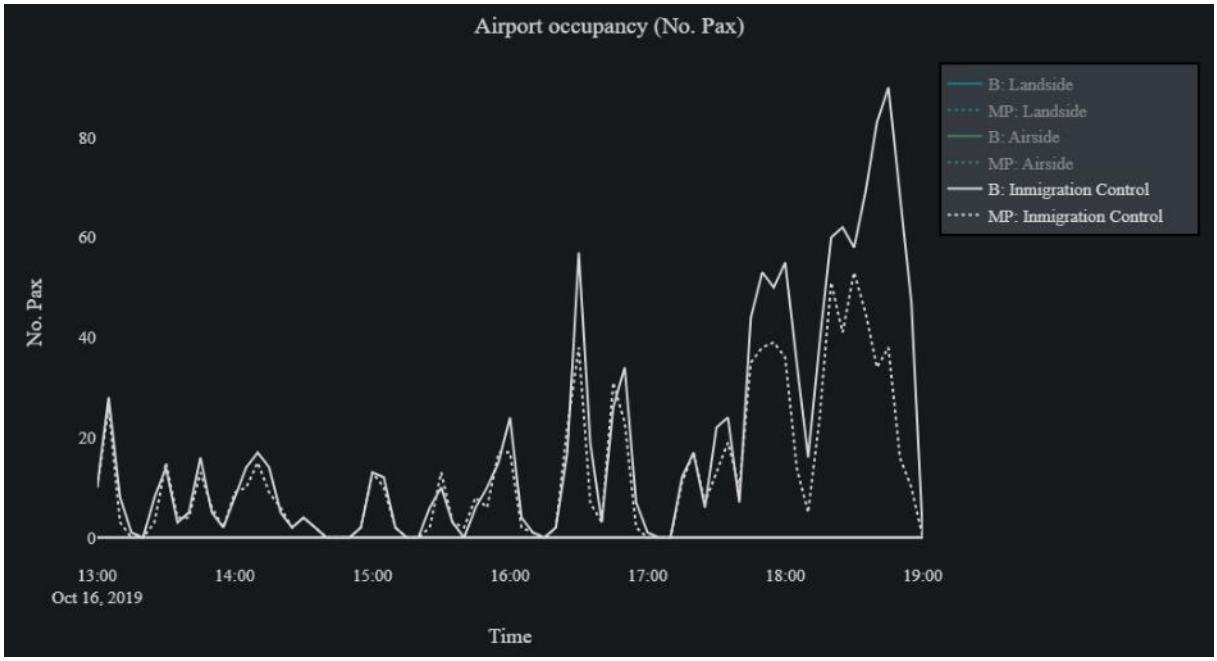

Figure 25. Reduction of immigration control area occupancy when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at LCY.

In this case, the management action on the surface consisted in opening an additional access to the terminal to lighten the rest of entries and exits in light of possible congestions 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 London City airport, the congestion produced is not significant. However, the reduction on the congestion causes a 1.51% reduction of CO_2 emissions, decreasing from 151.9 kg/h to a 149.6 kg/h, as presented in Figure 26. As mentioned in Table 10, due to the frequency and capacity of the DLR, which is able to absorb potential delays, the implementation of a modal

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change from DLR users to taxi due to passenger waiting times, as in the case of Palma, was not reasonable in this case. Therefore, it is worth noting that the reduction of the carbon emission is purely produced by the reduction of the congestion on the access caused by the opening of an additional access road.

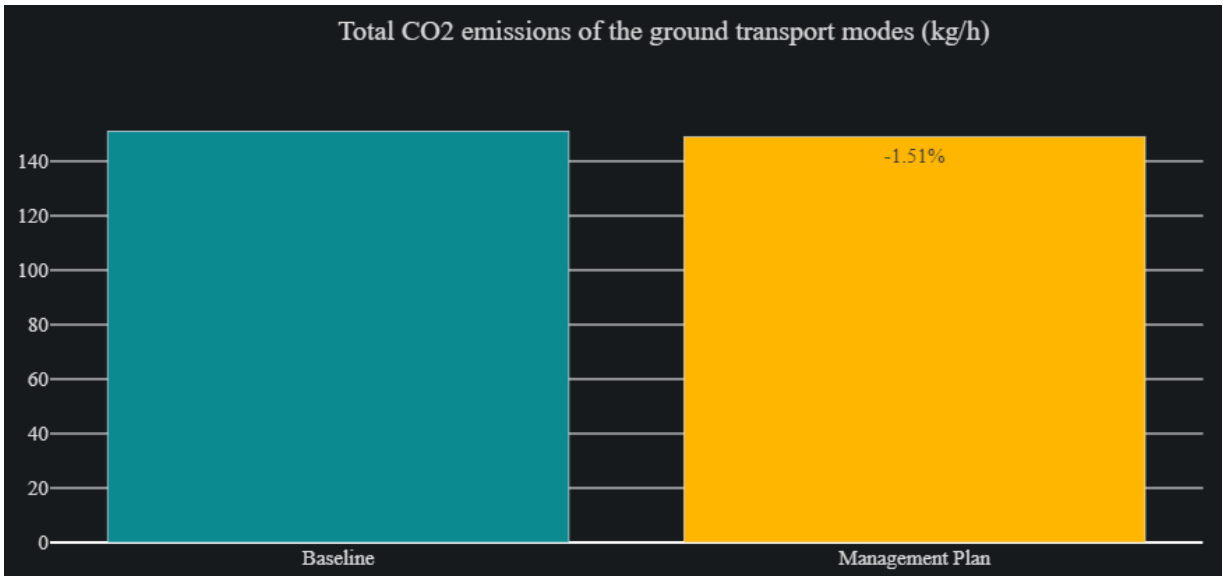

Figure 26: Reduction of CO_2 emissions when applying the management plan in comparison with the baseline scenario for the use case 'Delayed arrivals' at LCY.

4.1.2 Delay of departures

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

Table 15: Synthetic description of the 'Delay of departing flights' scenario

	PMI	LCY
Summary	Substantial delay to a significant proportion of flights departing from the airport	
Disruption	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.	

4.1.2.1 Palma de Mallorca

The management actions performed slightly reduced the travel times of passengers whose flights have been delayed. This is shown in Figure 27, where a reduction of passengers with longer travel times in the airport terminal is clear and the peak of passengers with shorter travel times (around 70-90 minutes) has increased.

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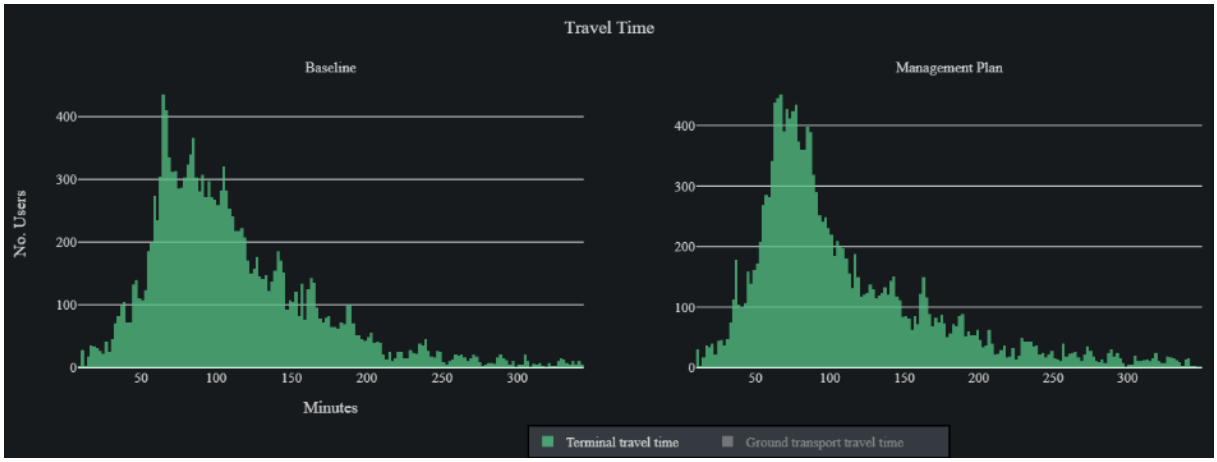

Figure 27. Reduction of terminal travel times when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at PMI.

The modal share is slightly modified due to the change of some of the delayed passengers to public transport modes, which translates into a 2% increase of the public bus share, 3% in the baseline vs 5% afterwards (see Figure 28). 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 counteracts this effect. Therefore, the reduction of the CO_2 emissions is not as significant as expected.

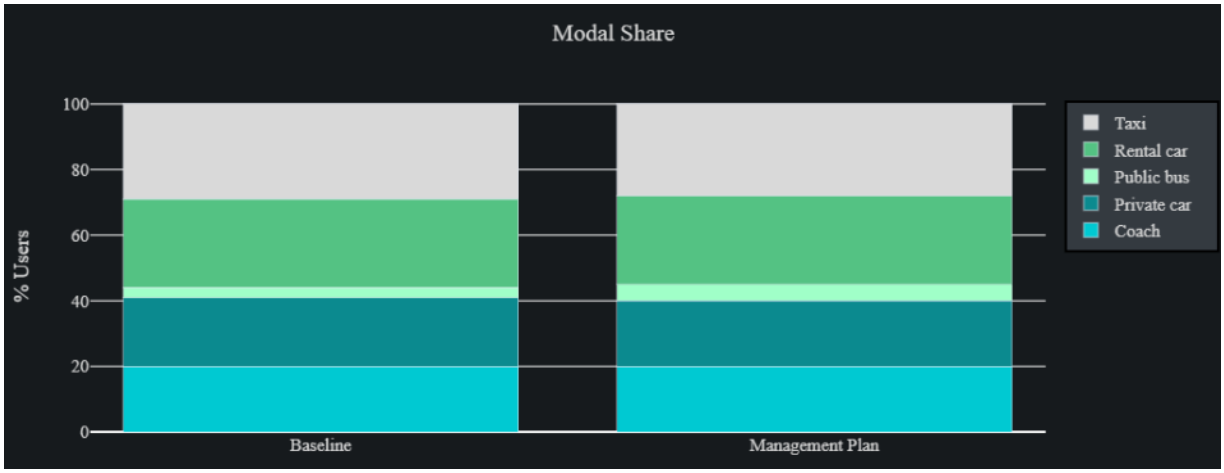

Figure 28. Increase of PT modal share when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at PMI.

The increase of users on the public transport modes can be also notably appreciated when displaying the occupancy on the public transport alternatives (Figure 29), where, during the times affected by the delayed flights, the occupancy in the public transport vehicle significantly raises. Additionally, due to the increase of the PT frequency, there is a marked reduction in the passenger waiting times at the public transport stop (Figure 30) and, additionally, also new passengers that modify their access mode to public transport alternatives have reduced waiting times.

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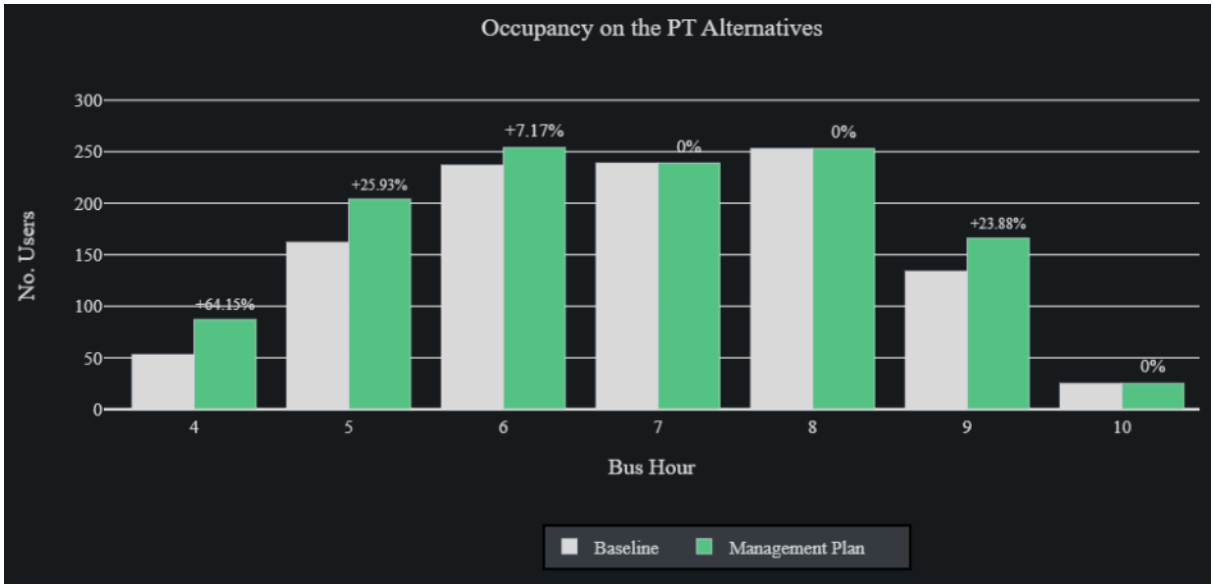

Figure 29. Variations in PT occupancy between the management plan and the baseline scenario for the use case 'Delayed departures' at PMI.

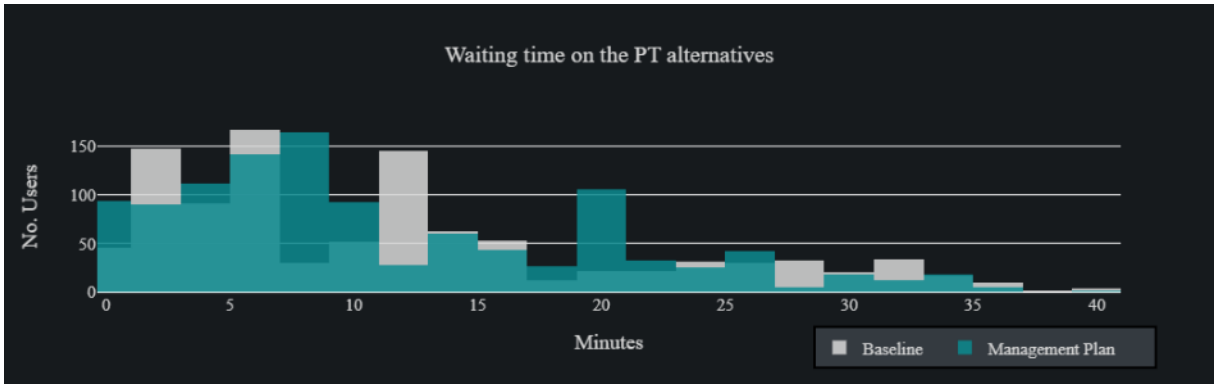

Figure 30. Reduction of PT waiting times when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at PMI.

Regarding the terminal, the delay of the passengers' arrival time to the airport not only does not affect negatively the number of flights missed but also contributes to the reduction of flights missed by passengers. Figure 31 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. This is likely to be due to a reduction in the congestion during the access and on the terminal, caused by the more gradual arrival of passengers at the airport and the shift of some passengers to public transport modes. Additionally, the reduction of flights missed at the gate may also be produced by the reduction of the congestion at the security control due to this more gradual arrival of passengers, and the terminal management action performed that allows delayed passengers to use the fast-track lane to access the security control.

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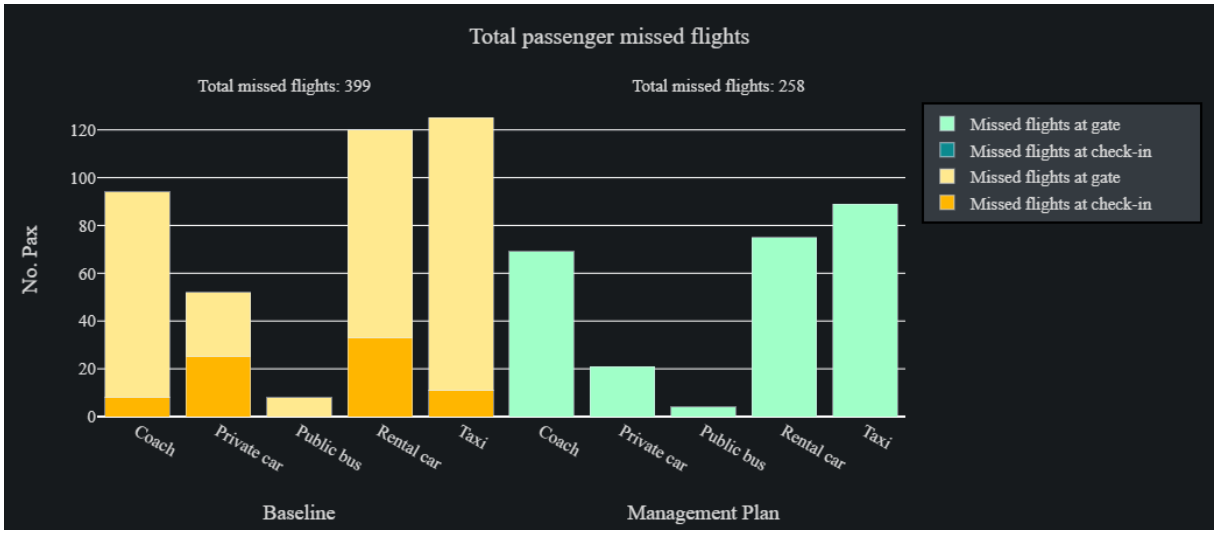

Figure 31. Reduction of the number of missed flights when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at PMI.

When analysing the queueing time at security (Figure 32) a reduction is apparent between 07:30 and 08:30 as some passengers (now aware of the delayed departure of their flight) arrive later at the airport, thus avoiding this busy hour. Additionally, the waiting time peak decreases from 19 to 16 minutes.

Figure 32. Reduction of passenger queuing times at security control when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at PMI.

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4.1.2.2 London City

For London City, the results display similar behaviours as in Palma de Mallorca. In this case, the increase in the share of DLR goes from an initial 47% to a 49%, resulting in a reduction of CO_2 emissions. As in London City the public transport modes (DLR) are not modelled, the graph presented in Figure 33 just includes private traffic emissions (private car and taxi); emissions are reduced by around 3%, going from an initial 207 kg/h to 200 kg/h. The reason that the emissions are much lower than in the PMI case study is because the LCY surface model just includes the surroundings of the airport, while the PMI model is more complex and includes a larger portion of the road network.

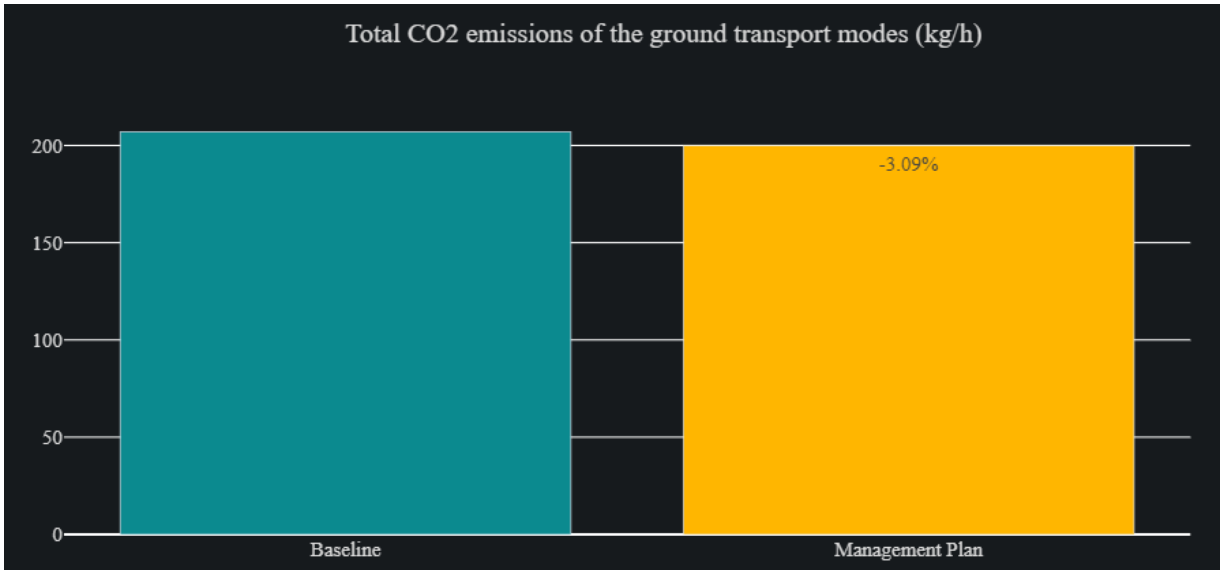

Figure 33. Reduction of CO_2 emissions when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at LCY.

Inside the terminal, the security control 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 34). This is beneficial to the airport as it facilitates the management of resources allocated to the security control. Additionally, the maximum peak of passengers also slightly rises from 277 to 284.

The effect of delaying the passenger arrival, can be also appreciated on the airside dwell time. The comparison presented in Figure 35 shows a reduction, where the maximum average dwell time decreases from 107 to 101 minutes, as well as the Q1 and Q3 quartiles, which drops from 140 to 136 minutes and from 28 minutes to 24, respectively.

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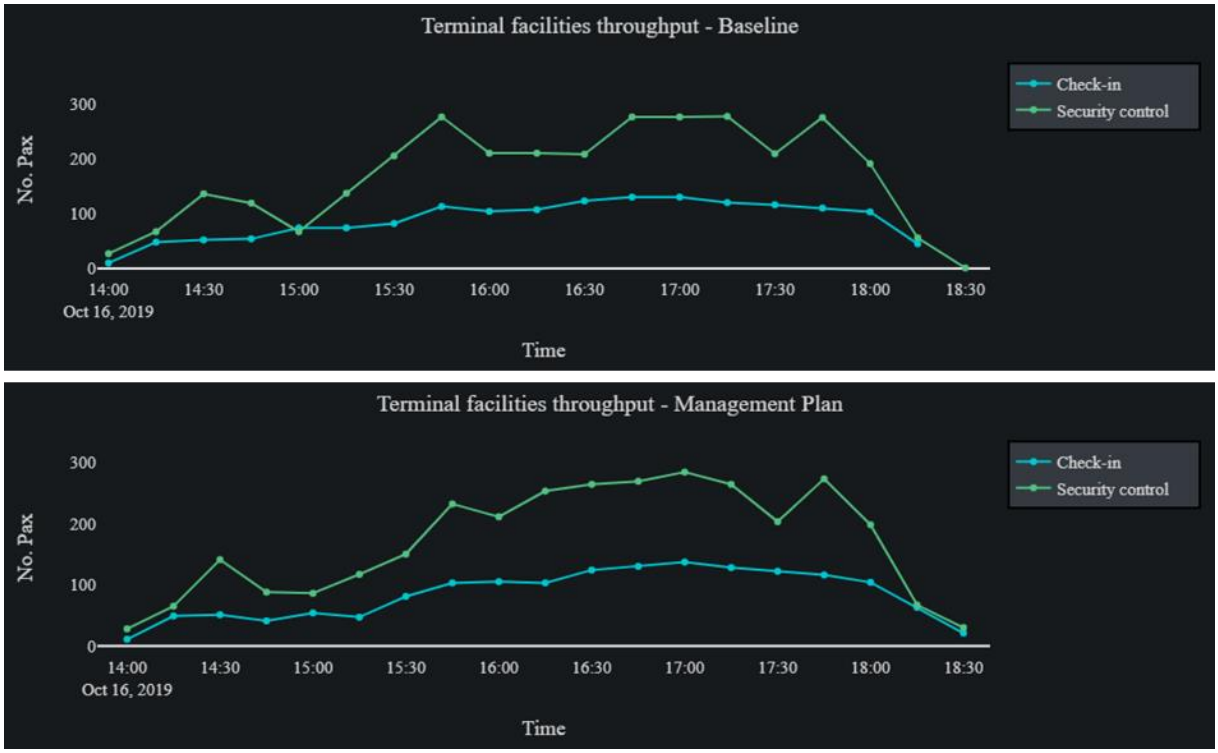

Figure 34. Increase of the security control throughput in when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at LCY.

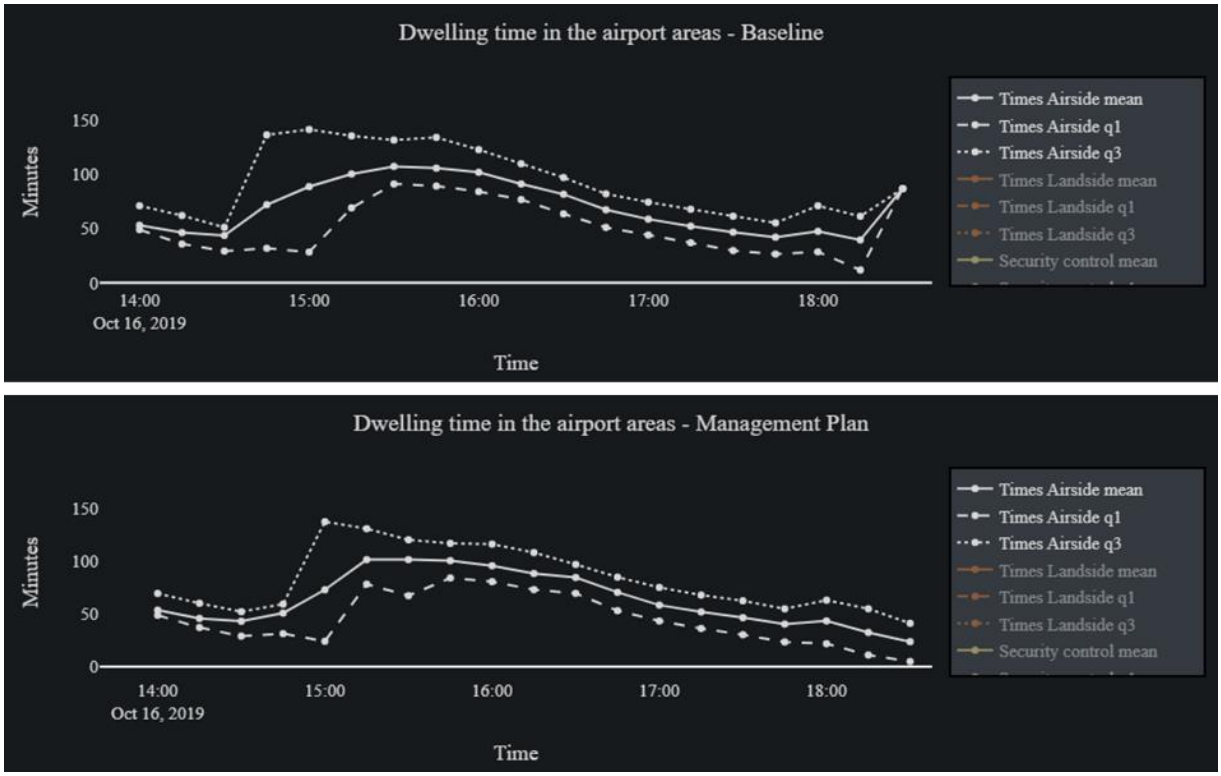

Figure 35. Decrease in the airside dwell times when applying the management plan in comparison with the baseline scenario for the use case 'Delayed departures' at LCY.

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4.1.3 Disruption in surface access transport

For quick reference, this is a synthetic description of the simulation scenario concerning the disruptions in surface access transport:

Table 16: Synthetic description of the 'Disruption in the surface access' scenario

	PMI	LCY
Summary	A critical disruption to the main transport system used to access the airport	
Disruption	Closure (followed by partial closure) of the main motorway in the direction from the city to the airport. Coincides with the morning peak of departures	Unbalanced distribution of passengers arriving by DLR due to a planned disruption in the London Underground network (i.e., a strike) 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

4.1.3.1 Palma de Mallorca

Providing information to passengers so they can adapt to the current status of the road enables them to depart earlier and, as a result, the congestion in the airport access is reduced. This has an effect on the travel time, which has been slightly reduced, as well as in the CO_2 emissions. The travel time is presented in Figure 36, and it is appreciated that the number of passengers spending more than 100 minutes in the access has been reduced (see Figure 36b), and the peaks of passengers around 20-25 minutes and 45-55 minutes have increased (see Figure 36a).

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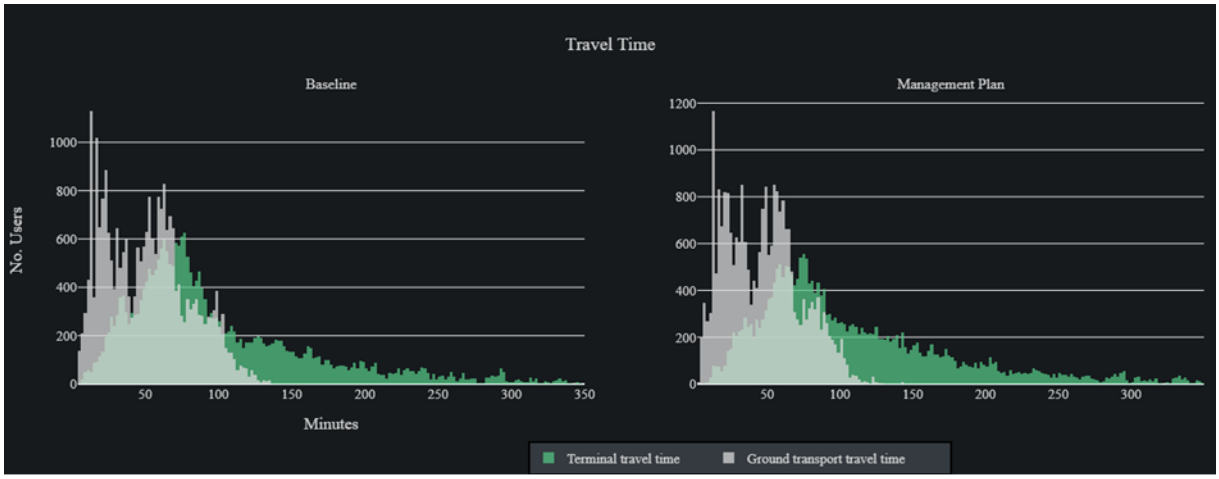

a)

b)

Figure 36: Reduction on travel times when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at PMI (a) and detail on times between 70 and 140 minutes (b).

Regarding the environmental footprint, the CO_2 emissions have been reduced from a 3,264.6 kg/h to 3,192.6 kg/h, which represents a 2.2% of reduction (see Figure 37). It is important to remark that this reduction in carbon emissions is purely due to the reduction of the congestion caused by an early arrival of passengers to the airport, as in this scenario the switch of passengers from one mode to another has not been considered.

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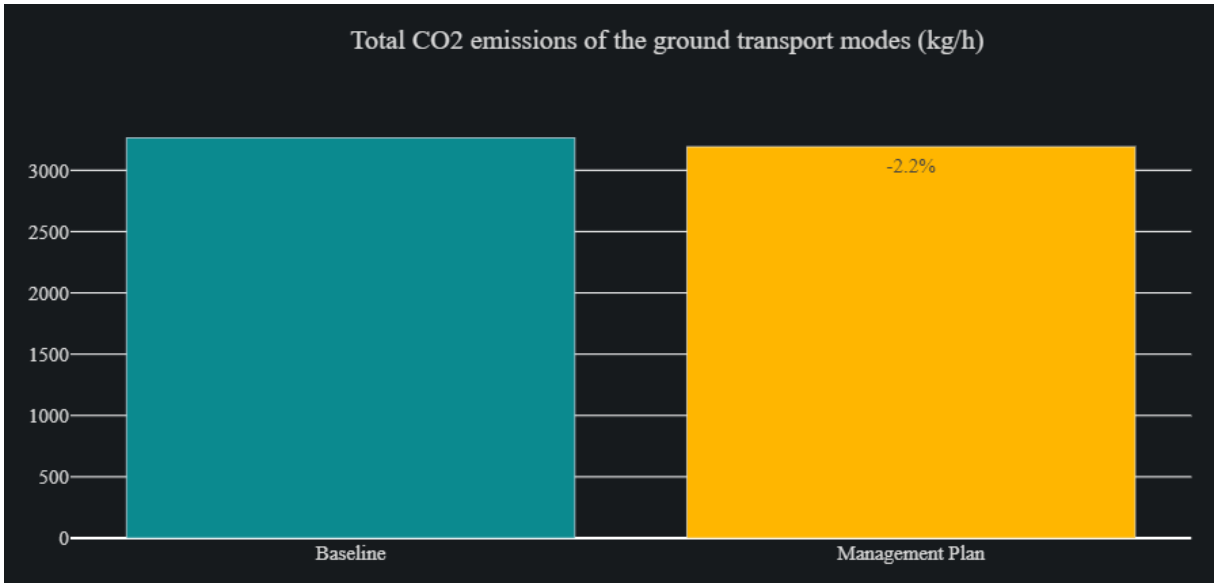

Figure 37. Reduction of CO_2 emissions when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at PMI.

The management actions notably reduce the total number of passengers that miss their flights from 321 to 209 (see Figure 38). From this total number, 53 passengers would have missed their flight at the check-in but it has been reduced to 17 due to a reduction in their access time. Additionally, from the initial 268 passengers that missed their flight at the gate, thanks to the management actions on the surface and the terminal this number is reduced to 192.

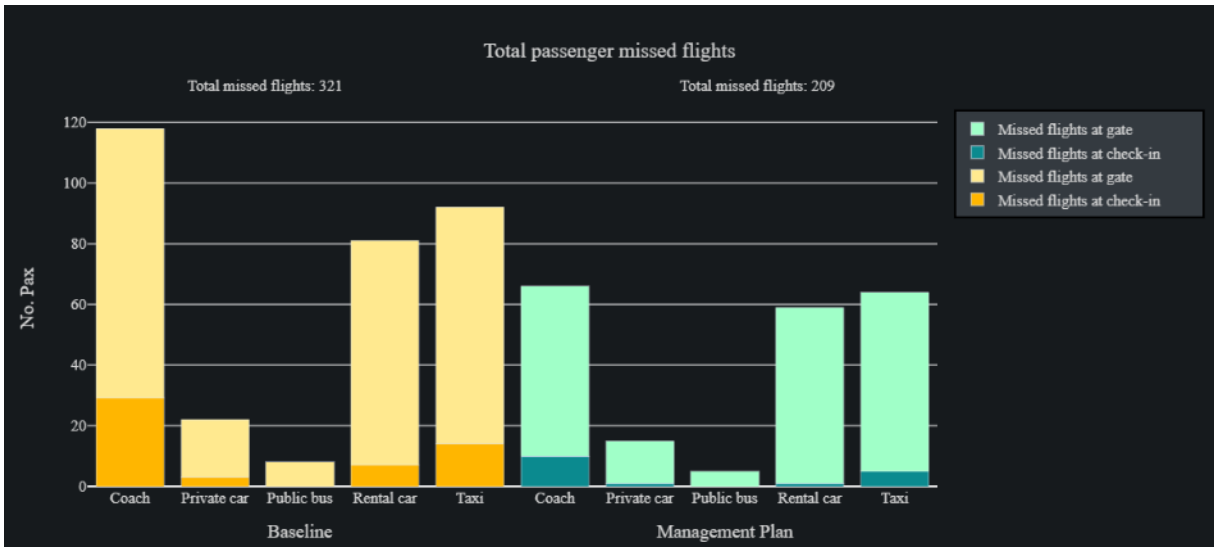

Figure 38. Reduction of the number of missed flights when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at PMI.

Part of this reduction in the number of passengers who miss 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. Figure 39 shows how the security control queuing time at the 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.

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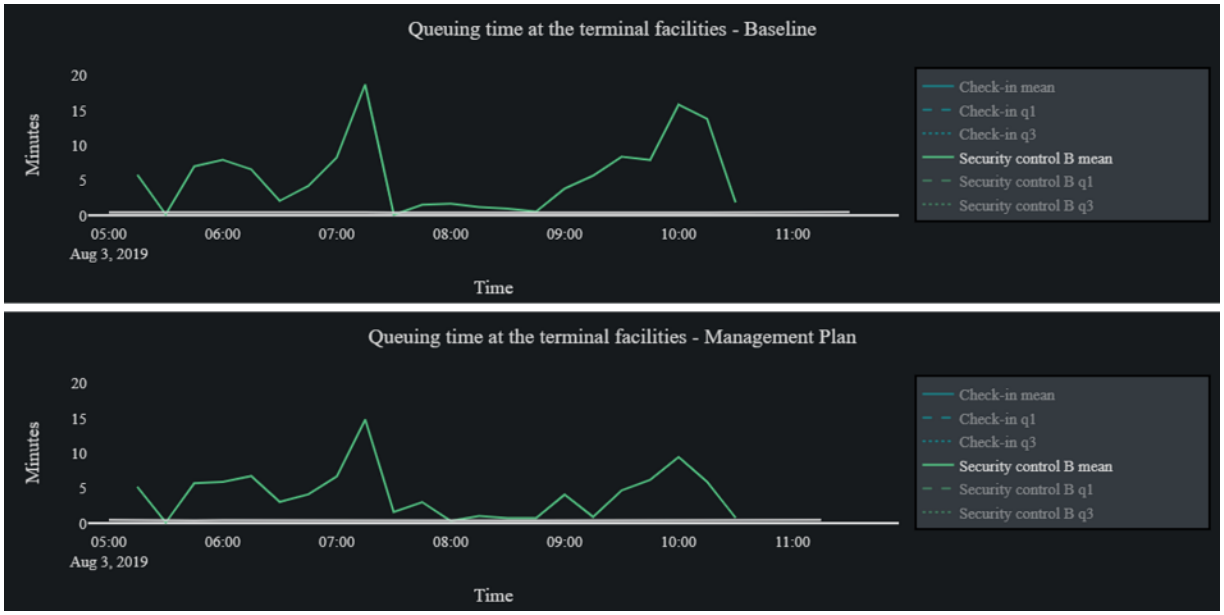

Figure 39. Reduction of passengers queueing time when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at PMI.

Finally, the earlier arrival of passengers to the airport produces an increase in the passenger stay times at the airport. This may promote the use of shops, restaurants and other services which have an economic impact on the non-aeronautical revenues for the airport. Figure 40 presents a comparison of the airport occupancy, where it can be appreciated the increase on the different airport modules and terminal occupancy.

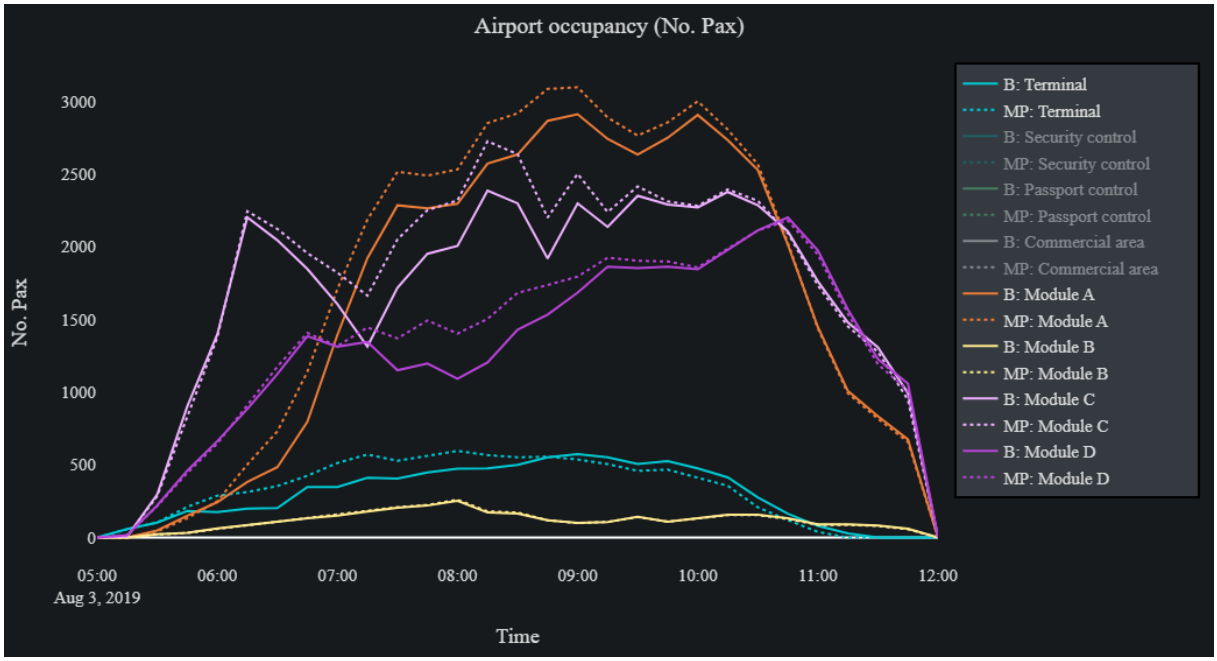

Figure 40. Increase of the airport occupancy when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at PMI.

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4.1.3.2 London City

At London City, the action for reducing congestion is opening an additional access, aiming at reducing the traffic on the rest of the entries. Due to the reduced geographical scope of the LCY model, there is not a significant decrease in the travel times. However, the level of CO_2 emissions is reduced from 188.2 kg/h to 186.9 kg/h, representing a 0.7% of reduction, as presented in Figure 41.

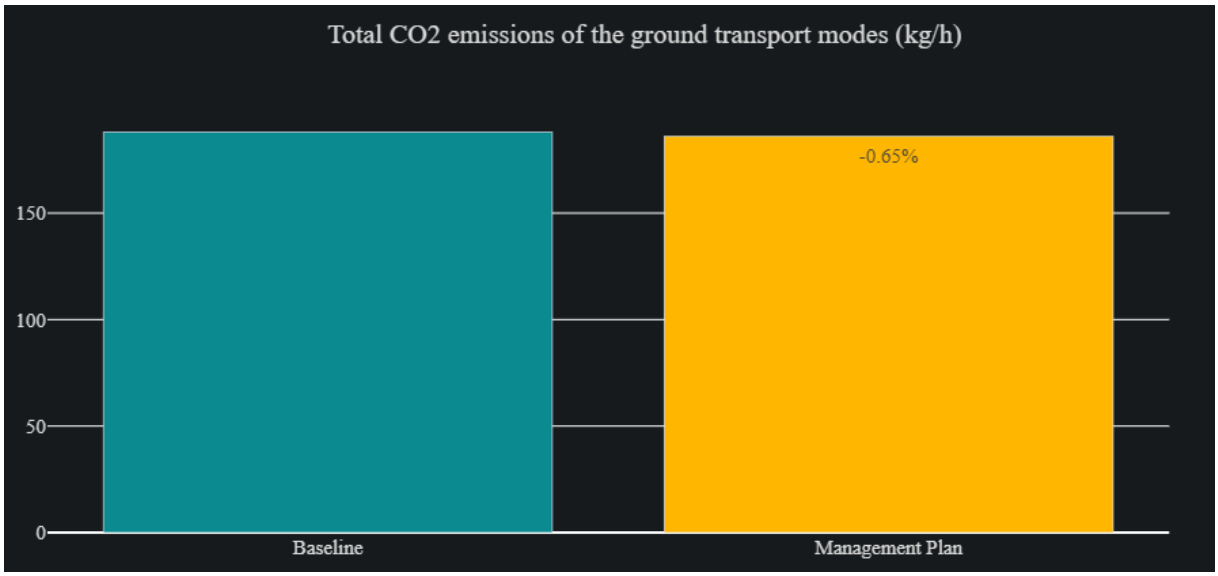

Figure 41. Reduction of CO_2 emissions when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at LCY.

At the terminal, the queue time at the security control is also remarkably reduced. Once the management action is applied, the queue time does not exceed 6 minutes, while before peaks reached 10 minutes of waiting time (Figure 42).

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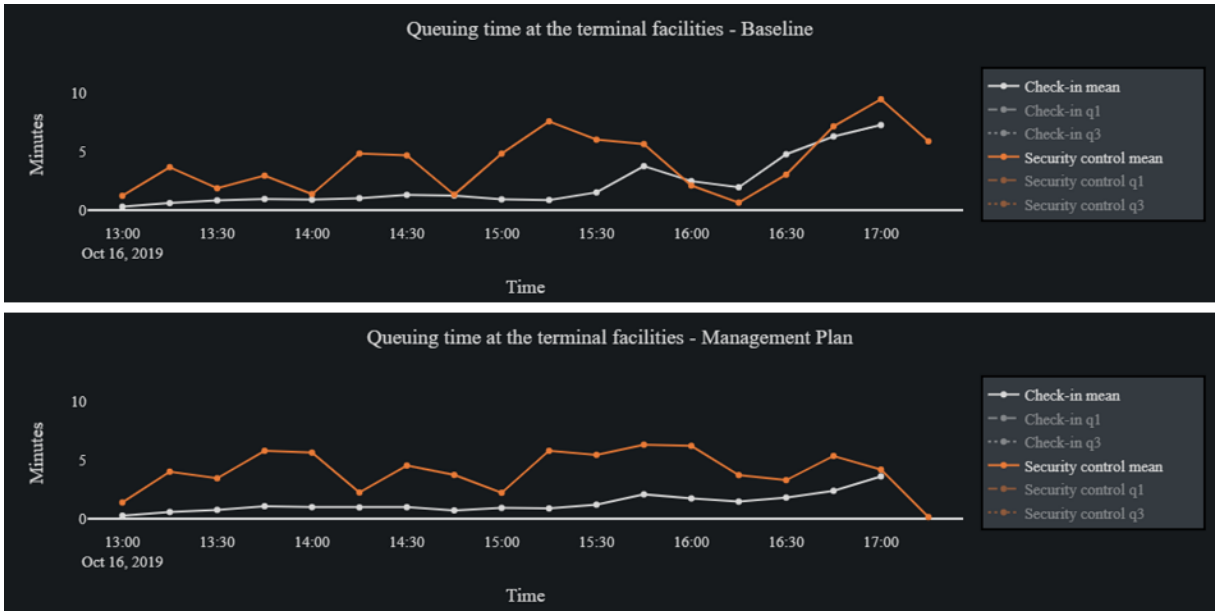

Figure 42. Reduction of passengers queueing time when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at LCY.

Similarly, as in the case of Palma de Mallorca, airside occupancy is increased due to an earlier arrival of passengers to the airport (see Figure 43), which can lead to promoting the use of shops, restaurants and other services which have an economic impact on the non-aeronautical revenues.

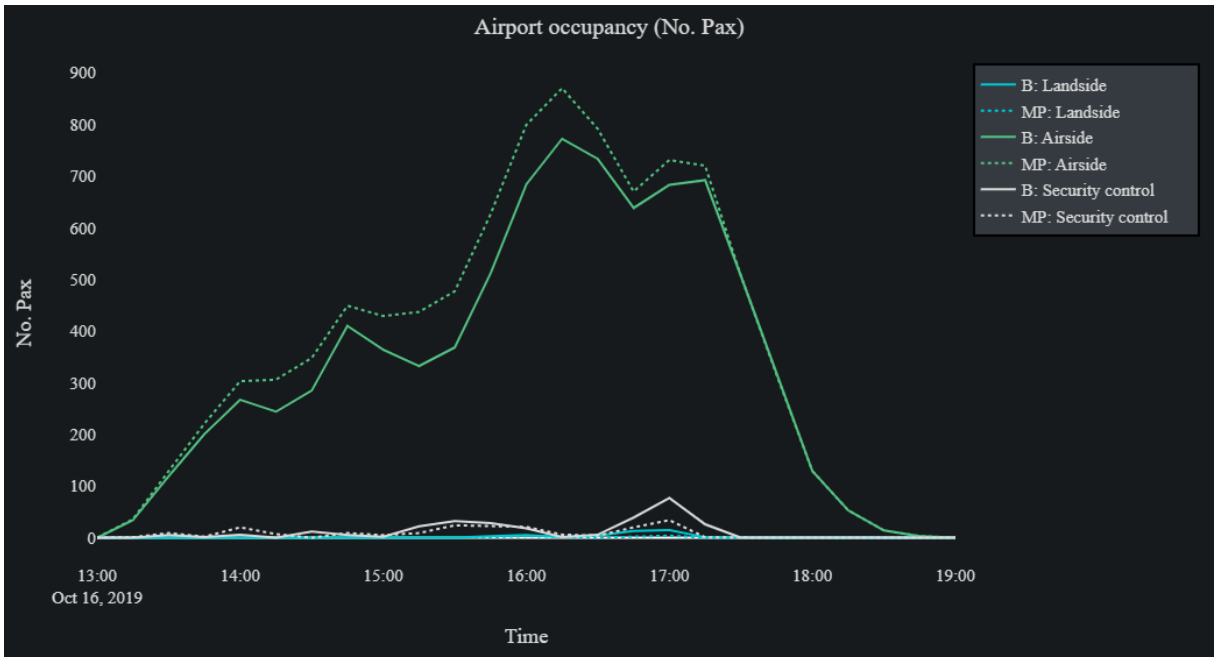

Figure 43. Increase of the airport terminal occupancy when applying the management plan in comparison with the baseline scenario for the use case 'Airport access disruption' at LCY.

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4.2 Discussion of results

The three simulated scenarios presented different management challenges for the airport and ground transport stakeholders. Despite these differences, each scenario demonstrated that the holistic view of the passenger flows and the coordination between the airport and the ground transport modes contributed to the improvement of the conditions of the whole transport network, bringing significant benefits to the involved stakeholders (airport and ground transport operators) as well as to the passengers and the environment.

The first scenario, delay of arrivals, focuses on the benefits of the coordination in the case of disruptions in the arrival of passengers to the airport. This phase of the trip is sometimes underestimated when compared with the departures, but also plays an important role in the overall passenger experience. Therefore, the capacity to anticipate possible issues in the arrival of passengers provides an important competitive advantage to the airports. In this case, sharing of information from the airport to the ground transport modes leads to a higher predictability of the unexpected arrival of passengers, thus being able to provide adequate public transport capacity to meet the actual demand. The results of this scenario present relevant benefits for the involved stakeholders, especially for the ground transport operator, who is given the possibility to adapt their resources and offer a better service to the passengers. It also shows significant benefits for the passengers, who see how their waiting times and overall travel times from the gate to the final destination are reduced, thus improving the trip experience. Additionally, the management actions implemented lead to a reduction of the carbon footprint.

The second scenario, delay of departures, focuses on one of the most relevant points of the new proposed concept, which is the possibility to provide updated information to the passengers, allowing them to be more in control of their journey and adapt their trip to the current status of the transport network. In this case, passengers are advised to delay their arrival to the airport in light of relevant delays in a subset of flights. The assumptions taken were based on the experience of the stakeholders involved: a 50% of acceptance of the advice was assumed, as well as a potential 10% (which has been considered as a conservative value) of modal change to PT modes due to extra time to arrive at the airport caused by the delay. It has been proven that this countermeasure significantly reduces the travel time of delayed passengers, thus potentially improving the passenger satisfaction level. Additionally, the measure contributes to the reduction of the congestion on the access and the occupancy of the airport terminal during peak hours, thus also affecting the rest of non-delayed passengers and enhancing their passenger experience.

Due to the lack of empirical data on passenger behaviour in cases of disruptions, the assumptions made on the potential modal change were based on the judgment of transport experts from the involved organisations. These assumptions may vary depending on the airport of implementation, as the ground transport operator in charge of providing the public transport services may differ on the amount of share that they can capture depending on the different actions performed. Similarly, the level of acceptance of the advice was assumed in order to test which will be the outcome of this measure. The evaluation of the scenario shows that, even when not all the passengers listen to the advice, the consequences have a relevant effect, not only to the passengers who follow the advice, but also to the rest of the passengers not affected by the delay. Conducting stated preference surveys focused on the potential passenger behaviour (possibility to change to public transport modes in case of delay or the potential acceptance to use a tool to receive trip advices) could be a way to have a clearer idea of what the passenger behaviour will be in that case; alternatively, passively collected

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data, such as the mobile network data used by the IMHOTEP project, could be used to monitor the behaviour of the same passenger under both nominal and disruption scenarios.

The modal shift modelled in this scenario is limited to shift from taxis to public transport, but this benefit may be much higher if passengers have the information well in advance so that it allows some of them to switch from private cars too (i.e., planning to use the car in an early morning flight when no bus service is available but, due to a delay, at the new departing time bus services are already running). In this regard the implementation of the IMHOTEP ConOps will have a more long-term effect on passenger behaviour, elevating public transport as an attractive option not only saving passengers' time but also enabling them to consider a wider choice of options as a customer and improving the image of public transport as the preferred option to travel from and to airports.

The last scenario, the disruption to the access to the airport, is probably the one in which it is most clear how the complete view of the passenger flows contributes to mitigate an adverse event for the airport. In this case, the airport is able to foresee potential airport access issues through the novel mechanisms implemented, and can notify passengers to anticipate the start of their trip to the airport. In this case, a 25% of passengers following of the advice is modelled in order to see how a lower acceptance of the advice affects the transport network. Additionally, a novel action on the airport terminal is modelled, allowing the delayed passengers to skip the security control queue, thus contributing to the reduction of times in the security for these passengers. The results show that the mitigation action contributes to reducing the level of congestion on the airport access, as well as to shorten the security control times, thus facilitating the on-time arrival of passengers to the flight. The main outcome of this scenario is the reduction of the missed flights, but also the significant reduction of the CO_2 emissions in the access leg.

It is worth noting that, although in some of the scenarios the reduction of CO_2 emissions can be derived from an assumption made on the modal shift (which can be different in other airports with different transport access modes or behaviour), in other scenarios this is not modelled, and the situation is the same as in the baseline scenario, with the same number of public and private vehicles. In these scenarios, a reduction of carbon emissions also takes place. This is the case of the disruption on the access leg, which achieves a 2.2% and a 0.7% of reduction of the CO_2 emissions for Palma and London City, respectively, due to the reduction of congestion in the access roads. This is also the case of the delay of arrivals in London City, where no modal change has been modelled as the DLR has enough capacity to absorb this kind of disruptions, and a 1.5% of reduction of the CO_2 emissions was achieved due to the reduction of the congestion achieved by opening a new access lane.

All the management actions and assumptions taken in consideration during the definition and evaluation of the use cases have been discussed and agreed with the current stakeholders involved in the project (airport and ground transport operators). However, the inclusion of additional stakeholders such as AUs or ANSPs could provide a second view of the assumptions made as well as help propose other potential mitigation actions and other relevant KPIs. In addition, it is likely that, if applying the same concept in different airports, the same stakeholders have different ideas of the potential management actions or the assumptions to consider, as the airport characteristics and objectives may be radically different from one to another.

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The results of the simulation scenarios demonstrate that the application of the proposed concept entails potential benefits for the involved stakeholders, the passengers and the environmental footprint. These benefits can be summarised as:

- **Shortening of passenger waiting times** in both the access and egress legs (waiting time for the public transport and reduction of surface network congestion) and the airport terminal (waiting time at the different airport facilities such as security control or passport control) and overall **travel times** for passengers, which would translate into an enhancement of the passenger experience.
- **Reduction in the number of flights missed** by passengers due to potential airport and access disruptions, which is directly translated into a better passenger experience.
- **Reduction of the congestion** on the access and egress from the airport, which not only leads to an improvement of the passenger experience, but also to the **reduction of the CO_2** emissions, thus improving the airport environmental footprint.
- **Better predictability** of the passenger flows and the overall transport network performance, which gives the involved stakeholders the possibility to better allocate their resources (human resources in the case of airport operators, and vehicle fleet in the case of ground transport operators). This is in turn translated into a potential improvement of the **Operational Efficiency**, a reduction of costs (**Cost-Efficiency**), an increase of **Capacity** and, ultimately, an improvement of the service provided to the passengers.

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5 Validation of the IMHOTEP Concept of Operations

5.1 Outcome of validation workshops

The first step in the two validation workshops at PMI and LCY included a detailed explanation of the IMHOTEP Concept of Operations. The partners involved at both airports were already aware of the concept of collaborative decision making at airports and how it can lead to improved system performance. Other stakeholders serving the airport (such as surface access providers) seemed less aware of this traditionally 'airside' concept, but all could see the potential benefit of (and fully supported) the expansion of this concept to airport access and egress. They also appreciated the clearer focus on a more 'passenger-centric' treatment of the entire journey involving both land and air elements and processes. There was a clearly stated acceptance of the proposed concept of operations at both validation meetings.

An initial set of seven potential simulation scenarios were presented to PMI stakeholders in the first validation workshop. Working groups with representation from each stakeholder discussed each potential simulation scenario in detail and considered what the management actions should be. Each scenario was then ranked to reflect realism, impact and usefulness in the study. This process resulted in the three scenarios and associated management actions chosen, as described in the previous chapter. At the second validation meeting, this entire process was explained to LCY stakeholders and the results from PMI were described in detail. LCY stakeholders present were content that the same three scenarios would be best for them too, and they supported their adoption in the simulation.

Throughout the project airport stakeholders showed some specific concerns about the implementation of the proposed ConOps. Firstly, they were unconsciously reflecting the current setting in which ATM-related stakeholders are concerned with the management of 'airside' operations only. The validation workshop at PMI included a visit to the airport's Operations Control Centre, from which it was clear that there was no space (physically, technologically, and in the mindsets of the operators of the different stations) to consider surface transport-related events and operations. At a more general level, broadening the mental models of the stakeholders involved in the project as to the relevance of integrating information from the air and the ground realms is an initial benefit of the very definition of the IMHOTEP ConOps.

On a practical level, barriers remain to the use and implementation of the tools that enable better common situational awareness. The case of LCY is illustrative of this, as they were acutely concerned about the strain on resources that additional 'management actions' could entail in a context where the response to the Covid-19 pandemic had already reduced resource availability, especially human resources. The validation workshop at LCY was a good opportunity for the relevant stakeholders to make explicit the ways in which they currently deal with the interaction of surface transport and air-side operations, and the limitations that the key characteristics of the airport generate for responding to circumstances beyond the control of the airport.

The workshop was held at a time where LCY was receiving an unusual influx of passengers that did not match the airport's traditional profile as it was not suffering as much from the constraints and cancellations experienced in other UK airports during the summer season of 2022. Many of these

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passengers made atypical airport access journeys and arrived to LCY far earlier than the airport would normally expect. Airport operations and management realised that they normally deal with situations like this by following very manual processes that involved direct and repeated contact with the passengers involved. This worked well in most circumstances and somehow retained the work ethos and passenger experience the airport operator wants to deliver, but it may prove hard to extrapolate to more difficult situations or to bigger airports. At the very least, the situational awareness provided by IMHOTEP ConOps would enable a better planning of such responses too.

5.2 Definition of a validated ConOps

The results of these discussions, along with the assessment of the capabilities in the developed models and tools, allowed for a definition of a validated ConOps as shown in Figure 44 (with reference to the original scheme presented in Figure 2 and the description in section 2.1). The integration of the different data sources and simulation models allowed for an instantiation of Function #1, which enabled the creation of a baseline passenger ATD for the days of operation selected in each case study. Function #2 and Function #3 were implemented off-line in the sense that different simulation instances were created to represent the management actions that resulted in the re-planning of both terminal processes and access/egress alternatives. Function #5 was also implemented conceptually and off-line to the extent that the final simulation scenarios chosen were selected from disruptive events that determined the management actions. However, the fact that the ConOps was not implemented in the real setting of airport operations prevented this Function from actually enabling tactical management responses. Therefore, Function 5 is emulated in the simulation models given that the decision structure in the model resembles the application of management actions as the disruptive events unfold (for instance, a passport control booth is opened once queue length achieves a certain threshold).

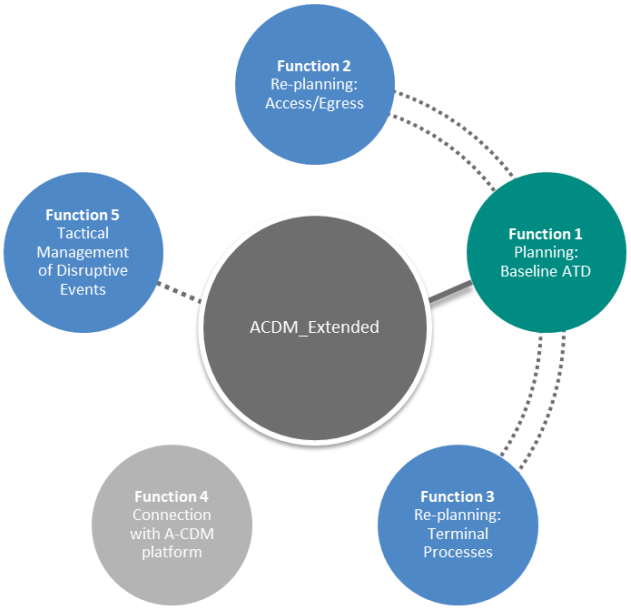

Figure 44. Functions in the IMHOTEP ConOps that were implemented in the case studies. Green indicates the Function was fully implemented in the IMHOTEP tools, blue that it was implemented off-line and grey that it was not implemented at this stage.

Finally, the same limitation of an off-line implementation implies that Function 4 is not considered in this assessment explicitly as there is no opportunity to connect with an existing A-CDM platform. This

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does not mean, however, that the function is not valuable. The validation process includes the possibility for passengers to actively change their decisions (for instance, take a bus instead of a taxi, or start their airport access leg sooner or later than what was established in the baseline model, emulating capabilities allowed by an enhanced situational awareness). Similarly, the simulation models envision the possibility of allowing airlines, as one of the key ATM stakeholders, to make decisions in response to the enhanced situational awareness. Potential airline actions have not been modelled (such as to delay flights if a given proportion of passengers were known to be too late to the departure gate) due to the absence of any airline representative within the project. However, these kinds of action should be inquired in further development steps.

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6 Conclusions and future orientation

6.1 Conclusions

IMHOTEP has addressed in a holistic manner the in-airport terminal leg and surface transport legs of air trips, traditionally assessed separately, and for the first time has closed this gap by linking both terminal and access and egress processes. The concept and tools developed within IMHOTEP have allowed the assessment of scenarios in which coordination between airports and ground transport stakeholders could help mitigate adverse situations, thus benefiting the involved stakeholders as well as passengers. The implementation of this idea is based on a passenger-centric view, articulated around the concept of the passenger ATD. All the data used is anonymous and follows the data processing principles defined by GDPR EU regulation; in further stages of the development of the concept, as new potential datasets become available and new stakeholders become involved, methods must be put in place in order to assure that the data processing methodologies and processes follow the existing rules and regulations regarding privacy and personal data protection.

The IMHOTEP project has brought together key stakeholders. Across both airport case studies involved, a number of key stakeholders had the opportunity to share their views and exchange ideas, practices and processes for the first-time. This cross-stakeholder engagement also helped to refine and focus the project. The project centred around a proof of concept based on three specific scenarios thought best able to demonstrate the potential optimisation available to management. These selected scenarios – delay of departures, delay of arrivals, and disruption in surface access transport – each reflect core challenges for aviation stakeholders, including the ever-present reality that events and circumstances can experience rapid deterioration from relatively minor to major delays and disruptions.

The project has considered a range of key performance indicators (KPIs), which form the basis for evaluating management actions. Modal share, travel times, CO_2 emissions, occupancy of PT alternatives, productivity of the ground side transportation, and PT waiting times have been used to assess the quality and efficiency of access/egress. The terminal view is underpinned by the KPIs of waiting times (queuing time) at check-in, security control and passport control. This view was also linked to the KPIs of occupancy and of dwelling times (both at airport defined areas). Finally, the KPI missed flights indicator relates to the quality of the journey from the passenger perspective. Ultimately, when the ground realm is viewed as intrinsically linked to the air realm, greater efficiencies are possible, especially when dealing with major delays and disruptions.

The project has revealed that delays and disruptions impact all key stakeholders and that meaningful and actionable management responses are more effective when a holistic view of the situation is mirrored in a multi-stakeholder approach. In this context, information from all key stakeholders is crucial, 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.

Communication was a key recurrent theme across both case study airports, including being raised and reflected on at each validation workshop. There was a tangible sense at each workshop amongst those stakeholders who were meeting for the very first time (of which there were a number) that mutual

learning and understanding were taking place. Included in this was a growing and evident realisation for key stakeholders that although different perspectives and priorities clearly existed, everyone was ultimately addressing common core challenges where impacts tend to radiate out to all across the system in one shape or another. Stakeholder engagement led to buy-in, and this mutual sense of ownership then led to a common view that management decision-making needs to be expansive and inclusive, and not based on silos or narrow agendas.

The potential for wider and deeper levels of communication were most evident at the nexus between the air realm and the ground realm. Both PMI and LCY have well-established communication links with taxi companies, although direct links with public transport providers were not as well developed for each. This context actually provides a valuable template for wider engagement with public transport providers, as simple and straightforward communication channels were shown to be effective in achieving a relatively quick surface transport response to delays and disruptions. Though public transport at airports around the world varies considerably (when indeed it is available), the practice of not communicating in any significant way with these public transport providers reveals an area where positive gains are ready to be made. These gains include, for example, reduction of congestion in the airport access, reduction in carbon emissions and reduction in passenger waiting times and travel times.

The air realm and the ground realm are definitions established in this project, overcoming traditional narrower definitions of airside and landside, but still represent demarcation areas that attempt to expand the boundaries of each by also encouraging a wider overlap between the two that is more reflective of a flexible zone than of a rigid border. Likewise, this project has primarily focused on bringing key stakeholders together and opening communication channels – many for the first-time. The project is just the beginning of a conversation that seeks to promote amongst all key stakeholders an exchange of views and experiences, together with mutual engagement and an exploration of possible solutions.

6.2 Benefits and challenges for the ATM ecosystem

As discussed throughout this report, one of the drawbacks of the current approach to collaborative decision-making in the ATM ecosystem is that it is naturally centred around airside operations. Proof of that is the lack of multimodal and passenger KPIs available in the current SESAR Performance Framework, which is based on a flight-centric vision. The overall impression during the different meetings and workshops conducted within IMHOTEP is the need to define multimodal and passenger-centric KPIs able to capture relevant aspects of the complete door-to-gate and gate-to-door passenger journey which are not captured by the current Performance Framework, letting the passenger (who should be one of the key agents of the transport system) out of the picture.

One of the first benefits of IMHOTEP is to break through the traditional barriers of understanding aircraft operations and extending models to embrace a passenger perspective that considers their journeys effectively door-to-door. It is clear that one of the natural limitations for an extension of the CDM concept is the availability of data beyond the borders of the ATM ecosystem. IMHOTEP has proven that combining different data sources is a viable alternative to create a comprehensive picture of the journey by means of the passenger ATD. As this is the core element of information in the IMHOTEP ConOps, there is an opportunity to interface with both traditional CDM and TAM implementations, as well as to sit alongside other information systems in non-CDM airports or larger secondary and regional airports (such as LCY) that, despite officially being non-CDM, already capture information for relevant A-CDM milestones.

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The IMHOTEP ConOps allows stakeholders not only to avoid current constraints, but to imagine gains from a new approach with far greater flexibility benefitting from a more predictable process. This includes the passengers' choice of the airport access/egress transport system as well as airport operators' capability to plan their landside and airside facilities in response to sudden, but better predictable delays and disruptions (provision of commercial offers for the passenger at the most relevant point of the journey and agreements with border control and airport security agencies' as to increase their flexibility to working time arrangements of their staff). Better knowledge of the door-to-door journey will therefore open-up opportunities currently hidden or declared impossible to resolve due to lack of data and transparency of the process.

Another measurable success of the project is the intention disclosed by LCY to join EUROCONTROL's A-CDM initiative, as the 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. Initial approaches in this respect have been discussed with both PMI and LCY, but to date have had to be left for further elaboration due to staff and resource restrictions caused by the Covid-19 pandemic.

The case studies analysed in this report show a clear interaction between events in the air and ground realms, that is, disruptions in the surface access transport systems have clear implications for terminal processes and, vice versa, events in the terminal or airside environment (traditionally the realm of ATM only) have an impact on the operation of surface transport providers and hence on the overall quality of service delivered to the passengers. The interdependencies between airport terminal operations and the aircraft turnaround process (more clearly the subject of traditional CDM approaches) has been preliminarily studied in the literature and more detailed in IMHOTEP Deliverable 4.1. Indeed, there are terminal processes that can either be affected by disruptions in the turnaround, or that could be used proactively as management actions to cope with disruptions in both the air and the ground realms, chiefly:

1. Late start of the boarding process;
2. Slow progress of the boarding process;
3. Change of departure gate;
4. A combination of the elements above.

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. By way of example, Figure 45 shows the application of the simulation model developed for LCY to an exploration of passenger interactions that could lead to further delays or missed flights when a gate change occurs very close to the flight's expected departure time, and it is situated nearby another gate with boarding in process. Although overall the definition of the simulation procedure did not consider gate allocation explicitly (hence 'gate change' could not be determined as a management action at this stage), stakeholders in the ATM ecosystem (AU, ANSP and airport operators) could be interested in shuffling departure gates to reduce walking times of passengers delayed in the surface access leg to enhance the performance of the system, or even to enable arrival passengers to 'connect' to surface transport alternatives, similarly to what they could do to connect to other flights. This is something that needs to be further studied in successive implementations and refinements of the tools developed in the project.

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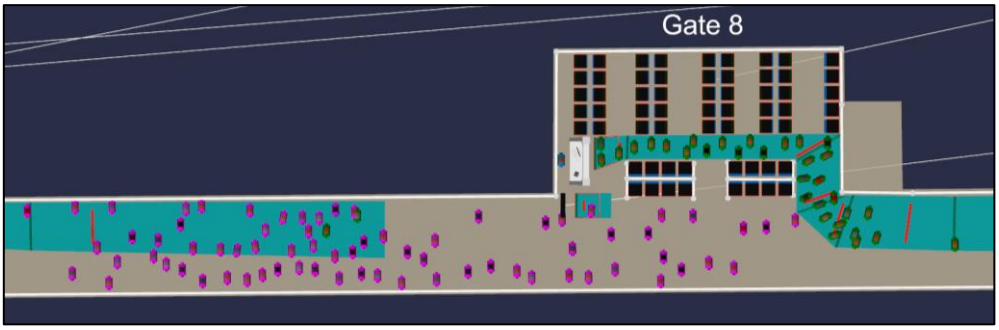

Figure 45. A simulation of the interactions between passengers at LCY when a gate change occurs very close to the expected departure time.

6.3 Future orientation

In continuation of the IMHOTEP project, the granularity of the KPIs can be increased while other key stakeholders (i.e., airlines, airport security operators, immigration agencies, etc.) can be integrated to extend benefits of IMHOTEP. Airport operators could be engaged in a holistic discussion about forms of passenger services offered. For example, LCY was obviously impressed with the IMHOTEP concept 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.

Though many airports are presently undergoing a fundamental transformation towards greater flexibility through digitalisation of the airport management process, 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 bringing together key stakeholders who typically have not met each other (certainly not in any significant manner before), the IMHOTEP project 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. Potential benefits of the concept include:

- Improved passenger experience
- Potential positive impact on airport non-aeronautical revenues from less stressed passengers
- Reduced waiting time and total journey time
- More effective use of existing infrastructure and human resources
- Reduced probability of requirement for expansion of terminal infrastructure to meet peaks
- Reduced of CO_2 emissions

Similar cases are possible for other airports, predominantly served by one or two monopoly ground transport operators. Airports with high seasonality would benefit from delayed investment into larger terminals. The possibility for tour operators to better predict travel times from hotels and resorts to the airport will reduce the time window to bring passengers to the airport and reduce the number of passengers dwelling in the passenger terminal during peak periods.

Also, the need to rethink the airport business model as a result of uncertainties for the aviation industry triggered by Covid-19, the need to reduce carbon emissions considering climate change and increasing energy costs require airports to better link-up to the cities and regions they serve. The IMHOTEP platform can easily be extended to include new transport operators in improving regional connectivity and reducing unnecessary congestion.

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Appendix A Palma de Mallorca Workshop validation material

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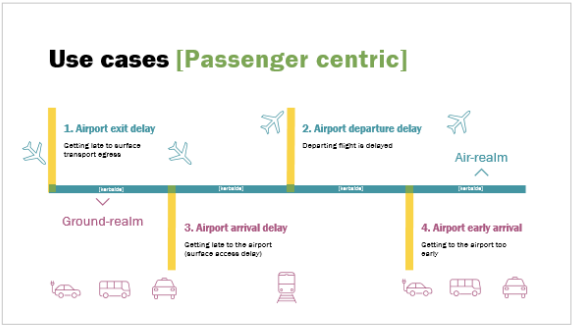

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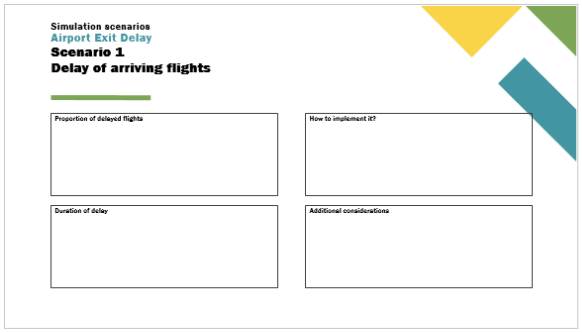

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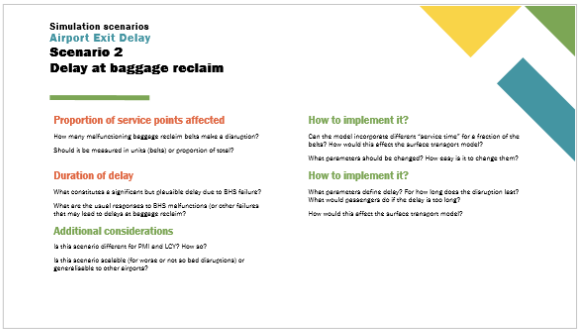

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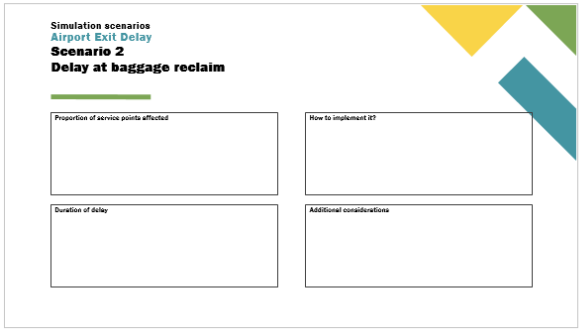

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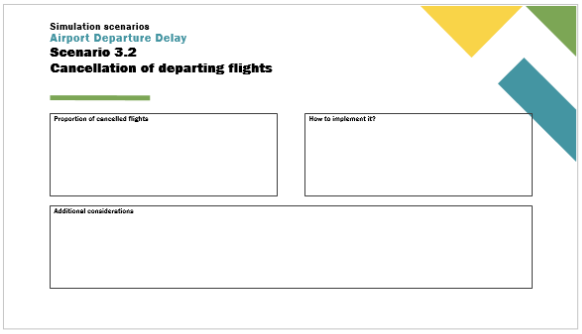

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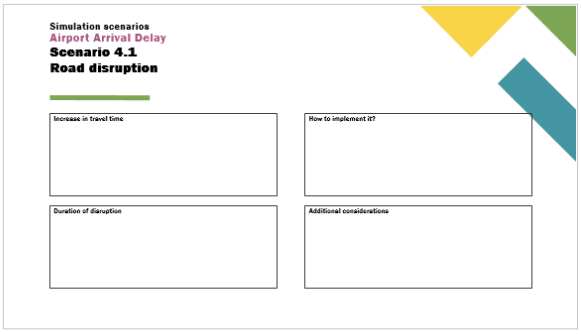

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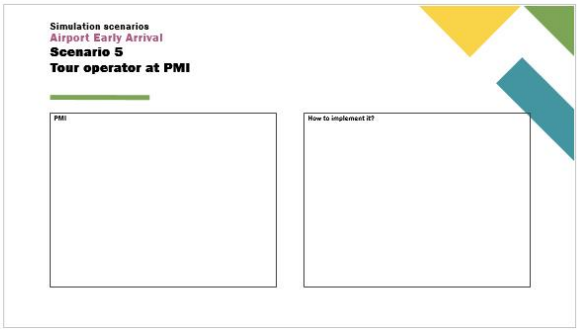

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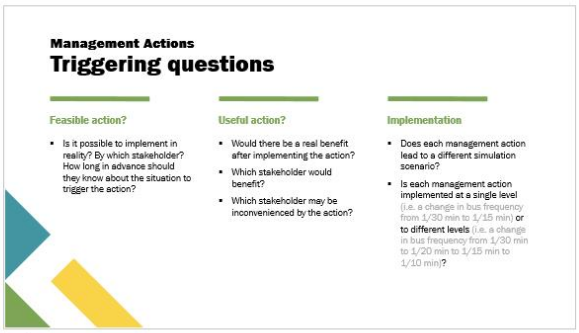

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Management Actions
Air-realm

Scenario	Air stakeholders	Ground stakeholders
S1. Delay of arriving flights	• Increase service points (i.e. open more passport control lines)	• Change frequency of public transport alternatives
S3.1. Delay of departing flights (S3. Tour operator as PMI as a special case)	• Delay opening time of facilities (i.e. check in) • Early opening time of facilities (i.e. check in) • Off-airport check in	• [Passenger] Delay departure time of surface access leg or change transport mode • Change frequency of public transport alternatives

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Management Actions
Air-realm

Scenario	Air stakeholders	Ground stakeholders
S1. Delay of arriving flights		
S3.1. Delay of departing flights (S3. Tour operator as PMI as a special case)		

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Management Actions
Ground-realm

Scenario	Air stakeholders	Groud stakeholders
S4.1. Road disruption (S4.2. Public transport disruption as a special case)	• Delay flight(s) • Allow delayed passengers to use fast track security • [LDY] Open airport-owned access road	• Change frequency of public transport alternatives • [Passenger] Delay departure time of surface access leg or change transport mode

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Management Actions
Ground-realm

Scenario	Air stakeholders	Groud stakeholders
S4.1. Road disruption (S4.2. Public transport disruption as a special case)		

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KPI
Terminal processes

KPI	How to measure it?	Aggregation	Segmentation	Visualization
Waiting times (queuing time) at: •Check-in •Security control •Passport control	Evolution of the pax waiting time through the simulation time.	15 min	•Group destination •Airline (check-in)?	Line plot
Facilities throughput	Evolution of the pax throughput during the simulation time.	15 min	-	Line plot
Occupancy at: •Airport defined areas	Evolution of the pax occupancy in a specific area throughout the simulation time. Occ = total time spend in the area/ total time interval	15 min	•Group destination •Business/Leisure	Line plot / heatmap
Times (dwelling time) at: •Airport defined areas	Evolution of the pax dwelling time in a specific area throughout the simulation time. Possibility distribution	15 min	•Group destination •Business/Leisure	Line chart including +- percentile
Missed flights indicator	Total and perc of missed flights (modifiable by the user)	Total time window	•Cause (check-in vs gate) •Flight/airline •Access mode	Bar plot

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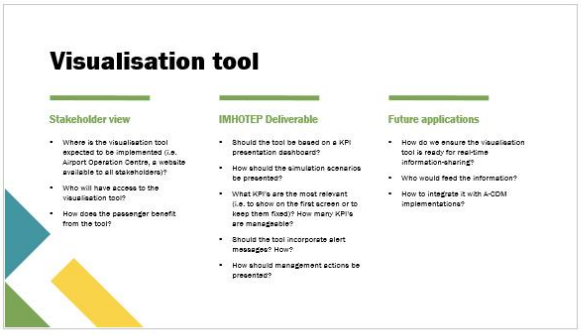

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Appendix B London City Workshop validation material

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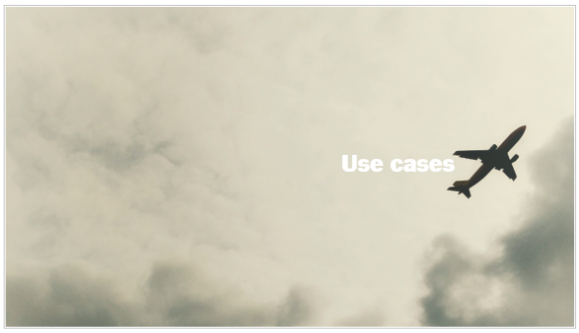

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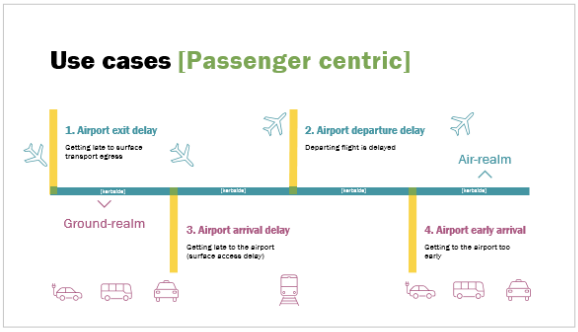

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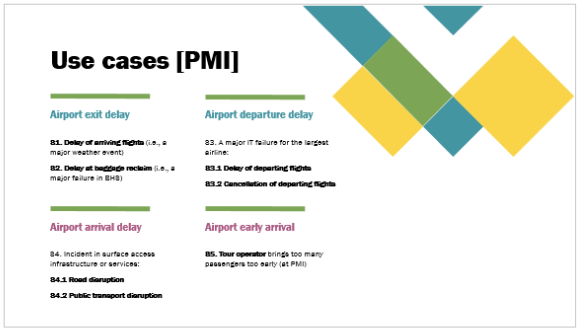

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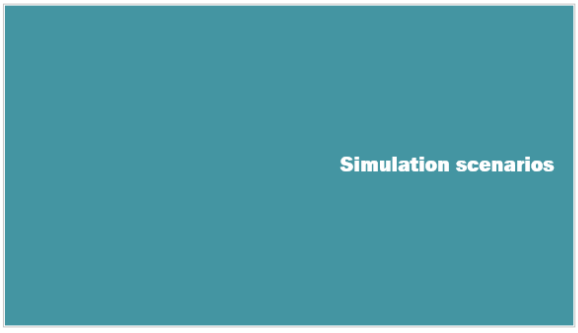

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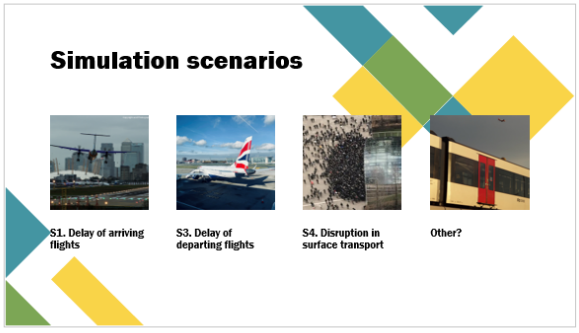

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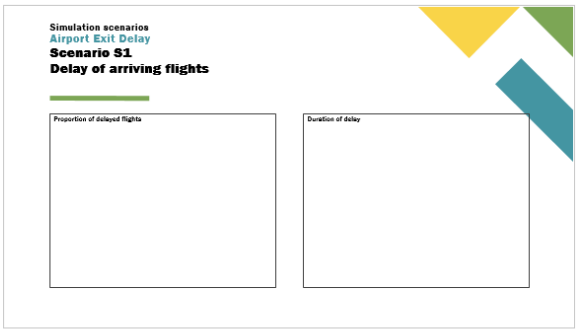

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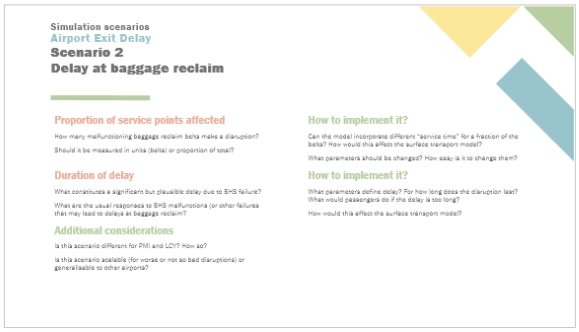

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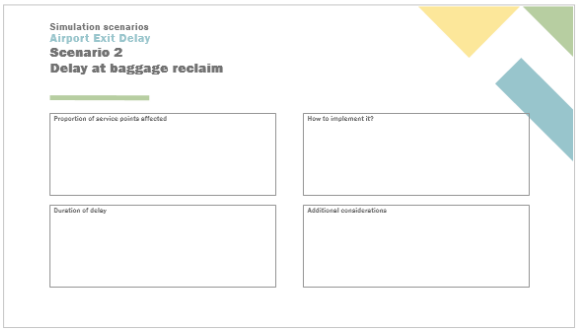

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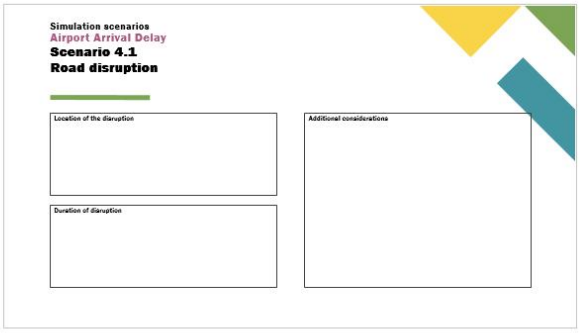

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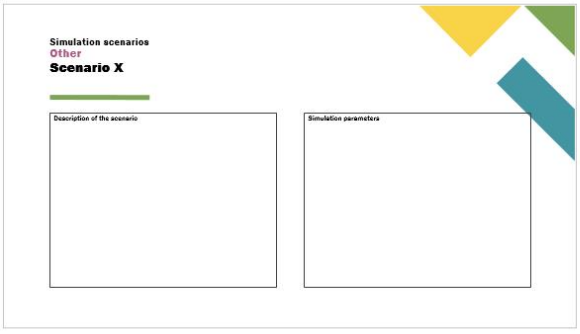

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Same material as Appendix A onwards.

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