MultiModX

Technical Summary

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Abstract

This MultiModX Technical Summary provides an overview of the solutions developed under the SESAR 3 Joint Undertaking's MultiModX project. It describes the scope, methodological approaches and capabilities of the three solutions – Multimodal Performance Assessment, Multimodal Schedule Design, and Multimodal Disruption Management – and outlines how they collectively contribute to advancing multimodal transport integration in Europe. The document serves as a comprehensive reference for understanding the design, operation, and potential applications of the MultiModX solutions in supporting more efficient, resilient, and passengercentred transport systems.

Executive Summary

The MultiModX project advances Europe's vision for seamless, sustainable, and resilient longdistance passenger transport by developing and validating three innovative multimodal decisionsupport tools. Building on SESAR and EU policy ambitions such as Flightpath 2050 and the Sustainable and Smart Mobility Strategy, MultiModX aims to enhance integration between air and rail networks through coordinated planning, performance assessment, and disruption management.

Three core solutions have been developed and tested:

1. Performance Assessment Solution (SOL1) – a comprehensive multimodal performance framework and modelling platform that evaluates both strategic and tactical network performance from a passengercentric perspective. It quantifies doortodoor travel time, reliability, and environmental impact, offering the first digital catalogue of multimodal performance indicators in Europe.
2. Schedule Design Solution (SOL2) – an optimisation tool that generates coordinated air-rail timetables based on passenger demand, infrastructure constraints, and policy scenarios. Applied to the Spanish network, it reduced average connection buffer times, shortened doortodoor travel durations, and increased connecting passenger volumes by up to 7.5 percent.
3. Disruption Management Solution (SOL3) – a tactical optimisation model that replans multimodal schedules in response to disruptions such as airport closures or rail capacity reductions. It enables both decentralised and centralised coordination among operators. In simulations, the centralised approach reduced average journey times by nearly 20 percent, stranded passengers by 17 percent, and delays by 50 percent.

All three solutions are supported by a shared analytical backbone – passenger archetypes, regional archetypes, and policy packages – which capture behavioural, spatial, and regulatory diversity across Europe. Together, these tools provide the foundation for evidencebased, passengercentred multimodal mobility planning, aligned with the EU's decarbonisation and resilience objectives.

MultiModX demonstrates that integrating air and rail systems through datadriven scheduling, performance evaluation, and coordinated disruption management can enhance network efficiency, passenger experience, and system resilience, paving the way toward the 4hour doortodoor target envisioned in Flightpath 2050.

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1 Introduction

1.1 Background and Context

The European transport landscape is undergoing a profound transformation guided by strategic visions such as Flightpath 2050: Europe's Vision for Aviation and Fly the Green Deal: Europe's Vision for Sustainable Aviation ([1], [2]). These initiatives envisage a future where air and rail operate as complementary pillars of a connected, sustainable, and resilient European mobility system, enabling 90 percent of intraEuropean journeys which use aviation to be completed within four hours. Complementing these longterm ambitions, the European Commission's Sustainable and Smart Mobility Strategy ([3]) provides the policy framework for delivering a transport ecosystem that is efficient, interoperable, and socially inclusive.

Despite this shared vision, Europe's longdistance transport system remains fragmented. Air and rail services are typically planned and managed in isolation, with limited data exchange, inconsistent performance metrics, and insufficient coordination mechanisms. This fragmentation constrains efficiency, multimodal connectivity, and the passenger experience. To address these gaps, the MultiModX project developed and validated a suite of support tools that enable coordinated planning, scheduling, and management of multimodal networks from a passengercentric perspective. Building on the achievements of the SESAR H2020 MODUS project ([4]), MultiModX ([5]) moves from conceptual analysis to operational application – providing tested tools capable of quantifying multimodal performance, optimising schedules, and managing disruptions across modes.

The project's objectives are threefold: (i) to identify representative scenarios for longdistance multimodal travel in Europe; (ii) to develop and validate three integrated solutions – Multimodal Performance Assessment, Schedule Design, and Disruption Management; and (iii) to synthesise the results into a coherent exploitation roadmap for future research, deployment, and policy uptake. The scenario analysis establishes the contextual foundations of the project by defining passenger and regional archetypes, policy environments, and disruption conditions that serve as the experimental framework for all solutions.

Through these developments, MultiModX contributes directly to Europe's ambition of a seamless, efficient, and lowcarbon transport system. Its outcomes demonstrate how datadriven coordination between air and rail can enhance network performance, passenger satisfaction, and system resilience – thus advancing the broader European goal of doortodoor multimodality by midcentury.

1.2 Scope and Objective of this Report

This Technical Summary aims to provide a comprehensive account of the MultiModX solutions, detailing their respective scope, methodological approaches, capabilities, inputs, and constraints, while synthesising the project's overall achievements and lessons learned. It brings together the key elements of the three solutions developed within the project – Multimodal Performance Assessment, Multimodal Schedule Design, and Multimodal Disruption Management.

The document offers an integrated understanding of how these solutions collectively advance multimodal transport in Europe by improving performance assessment methods, enhancing schedule coordination across modes, and enabling more resilient operations under disruption. It also highlights the shared analytical components underpinning the three solutions, including passenger and regional archetypes and the policy environments considered in the project.

Serving as a reference for stakeholders involved in multimodal transport innovation and policy – such as research institutions, transport operators, regulators, and policy makers – this Technical Summary supports evidencebased decisionmaking for the development of efficient, passengercentred, and sustainable multimodal transport systems.

1.3 Structure of the document

This document presents the conceptual foundations, methodological approaches, and key results of the three solutions developed within MultiModX, addressing performance assessment, multimodal schedule design, and disruption management. Section 2 outlines the three Solutions, highlighting their respective methodologies and capabilities. Section 3 describes the analytical components common to all Solutions, including passenger and regional archetypes and the policy environments considered. Section 4 examines the impacts and benefits of each Solution, while Section 5 summarises the main conclusions and presents policy recommendations.

2 Solutions Description

2.1 SOL399/SOL1 Multimodal Performance Assessment Solution

The Multimodal Performance Assessment Solution (SOL399/SOL1) aims to develop a 1) multimodal performance framework and a 2) multimodal modelling and evaluation platform for strategic (planning) and tactical (on the day of execution) operations.

The Multimodal Performance Framework builds on the work from previous multimodal research projects and extends the work with collaboration with other SESAR Exploratory Research (ER) and Industrial Research (IR) initiatives.

The multimodal modelling and evaluation platform is divided into two distinct parts:

- A Strategic Multimodal Evaluator, which focuses on the evaluation of flight schedules, rail timetables and other infrastructure characteristics, e.g. minimum connecting times intra and intermodes, to assess mobility from a passenger-centric perspective, providing metrics at the region, the infrastructure (airport, rail station) and the operator level. This network can be either a planned or a replanned network which considers the impact of known disruptions.
- A Tactical Multimodal Evaluator, which can simulate the operations as they unfold on the day of execution. This model tracks vehicles (flights and trains) and passengers, providing passengercentric metrics, e.g. missed connections and total delays.

2.1.1 Multimodal Performance Framework

2.1.1.1 Methodology

The multimodal performance framework developed as part of MultiModX project relies on a literature review of previous work in the field and interaction and feedback obtained from stakeholders and other related research projects. As shown in Figure 1, the framework identifies three levels of development of potential multimodal indicators:

1. Indicators at Level 1 are indicators currently part of the SESAR3 Performance Framework. These indicators have, by their nature, a stronger focus on the gatetogate component of the passenger journey.
2. Indicators at Level 2 comprise indicators that are currently (or are planned) to be at least modelled by research projects. These mature some aspects of passenger experience and focus on multimodal considerations such as reliability. Within this level, the indicators can be categorised as Level 2.1 for indicators that are good candidates to be promoted to Level 1, i.e., included in the next version of the SJU Performance Framework; and as Level 2.2, which contains the rest of the indicators.
3. Level 3 contains more ambitious indicators that aim to capture the total experience of passengers in their doortodoor journey. These represent indicators that can be more desirable but currently not feasible due to several limitations, such as data availability.

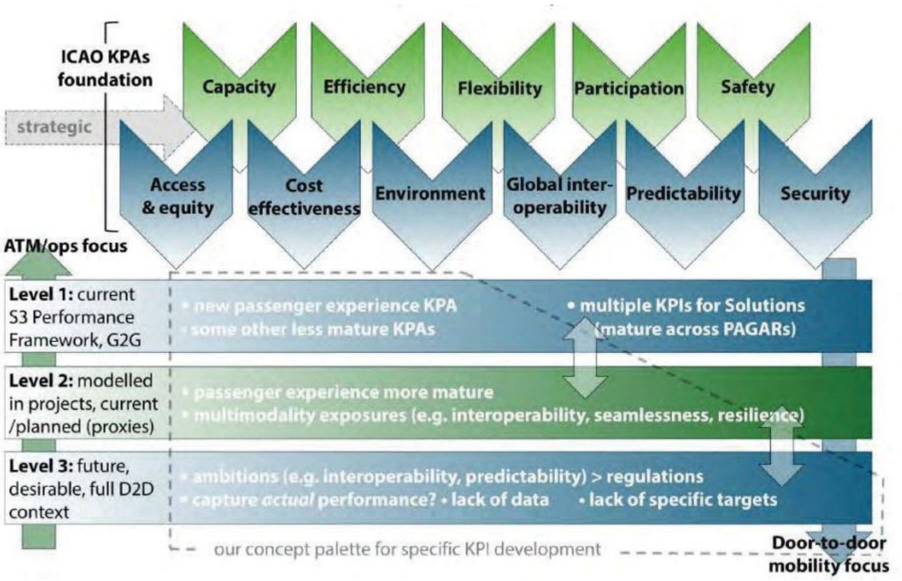

Figure 1. Performance Assessment – Multimodal Performance Framework Concept

It is worth noticing how the same aspects could be found at different levels, e.g. interoperability is a multimodality exposure (at Level 2) while part of the ambitions for full doortodoor performance at Level 3.

The work performed by MultiModX on the further definition of this multimodal performance framework represents an improvement to the EU mobility system as these aspects are currently not monitored and are out-of scope of the system's considerations.

2.1.1.2 Digital catalogue of indicators

The digital catalogue of indicators is currently available in Confluence, a wiki-like collaborative site:

https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY

This page is an open access digital catalogue, which is a live space that evolves along the gap analysis as the conditions of the operational environment change (e.g. datasets available, deployment of data collection and processing). These activities should be developed fur-ther by the Passenger Experience and Multimodality Flagship.

2.1.2 Strategic Evaluation of Networks

2.1.2.1 Scope

The Strategic Multimodal Evaluator is comprised of three main elements:

- Strategic Planned Network Evaluator, which, from the characteristics of demand (origindestination (OD) demand) and supply (flight and rail schedules and infrastructure aspects), computes the materialisation of the supply and demand characteristics in the network.
- Passenger Reassignment on Replanned Network, which assesses the impact of modifying the supply (flight schedules and rail timetable) on the already planned operations.
- Performance Indicators Computation, which, considering the outcome of the Strategic Planned Network Evaluator (or the Replanned network analysis), computes mobility performance indicators.

2.1.2.2 Evaluation of planned networks

2.1.2.2.1 Methodology

The multimodal networks are modelled following the principle of mobility layers connected between them with temporal multiplexes [7, 8], as shown in Figure 2.

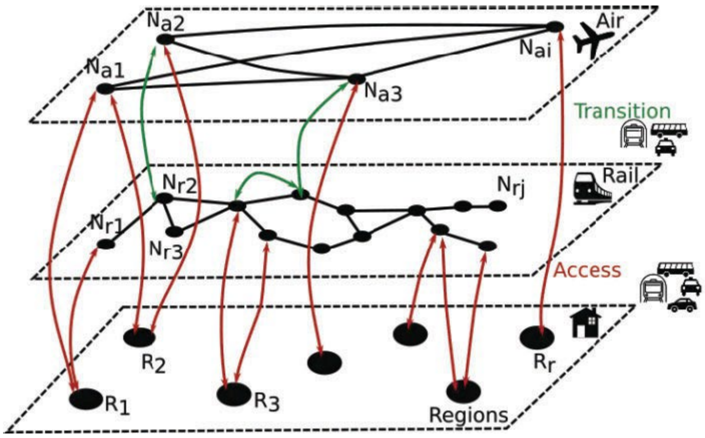

Figure 2. Multilayer modelling approach

This modelling considers the demand between regions by passenger archetypes; the characteristics of the infrastructure which enable access to the mobility layers and the transition between them; supply information that enables moving through the layers (i.e., flight schedules and rail timetables); and policies, which impact some of the previous elements.

The starting point of the mobility network modelling is the definition of regions with their demand between them and the infrastructure (airports and rail stations) that can be accessed from them. For example, we modelled intraSpain mobility with regions defined at the level 3 of the nomenclature of territorial units for statistics (NUTS3 level) in the case study provided.

Note that passengers in each region can start and end their journeys at any of the infrastructure nodes (airports and rail stations) accessible from the region (even if these might be located outside of them). Adequate access and egress times from each region to each infrastructure node are provided to estimate representative doortodoor total travel times.

The approach for the evaluation comprises four functionalities, as shown in Figure 3 and relies on mobility network modelling.

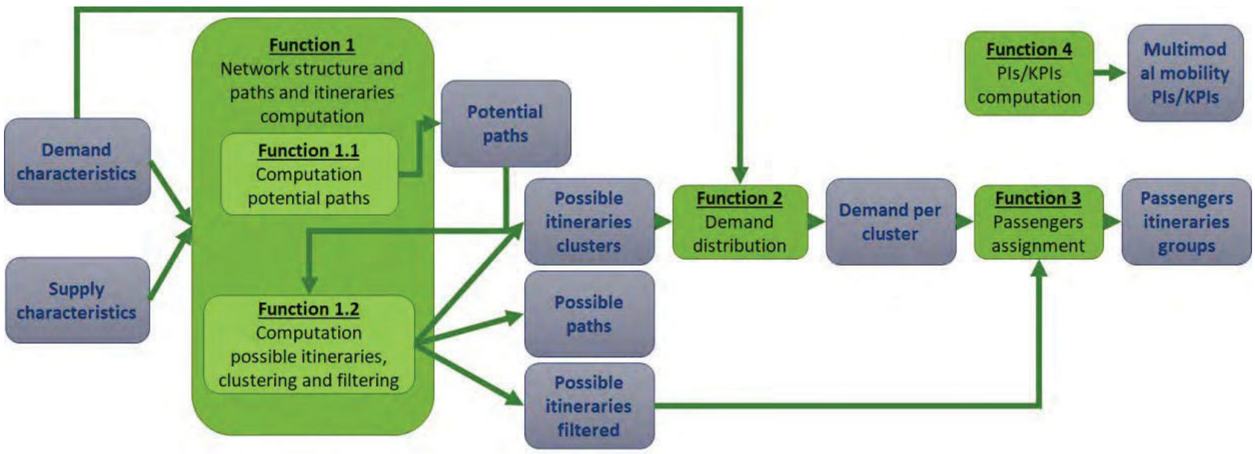

Figure 3. Functional diagram of the Strategic Multimodal Evaluator

Function 1 of Figure 3 will create the mobility network previously described, and apply two highlevel functionalities to find potential and possible paths between regions.

The (n)fastest possible itineraries, considering service schedules and respecting the minimum connecting times, are computed.

For each itinerary, performance indicators relevant to passenger preferences are evaluated as listed below:

- Total travel time
- Total CO_2 emissions
- Total cost
- Number of connections
- Mode type

The itineraries are grouped into clusters of equivalent alternatives from the passenger's perspective, based on these indicators. The average performance of each cluster is calculated (average total travel time, CO_2 and cost) and used to retain only Paretoequivalent clusters, allowing for some margins per indicator, reducing the number of alternatives.

The overall task of assigning passengers to the individ-ual services (i.e., itineraries) is a difficult optimisation problem. To manage complexity, the problem is divided into demand distribution (demand distributed/assigned to a cluster of itineraries) and passenger assignment (demand assigned within the cluster) steps.

In the demand distribution, the demand between origindestination is allocated to passenger flows with the help of a previously calibrated logit model. The logit model is a statistical model which calculates the proba-bility of choosing a specific alternative for each passen-ger archetype when presented with several options for travelling between a given origindestination pair. The probability of an archetype selecting a given itinerary alternative (cluster) is based on a linear combination of total travel time, total CO_2 emissions and total travel cost

To finalise the network loading, the next step is the as-signment of passengers from the flows to individual op-tions within each cluster, i.e., to the individual services (flights and trains), while considering their capacity.

This is computed with a lexicographic optimisation framework with integer programming with three ob-jectives: maximising the total number of connecting passengers, then the overall number of passengers assigned, and finally minimising underutilisation. This ensures that passengers with multiple legs can use the system's capacity and that passengers are distributed among different services, avoiding bunching of passen-gers in services.

The outcome of the Strategic Multimodal Evaluator is the possible itineraries between regions, the desired demand (passenger flows), and the individual passen-gers' itineraries. These datasets can then be processed to compute mobility indicators such as total travel time, modal share, CO_2 emissions.

The Strategic Multimodal Evaluator has been released as an opensource tool, and it is available in GitHub:

https://github.com/UoW-ATM/MultiModX

2.1.2.2.2 Capabilities

The Strategic Multimodal Evaluator uses as input the supply characteristics, i.e., flight schedules, rail timeta-ble, minimum connecting time between services intra and inter modes connections considered, access and egress times to infrastructures (airports and rail stations), alliances and operators integrated ticketing, and the demand characteristics (number of aggregated pas-sengers (per passenger archetype) for each origindestination of interest). Note that the flight schedules and rail timetable could come from historical data, or being the outcome of some optimisation, e.g. MultiModX's Schedule Design Solution SOL400/SOL2.

Many mobility related changes to the system can be easily evaluated by modifying the Evaluator's input. For example, infrastructure changes (e.g. new access and egress times or improved minimum connecting times), policies (e.g. removing flights within a threshold (flight-ban), or increasing cost of services due to taxes (even only for specific archetypes, such as frequent flyer levy)), or even changes to demand characteristics (e.g. new ar-chetypes or sensitivity towards travel parameters).

2.1.2.3 Evaluation of replanned networks (under disruptions)

2.1.2.3.1 Methodology

The computation flow of passenger replanning is car-ried out in the following steps. Firstly, the planned net-work's (prior to disruption) supply (flight schedules and rail timetables) is modified. When disruptions impact the network in a significant manner, the air and rail op-erators will modify their services (e.g. cancelling flights, delaying services, rerouting). These modifications are applied on the planned network to create a replanned network.

Next, the algorithm identifies passengers that need re-assignment. These could be passengers whose service has been cancelled or whose connection is no longer possible due to delay. The passengers with itineraries still feasible in the replanned network follow their orig-inal itineraries. Then, for each service in the replanned network a spare capacity is calculated considering the passengers not impacted by replanning.

The possible itineraries between each origin and desti-nation of the affected passengers are computed. Then, the (n)fastest possible itineraries, considering service schedules and respecting minimum connecting times are computed.

Passengers replanning alternative	Short description
PA01	Close to planned
PA02	Allow different path
PA03	Allow different path and mode swap
PA04	Allow different path, mode swap and different operators
PA05	Allow different path, mode swap, different operators and leave 'home' earlier than initially planned

Table 1. Passengers replanning alternatives.

When considering possible itineraries in the replanned network, different alternatives are possible. These are grouped into five alternatives, as summarised in Table 1: from restrictive conditions when passengers can only be accommodated in very similar itineraries as originally planned in PA01 (e.g. using the same operators and path originally considered), to full flexibility in PA05 where even departing before initially planned is available.

The last step is the assignment of passengers to individual possible itineraries, i.e., to the individual services (flights and trains), while considering their capacity. A lexicographic optimisation is used to perform the reassignment of passengers to potentially suitable itineraries. The optimisation is performed sequentially, first maximising the total number of passengers reaccommodated, then minimising the arrival time to their final destination, maximising the itineraries following the same path as planned before the disruption, and finally maximising the number of itineraries starting and ending in the same infrastructure.

2.1.2.3.2 Capabilities

Passenger Reassignment on Replanned Network assesses the impact of modifying the supply (flight schedules and rail timetable) on the already planned operations. When disruptions impact the network in a significant manner, the air and rail operators could consider changing their services (e.g. adjusting flight schedules and rail timetables, cancelling services) either to just adjust to the disruption (e.g. cancelling flights planned to operate in a closed airport) or to mitigate the impact of such disruptions (e.g. adjusting schedules to minimise missed connections). This replanning of operations to maximise the supplied demand while considering the limited system capacity is the objective of MultiModX's Disruption Management Solution (SOL401/SOL3). The Strategic Multimodal Evaluator can then reassign the demand of passengers impacted by these changes. This reassignment can be done considering different levels of flexibility enabled to the passengers (as presented in Section 2.1.2.3.1).

The overall process is similar to the Strategic Planned Network evaluation,but the passenger demandis already in the form of passenger itineraries, and only passengers impacted by the replanned operations are considered.

Some of the replanning scenarios that can be evaluated include:

- The closure of rail link,
- Closure of an airport,
- Air Traffic Flow Management (ATFM) regulations at an airport e.g. due to industrial action,
- Reduction of capacity at an airport.

2.1.3 Tactical Evaluation of Networks

2.1.3.1 Scope

The Tactical Multimodal Evaluator of the Performance Assessment solution focuses on simulating a day of operations in the network, tracking individual flights and passengers. The input to the Tactical Multimodal Evaluator is the individual flight schedules, rail timetables, passenger itineraries and any other tactical operational parameters (e.g. probability of air traffic flow management (ATFM) regulation, turnaround times, etc.).

2.1.3.2 Methodology

The Tactical Multimodal Evaluator extends the Mercury model from a gatetogate simulator to a full multimodal evaluator [9, 10]. The platform can track individual flights, trains and passengers. This facilitates the computation of very lowlevel passengercentric indicators, such as missed connections, waiting times, total journey times, etc.

Mercury is an opensource flight and passenger mobility model developed over 10 years on several SESAR Exploratory Research projects. https://github.com/UoW-ATM/Mercury

The model follows an AgentBased approach describing with agent and roles the main components of the air traffic management (ATM) system. Mercury uses an eventdriven engine to simulate the main processes.

A full day of ECACwide operations (around 27K flights and 3M pax) can be simulated in under 25 minutes.

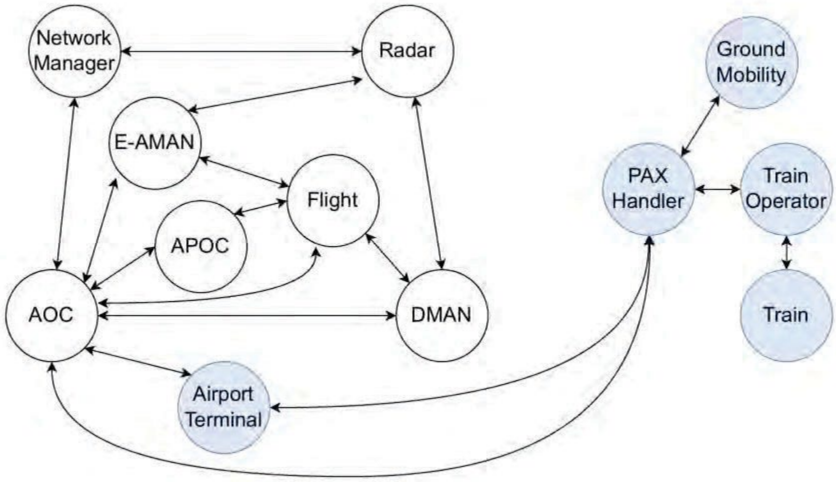

Figure 4. Tactical Multimodal Evaluator model – Agents Architecture

As presented in Figure 4, the agents (Airline Operating Centres (AOC), Airport Operating Centre (APOC), Flight, etc.) responsible for the functioning of the air network have been extended to enable multimodal operations in the following way:

1. The Airport Terminal Agent includes processes to estimate the kerbtogate and gatetokerb for multimodal passengers.
2. The Train Operator and Train simulate the arrival and departure of trains to the rail stations where multimodality is enabled. The Train Operator could also reallocate passengers to subsequent trains in case of missed connections.
3. The Ground Mobility agent provides estimations and realisation of times to transfer between air and rail infrastructure.
4. The Pax Handler agent proactively captures the decisionmaking process of passengers (or travel companions) to rebook passengers for subsequent flights or train services.

The model's bydefault version represents 'basic' multimodal operations. The flexibility of Mercury enables the extension of the model by creating Modules (which can change the behaviour of roles). This allows, for example, the evaluation of multimodal supporting mechanisms by modifying the bydefault behaviour of the agents. For example, modelling a fast track at the airport to process delayed multimodal passengers by modifying the Airport Terminal Agent [11].

2.1.3.3 Capabilities

The model can simulate disturbed conditions, such as daytoday small delays, and stressed nominal conditions (e.g. ATFM regulations, delays on the ground system linking the rail stations with the airports). Therefore, the Tactical Multimodal Evaluator can assess how the planned operations (as derived from the Strategic Multimodal Evaluator) unfold on the day of operations. Mechanisms can be implemented and integrated into the platform to assess their performance in supporting multimodal journeys (e.g. fasttrack at airports for delayed multimodal passengers). Finally, if larger networkwide disruptions, which require some replanning of operations instead of a reactive approach whenmanaging passengers and services, are experienced, the network would be replanned (as presented in the Strategic Multimodal Evaluator description), and the Tactical Multimodal Evaluator could then assess this new network.

2.2 SOL400/SOL2 The Schedule Design Solution

2.2.1 Methodology

2.2.1.1 Introduction

SOL400/SOL2, also known as the MultiModX's Schedule Design Solution, is a strategic schedule optimiser. The Schedule Design Solution can optimise jointly flight and train schedules, considering the network characteristics and what prospective passengers want to do. The Schedule Design Solution considers industry constraints such as airport capacity, overhead times, minimum waiting times, transfer times between train stations and airports, and provides realistic new schedules for rail and air operators.

The scope of the Schedule Design Solution can be quite wide. The tool is capable to optimise schedules for an entire day in a network corresponding to a whole country like Spain, but this scope can be reduced if looking are more targeted air and rail optimisation. The Schedule Design Solution can respect air and rail alliances when doing the optimisation, and it can also provide optimised schedules assuming coordination between different airlines and train companies.

The Schedule Design Solution can function as a standalone tool, but its full potential shows when using it in coordination with the Strategic Multimodal Evaluator. The integration between the two Solutions allows the evaluation of the network before and after the schedule optimisation, and additionally, it allows to observe the changes in demand patterns triggered by the optimisation of the schedules.

2.2.1.2 Inputs and constraints

The inputs of the Schedule Solution can be divided in two categories: demand characteristics and supply characteristics. The multimodal network is modelled as a multilayer network, where it is possible to transfer from the air and rail network if two stations are connected.

The user provides the connected stations and the transfer times. Additionally, the user provides the initial air and rail schedules, along with the itineraries, c'estàdire, the possible concatenation of successive connected services. Whether two services are part of the same itinerary is decided based on their schedules and the connection/transfer times between their two stations. This information can come from the Strategic Multimodal Evaluator, or directly from the user. Finally, the user also provides the specific demand for each itinerary: How many people take this train/plane? This information can also come from the Strategic Multimodal Evaluator, or directly from the user. With this, the Schedule Design Solution is ready to start providing optimised schedules.

To ensure realistic optimisation, the Schedule Design Solution, has some built in constraints. These include running time constraints, dwell times constraints, capacity constraints, and headway constraints. By applying these constraints to the optimisation model, we ensure that the resulting schedules can be implemented.

2.2.1.3 Optimisation mechanism

There are five key functions that form part of the Schedule Design Solution (Figure 5).

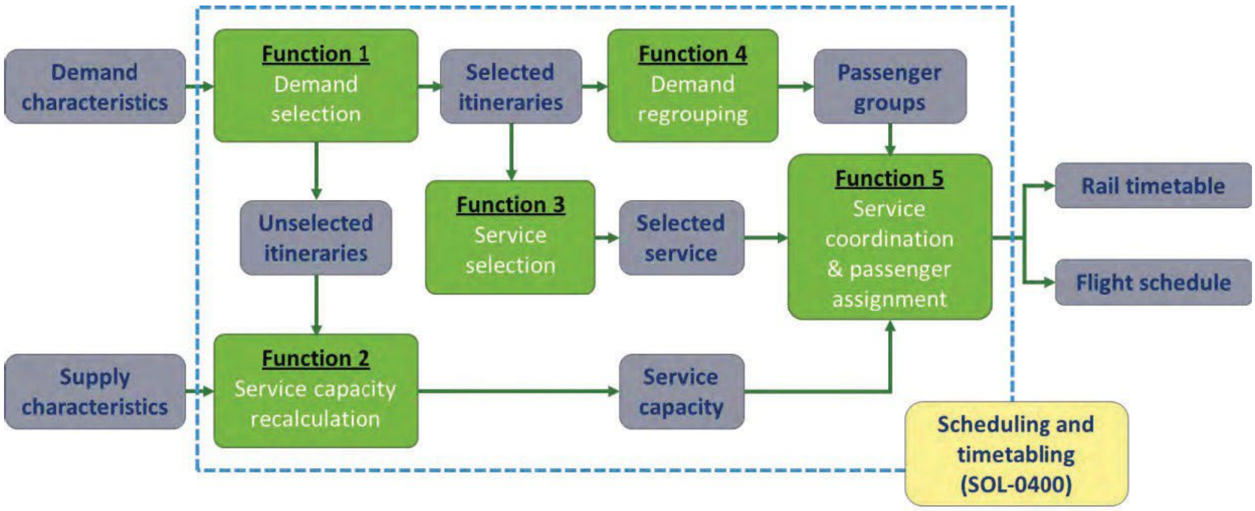

Figure 5. Functional form of the Schedule Design Solution

1. Demand selection: Since the Schedule Design Solution aims at improving connections, the first step in the optimisation is to select the itineraries that have such connections and filter out passengers that are not connecting. The optimisation is done based on the passengers taking connected itineraries, and the remaining passengers (the ones that are not connecting) affect the capacity of the services by occupying seats. The final output of this function are the unselected and selected itineraries.

2. Service capacity recalculation: Once the selection of itineraries is done, the unselected itineraries (with their demand) are used to recalculate the final capacity of all services.

3. Service selection: The selected itineraries are used to determine the candidate services to be optimised. These include the specific trains and flights from the selected itineraries and other services using the same sequence of infrastructure (path).

4. Demand regrouping: This function extracts the path of all the selected itineraries and calculates the total demand per paths (considering all the services that use these paths). This demand is grouped in multiple groups from a given size. These group of passengers might be assigned different services after the optimisation.

5. Service coordination and passenger assignment: This function generates the coordinated schedules and assigns passengers to the specific services using Mixed-Integer Programming (MIP) optimisation. The initial schedules are modified by shifting services in time (but not re-routing them). The optimisation problem is solved in a lexicographic manner: first the model maximises the served demand (i.e., prospective passengers assigned to services), then transfer times are minimised, and finally, schedules that minimise the difference between the original timetable are selected.

In this way, the Schedule Design Solution ensures that as many people as possible can travel, and minimises travel times between regions, carefully balancing supply, demand and constraints.

2.2.2 Conclusion

In conclusion, the Schedule Design Solution is a powerful strategic tool that improves passengers' transfer experience, maximises the operators' profits, and respects the networks' constraints. Its use also has the potential of improving air and rail integration and multimodality and advance in the direction of the objectives aligned with Flightpath 2050.

2.3 SOL401: Disruption Management Solution

2.3.1 Introduction

The Disruption Management Solution (SOL401) aims to design passengercentric, tacticallyadjusted schedules, for air and rail to manage disruptions. Those adjustments are designed to optimally manage passenger demands by minimising the effects of the disruptions. The Solution takes as input initial passenger flows, including the sensitivities of passenger types (i.e., archetypes) regarding several travel aspects, such as travel time or cost, when selecting a specific path and mode(s) to reach their desired destination. The flows of each path determine the demand to satisfy when managing the disruptions. The Disruption Management Solution then adjusts air and rail schedules, the corresponding train routing and flight diversion to accommodate the given demand under disruptions optimally and, therefore, replans the network in apassengercentric fashion.

SOL401 can operate at varying levels of centralisation, from decentralised management within airline alliances to fully centralised, multimodal coordination across all air and rail operators. The schedule adjustments aim to minimise disconnected passengers, additional detours, waiting times, and the need for replacement services, ensuring that passenger demand is managed efficiently during disruptions. Figure 6 presents an overview of the Disruption Management Solution (SOL401).

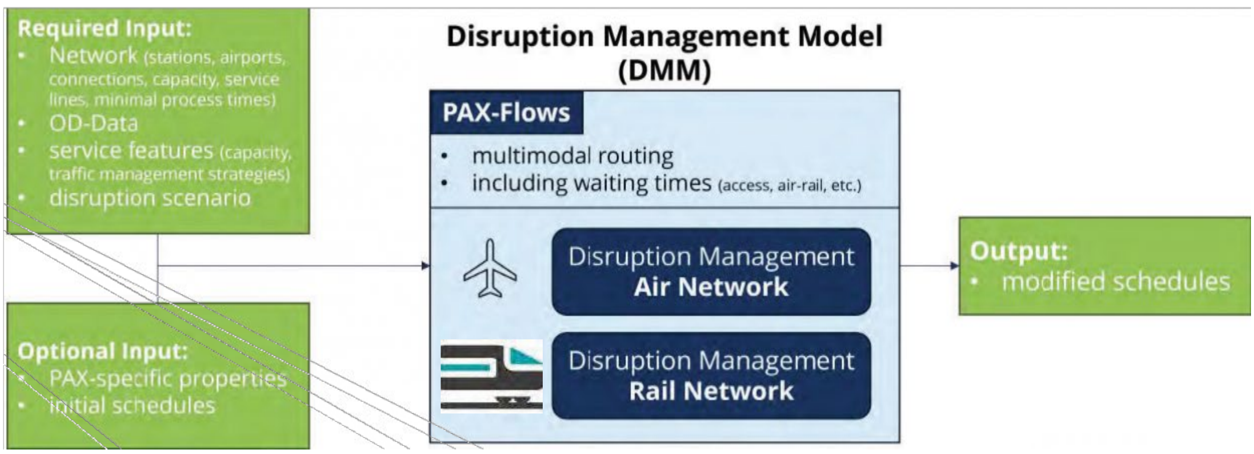

Figure 6. Overview of the Disruption Management Solution (SOL401)

2.3.2 Optimisation mechanism

The Disruption Management Model uses the characteristics of supply, demand and disruptions in combination with disruption management preferences to determine the adjusted schedules for rail and air.

The Disruption Management Model comprises three core functions, which are iteratively applied to determine the optimal, multimodal, passengercentric disruption management decisions. The overall functional decomposition and the respective interactions among the different functions are displayed in Figure 7.

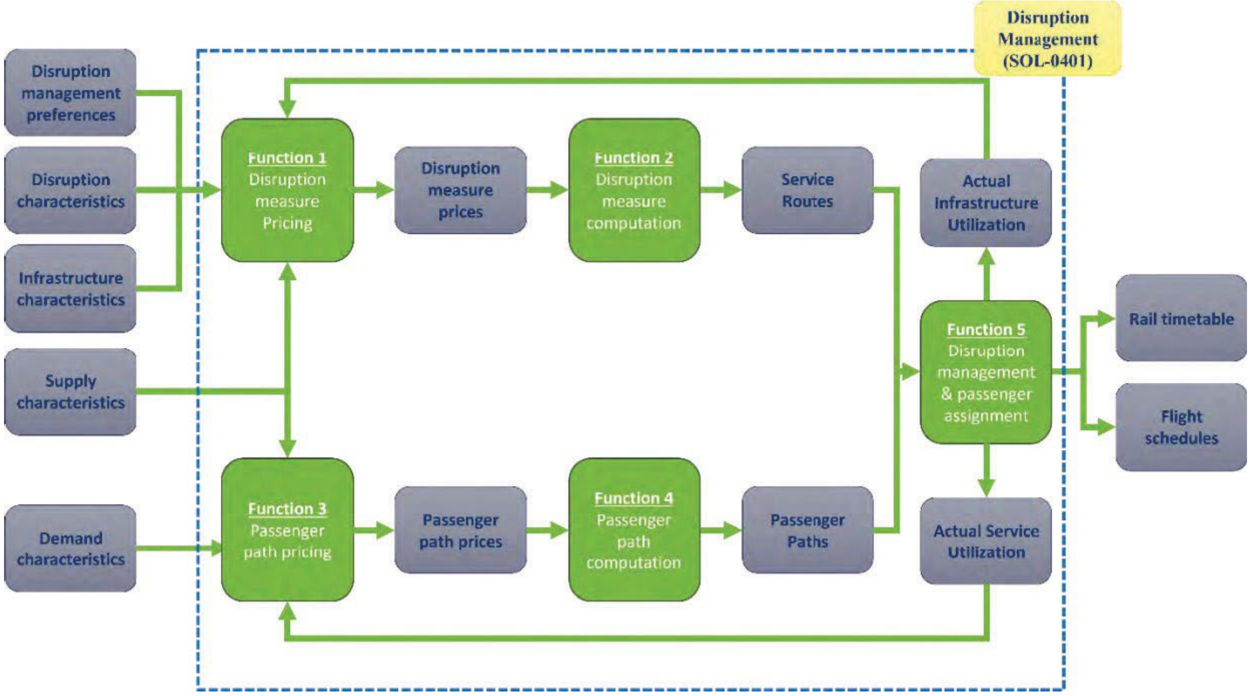

Figure 7. Disruption Management Model – Functionalities. Green: Functions, Grey: Data

Function 1 – Disruption measure pricing: Function 1 computes generalised disruption measure prices for each service by combining service characteristics, infrastructure attributes, disruption management preferences, and current network utilization into a single metric. These prices, representing the tradeoff between passenger benefits and operating costs, are updated iteratively during the optimisation process to guide disruption management decisions.

Function 2 – Disruption measure computation: Function 2 identifies the most costeffective disruption measures for each service – such as rerouting, schedule adjustments, shortturning, or cancellations – based on the generalised prices from Function 1, and provides the alternative service routes for further evaluation.

Function 3 – Passenger path pricing: Computes generalised prices for passenger paths based on demand, service characteristics, and current seat utilization, representing tradeoffs in routing for every origindestination pair. These prices are updated iteratively and used to identify potential capacity bottlenecks and passenger impacts during disruptions.

Function 4 – Passenger path computation: Determines the cheapest potential passenger paths for each origindestination pair based on the generalised path prices from Function 3, providing alternative paths for disruption management.

Function 5 – Disruption management & passenger assignment: Optimally assigns services, passengers, and schedules to minimise overall disruption costs – including detours, stranded passengers, and operating costs – and produces the adapted air and rail timetables along with updated infrastructure and service utilization for iterative feedback.

The overall solution operates in an iterative manner, which provides feasible results (i.e., timetables) with every run. The quality of the results improves with every iteration until optimality (i.e., no new adapted/alternative service routes and new passenger paths can be found by functions 1 and 3, respectively) or premature termination (i.e., it stops after a predefined number of iterations).

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found by functions 1 and 3, respectively) or premature termination (i.e., it stops after a predefined number of iterations).

2.3.3 Conclusions

The Disruption Management Solution represents a powerful decisionsupport tool as it enhances multimodality under disrupted circumstances and offers a better travel experience to passengers even under disruptions. The Solution allows to:

- Provide a holistic consideration of both air and rail system constraints as well as multimodal travelling possibilities, which improve the passengercentric performance of the system.
- Compute an adjusted multimodal schedule, including adjusted flight schedules and rail timetables, considering given disruptions.

Evaluate different approaches to replan the operations: decentralised vs centralised, enabling the creation of multiple experiment instances and comparing Key Performance Indicators (KPIs).

3 Common elements across all Solutions

All MultiModX Solutions are based, and evaluated, on common elements. The combination and variation of these elements form the MultiModX scenarios. There are three main pieces that constitute the scenarios, namely the regional archetypes, the passenger archetypes, and the multimodal policies.

3.1 Passenger archetypes

One of the main goals of the MultiModX is to identify and characterise current and future scenarios for long-distance passenger behaviour. To fulfil this objective, the project has developed methodologies for the characterisation of longdistance travellers pattern, generating passenger archetypes. This methodology has been put to the test in two regions, Germany and Spain. The passenger archetypes of the two regions have been compared to define the MultiModX passenger archetypes.

Different passenger archetypes have different preferences regarding mode choice, and different sensitivities with respect to time, price and emissions when choosing their itinerary on a given trip. These preferences are accounted for by the calibration of a unique discrete choice model per each passenger archetype.

3.1.1 Spanish passenger archetypes

The analysis of passenger behaviour has traditionally relied on surveys. They usually provide a detailed characterisation of travelling behaviours, but are costly, only capture data on a very limited population sample and period of time, and the accuracy of the responses may vary. Mobile Network Data (MND) is a new form of data that allows passive monitorisation of movements and longitudinal studies.

Mobile Network Data provides anonymised information about which antennas a given mobile phone is connecting to. This, in turn, gives an approximate proxy for the location of the mobile phone user, allowing for the characterisation of trips and of activity "diaries", i.e., a list of trips and duration of the trips, free from reporting bias, as represented in Figure 8.

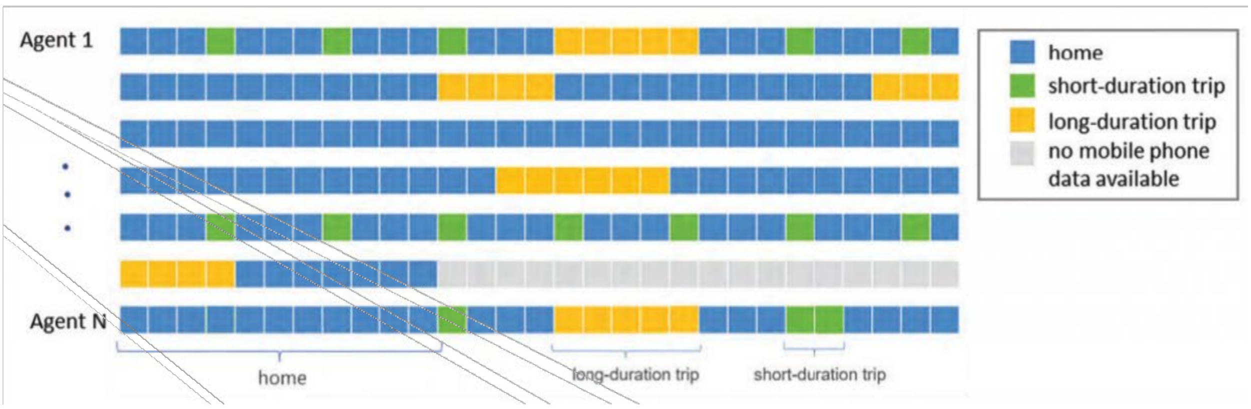

Figure 8. Travel diaries of different individuals

As part of the MultiModX project, we developed a methodology to extract these travel diaries for Spanish individuals, and cluster them according to their travel behaviour. This analysis yielded the archetypes summarised in Table 2.

Passenger archetype	Description
Sporadic longhaul traveller	These individuals occasionally perform longdistance trips. They have limited income and live in more rural areas.
Occasional weekday traveller	These individuals have a tendency to travel during the workweek, engage in trips with medium frequency, and prefer shortduration journeys over longduration ones.
Domestic summer traveller	These individuals travel mostly during the summer period for long periods of time. They usually cover long distances within the country.
Sporadic international traveller	These individuals usually go for mediumduration trips and often prefer international destinations over domestic ones.
Long distance actives	These individuals tend to be younger, higherincome than average and travel to various destinations.
International urbanites	These individuals live in big cities and tend to go abroad for their trips.

Table 2: Characteristics of Spanish travel behaviour

The identification of the different passenger archetypes served to highlight the diversity of behaviour regarding mobility. A good transportation network should be able to accommodate these different needs and desire to provide the best quality service and high passenger satisfaction.

3.1.2 German passenger archetypes

For developing the German passenger archetypes, we used simulated big data from an agentbased model designed to simulate longdistance travel behaviour in Germany . The model operates at a microscopic scale, explicitly simulating individual travel choices, including mode choice, trippurpose, trip duration, destination, etc. By applying the Kmeans clustering algorithm on the simulated travel of the German population, we obtained the following longdistance passenger archetypes for Germany:

1. The GenXer travelling mostly for business via rail

This passenger archetype represents predominantly middle- to oldaged travellers, spanning those between 25 and 65 years old, with a mean age of 48. With the secondhighest employment rate, this group commands the highest monthly personal and household income among all archetypes.

Their travel patterns are distinctive for covering the shortest distances, averaging just 259 kilometres per trip. Rail transport dominates their mode choice. These travellers typically complete their journeys within a single day with business reasons motivating nearly half their trips.

2. The GenXer travelling predominantly for private purposes via rail

This passenger archetype represents predominantly older travellers with a mean age of 56, concentrated among those over 45 and 65 years old. This group shows the highest employment rate but has the lowest monthly net household income among all archetypes.

Their travel behaviour features the secondlongest average distances at 295 kilometres per trip. Rail transport is their dominant choice. Unlike shorter business trips, their journeys typically extend to two or more days. Private purposes drive most of these journeys.

3. The GenZ youngster going on holiday

This passenger archetype represents predominantly very young travellers with a mean age of 26, concentrated among those under 24. This group has the highest rate of unemployment (including being a student) and has the lowest monthly personal income.

Their travel patterns feature the longest average distances at 301 kilometres per trip. Rail transport accounts for most of their journeys, but they demonstrate the highest propensity for air travel. Their trips typically extend to two or more days. Leisure purposes drives most of these trips.

3.1.3 MultiModX passenger archetypes

To obtain the MultiModX archetypes, we used the two distinct clustering exercises, each drawing from different datasets; one based on Spanish Mobile Network Data, and another using data from the Technical University of Munich agentbased model for longdistance travel in Germany. These two approaches offer unique insights into travel behaviour patterns, each with its own set of strengths and limitations.

The Spanish clustering limitations include travel motivations and round trips. The German clustering exercises offers a different perspective, incorporating sociodemographic characteristics alongside travelspecific variables. However, this dataset is also limited to only two variables directly related to travel behaviour: trip distance and trip duration.

Given the distinct advantages and limitations of each clustering exercise, we combined the results of both approaches. This method allowed us to leverage the strengths of each dataset while mitigating their respective weaknesses, capturing a wide range of travel behaviour characteristics, while incorporating sociodemographic factors that may influence travel patterns, and develop a robust, holistic set of travel behaviour archetypes going beyond each country's specificities.

The MultiModX passenger archetypes are the following:

- The shortdistance traveller

The shortdistance traveller are predominantly workingage individuals (between 25 and 65). In some countries, such as in Spain, this archetype has a larger share of population over 65, than the country as a whole does. They tend to live in smaller cities and may have a small household of two people. Thisarchetype does not engage in any longdistance travel throughout the year. These trips are of a short duration, typically lasting only one day. The dominant trip purpose is business (43%), followed by for private leisure purposes (33%). The dominant choice of travel mode is train (up to 100%).

- The sporadic GenX traveller

These individuals tend to be older, above the age of 45. They are slightly more prevalent in rural areas and coastal regions and may have a small household of two people. This archetype covers long distances, often choosing offpeak periods such as September and June. Trips are mostly taken for private purposes (e.g. to visit family and friends) (43%), followed by leisure purposes (30%) and last 4 days on average. The dominant choice of travel mode is train (between 5275%).

- The workingage weekday traveller

These individuals are predominantly working age (between 25 and 65), with a greater share of people over 45. They live in medium or small cities and may have a household of three people. This archetype covers long distances, usually during the workweek. Travel activity is spread throughout the year, but higher in autumn and spring. Trips are mostly taken for business purposes (49%), followed by leisure purposes (36%). The dominant choice of travel mode is train (between 5864%)

- The summer traveller

These are working age (between 25 and 65) individuals, with a greater share of people over 45. They reside in large cities and may have a household of four people. This archetype almost exclusively travels in July or August, for the longest trips among the clusters. These trips to predominantly domestic destinations (98%) are typically made twice per year, and on average last ~9 days. The dominant choice of travel mode is train (61%).

- The habitual traveller

These may be very young (<25 years) or working age (between 25 and 65) individuals. They reside in large cities and may have a household of four people. This archetype covers long distances at a higher frequency compared to the other archetypes. Trips are distributed throughout the year, with a slightly higher concentration during the summer. Trips are mostly taken for leisure purposes (47%), followed by business purposes (34%) and last 5 days on average. The slightly dominant choice of travel mode is train (51% – 52%).

- The sporadic global traveller

These individuals are mostly of workingage (between 25 and 65). They do not align with any particular category of home municipality size. This archetype very often prefers international destinations. The travel patterns do not follow any specific seasonality. These trips to predominantly international destinations (83%) are typically made three times a year, and on average last ~5 days. The dominant choice of travel mode is air (87%).

- The holiday globetrotter

These individuals are mostly of workingage (between 25 and 65). They live in big cities, especially in large metropolitan areas. This archetype explores international destinations during holiday periods (summer, Christmas, and Easter). These trips to predominantly international destinations (81%) are typically made three times a year, and on average last ~7 days. The dominant choice of travel mode is air (84%).

3.2 Regional archetypes

European regional archetypes are identified at NUTS 2 level with a view to detail the degree of applicability of internetenabled multimodal Mobility as a Service (MaaS) concept. This facilitates the evaluation of the impact of multimodality at this travel regions level, which could then be extrapolated to other regions of the same level even if not explicitly modelled. This creates, therefore, different suboperational environments based on these regional archetypes.

Once the regional archetypes are identified, passenger archetypes can be associated with them, thus estimating the average compositions of passenger archetypes within a certain regional archetype. This could facilitate the creation of new experiments by distributing origindestination demand between regions to demand per passenger archetype.

Three regional archetypes were identified by clustering on features related to sociodemographics (e.g. per capita Monthly Household Income), tourist volumes (e.g. arrivals at tourist accommodation), travel behaviour (e.g. departing air traffic), and innovativeness (e.g. Share of the population who ordered goods or services over the internet). Here, we describe these archetypes.

3.2.1 Advanced high Mobility as a Service (MaaS) potential regions

These regions represent an ideal environment for MaaS adoption. These highly urbanised areas benefit from exceptional infrastructure readiness with their dense railway networks and airport accessibility creating a fertile foundation for integrated mobility solutions. The predominantly young population aligns perfectly with typical early MaaS adopters, bringing digital fluency and openness to innovative mobility approaches.

The economic landscape further encourages adoption with high disposable incomes reducing price sensitivity concerns that might otherwise impede uptake. As innovation leaders, these regions likely possess both the public sector vision and private investment capacity to support sophisticated MaaS development. High tourism creates dual markets of locals and visitors needing intuitive navigation solutions. Furthermore, the highest per capita trip rates across Europe indicate frequent mobility needs that would benefit from streamlined options.

These regions can serve as innovation laboratories where comprehensive MaaS ecosystems develop first, testing subscription models, integrated payment systems, and personalized multimodal journey planning before such features spread to less advantaged regions.

3.2.2 Conservative regions for cautious Mobility as a Service (MaaS)adoption

These regions present a mixed landscape for MaaS adoption. These regions with median travel activity feature infrastructure that is adequate but not exceptional – with railway density at median EU levels and fewer airports per capita than other clusters. This provides a workable foundation for MaaS implementation.

The demographic profile poses a substantial barrier to rapid adoption. With the highest proportion of residents aged 45+ and lowest share of younger populations, these regions seem to lack the digitalnative demographics that typically drive early MaaS uptake. This age distribution aligns with the moderate ecommerce usage, suggesting some digital hesitancy that could slow MaaS adoption. Economic factors are more favourable, with neartop disposable income levels indicating purchasing power that could overcome price sensitivity concerns.

The median level of total trips per capita and preference for rail (though less pronounced than in the first archetype) indicate reasonable demand for integrated mobility solutions.

3.2.3 Emerging low Mobility as a Service (MaaS) potential regions

These regions face significant barriers to MaaS adoption despite some demographic advantages. These sparsely populated rural areas contend with fundamental infrastructure limitations that undermine MaaS viability. The lowest railway line density creates a fragmented mobility landscape that's difficult to integrate into cohesive MaaS platforms. Passenger volumes and overall trip rates are the lowest among all clusters, indicating minimal travel activity that reduces the practical value of comprehensive mobility services.

The younger population profile initially appears favourable for digital adoption, with high proportions of residents aged 044. However, this demographic advantage is offset by only median ecommerce usage, suggesting digital infrastructure limitations rather than agerelated hesitancy. The predominance of Emerging Innovator status (58%) indicates nascent innovation ecosystems that may lack the technical expertise and investment capacity to develop sophisticated MaaS solutions.

Economic constraints present perhaps the most substantial barrier, with the lowest disposable income among all clusters creating high price sensitivity. The low tourism rates further remove a potential adoption catalyst that might otherwise drive initial implementation.

MaaS implementation in these regions will likely be limited to targeted solutions addressing specific pain points rather than comprehensive platforms, with successful adoption requiring significant customization to rural mobility patterns and substantial public subsidies to overcome economic barriers.

3.3 Multimodal Policies

The development of multimodal networks is strongly influenced by policies. The current and future European regulatory framework and national policy environments were revised and analysed. In particular, the following policies and their impact on the demand and the supply were considered:

- Passenger rights and multimodality: Regulation 261, passenger rights, multimodal digital mobility services, extension of protections for enhanced multimodal passenger rights, and level of integrated ticketing, including operator alliances and rebooking policies.
- Limitation of aviation: Shorthaul flight bans.
- Environmental regulations: frequent flyer levy, rail incentivization, increased CO_2 cost.

These policies were grouped into policy packages which represent different representative operational environments, such as the ones described in Table 3.

ID	Policy package	Individual policies definition
PP00	Reference (no particular policies)	• Passenger rights and multimodality: No integrated tickets • Limitation of aviation: N/A • Environmental regulations: N/A
PP10	Multimodality incentivised	• Passenger rights and multimodality: Fully integrated (respecting alliances) • Limitation of aviation: N/A • Environmental regulations: CO_2 tax applied to emissions
PP20	Multimodality enforced	• Passenger rights and multimodality: Fully integrated (respecting alliances) • Limitation of aviation: Shorthaul ban if rail available between regions served by flights and rail service faster than a given threshold (2h30) • Environmental regulations: CO_2 tax applied to emissions

Table 3. Policy packages

4 Impact and Benefits

4.1 The Performance Assessment Solution

The MultiModx's Multimodal Performance Assessment Solution (SOL399/SOL1) aims to evaluate the performance of a planned and replanned multimodal mobility networks and multimodal Solutions (such as SOL400/SOL2). This is demonstrated through Performance Indicators of the Multimodal Performance Framework, which focus on mobility aspects driven by the passengers experience.

The results of different experiments showed the importance of disaggregating the indicators considering passenger types and suboperational environments to fully understand the impact of multimodal mechanism, such as policies and schedulers (e.g. SOL400/SO2). Otherwise, networkwise indicators might not vary in a significant way while mobility patterns emerge in some specific suboperational environments (e.g. hub airports, airports affected by flight bans, and regional airports).

For example, the Strategic Multimodal Evaluator can analyse the impact of different policy packages (as defined in Table 3) focusing on different infrastructure nodes. Figure 9Error! Reference source not found. shows how when these policy packages are applied to intraSpain mobility, the catchment area and the degree of multimodality of the regional airport of Valladolid (LEVD) changes. As depicted, when multimodality is incentivised (PP10) and when the flight ban is applied (PP20), the number of regions (and passengers) that use LEVD as their local regional connector increases. These effects are captured even if no direct changes are performed to LEVD. Multimodal mechanisms (e.g. policies) impact passenger flows on their doortodoor mobility.

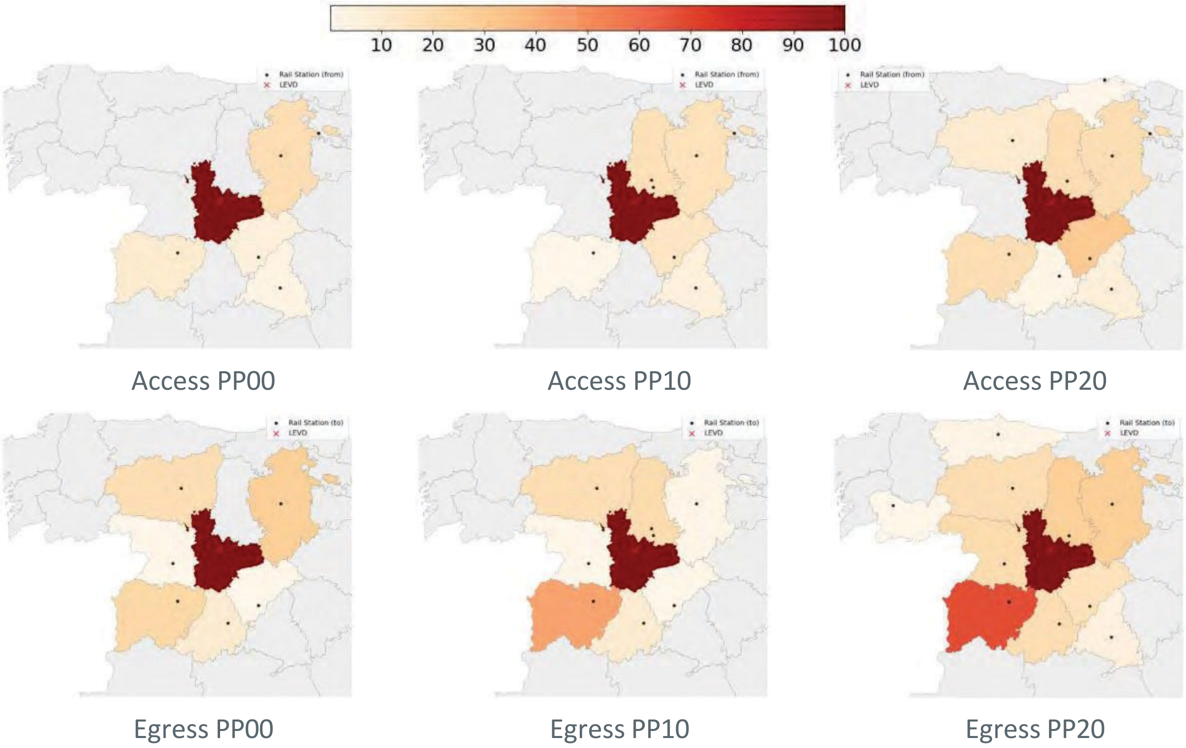

Figure 9. Access and egress (including from/to multimodal journeys) for Valladolid airport (LEVD) for three scenarios.

The Strategic Multimodal Evaluator can also evaluate the mobility under new optimised schedules (as the ones produced by the MultiModX's Schedule Design Solution (SOL400/SOL2)) and replanned networks from a passengercentric perspective. These replanned network can be the simple reaction to a given disruption or an optimised replanning from Disruption Management Solutions (such as SOL401/SOL3). This has been demonstrated using the Strategic Multimodal Evaluator capabilities to assess a range of disruptions under different replanning of passengers assumptions.

The results showed, once again, the importance of disaggregating the indicators on specific cases to fully understand the impact of the replanned operations, particularly looking at specific origindestination pairs and how they benefit (or not) from the replanned operations and the flexibility to reallocate passengers under different disruptions cases. This helps to identify which suboperational environments (e.g. islands, hubs) can (or not) support the disrupted passengers.

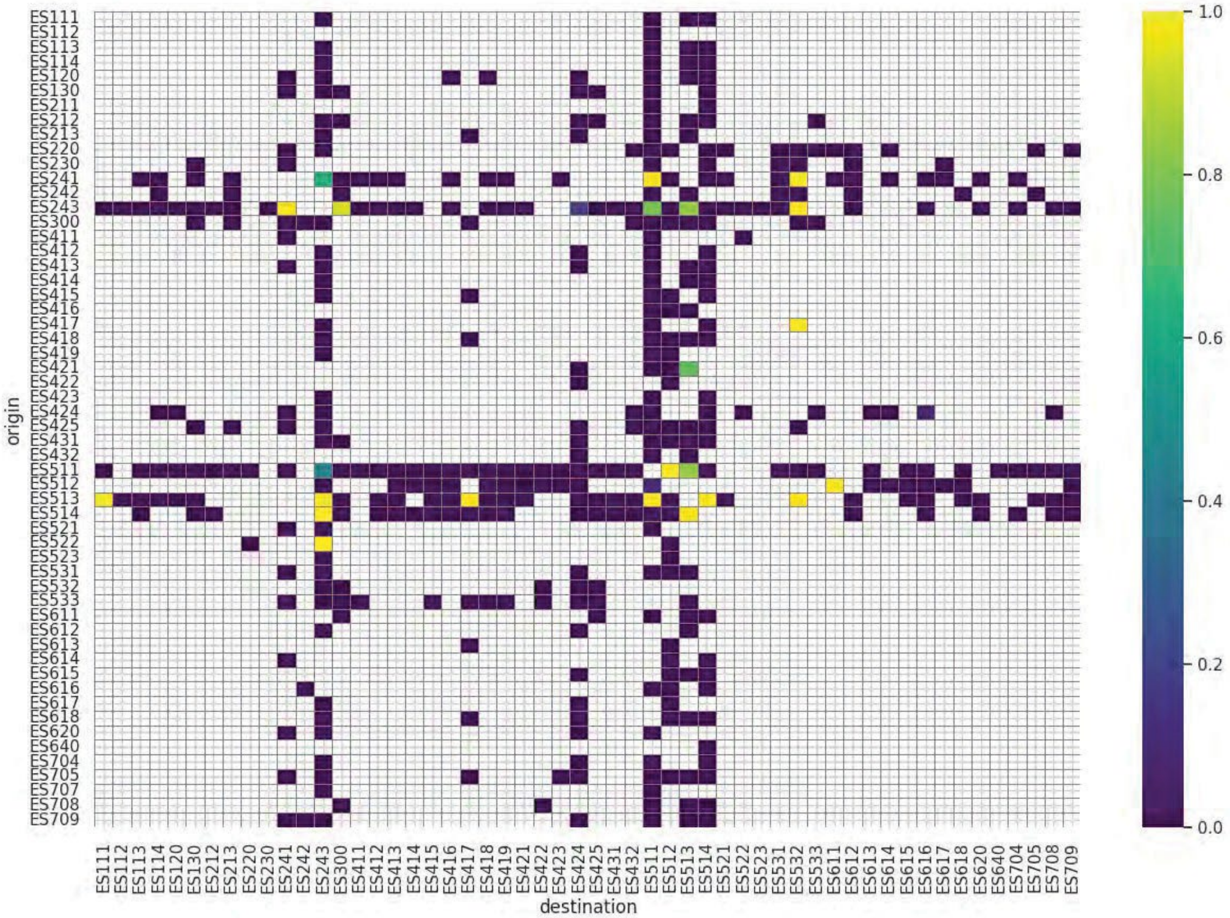

Figure 10. Percentage of passengers reassigned in case study of Madrid Atocha – Barcelona Sants rail link closure

Figure 10 shows an example of passenger reassignment for the case study of Madrid Atocha – Barcelona Sants rail link closure. The results identify 26 origindestination pairs which benefit from the reassignment, with most connecting itineraries being stranded. These regions can find alternatives to other rail services that are not cancelled.

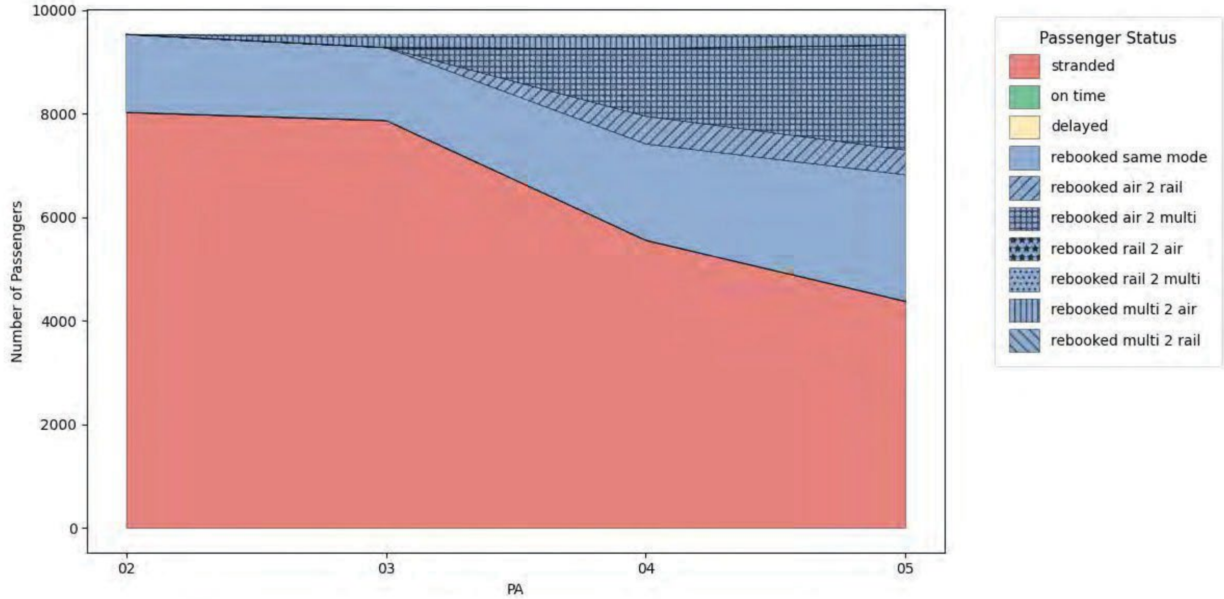

Figure 11. shows the status of the disrupted passengers in the case study of a closure of the airport of Málaga (LEMG).

Finally, SOL399/SOL1 has proven to be a versatile tool to evaluate the replanned itineraries. Many of the parameters used when defining the flexibility provided to passengers to reaccommodate their operations, and to optimise the assignment, are fully adjustable. In the conducted exercise, these factors have been grouped into representative alternatives (PA01 to PA05, as shown in Table 1). Figure 11 shows an example of this replanning flexibility for reallocating passengers impacted by disruptions in the case of the closure of Málaga airport (LEMG).

Finally, the capabilities of MultiModX's Tactical Multimodal Evaluator were validated to assess the performance of multimodal mechanisms to support these types of connections during the day of operations (e.g. fast track for multimodal passengers at airports), see [6] for example.

The Tactical Multimodal Evaluator can also assess the robustness of the planned networks (optimised or not); for example by estimating the number of passengers who could miss their connection in case of some disturbances on the intermode connection links.

4.2 The Schedule Design Solution

The MultiModX's Schedule Design Solution fundamentally affects the transportation network of the region where it is applied. As part of the MultiModX project, we tested the capabilities of the Schedule Design Solution by applying it countrywide to the air and rail network of Spain. Several hundred of services are shifted in time as a result of the optimisation (see Figure 12), creating new itineraries. We see that most itineraries are shifted by 20 minutes, the maximum allowed by the model in accordance to feedback from the Industry Board, showing that if these constraints are relaxed, the Schedule Design Solution has even more optimisation potential.

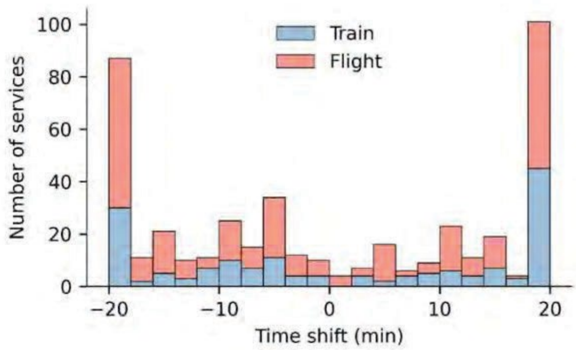

Figure 12. Services shifted after one application of the Schedule Design Solution

The Schedule Design Solution is capable of significantly reducing travel times in connecting itineraries by reducing buffer times, i.e., additional time spent between connections.

Additionally, consecutive iterations of the Schedule Design Solution with the Strategic Planned Network Evaluator can reduce even more these buffer times (see Figure 13). This generates a significant time reduction on connecting itineraries (see Figure 14).

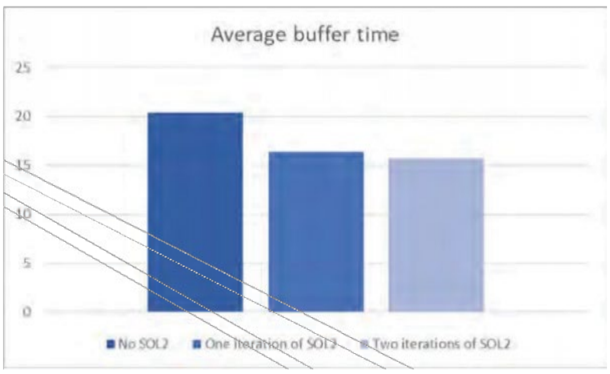

Figure 13. Average buffer times before and after the application of the Schedule Design Solution

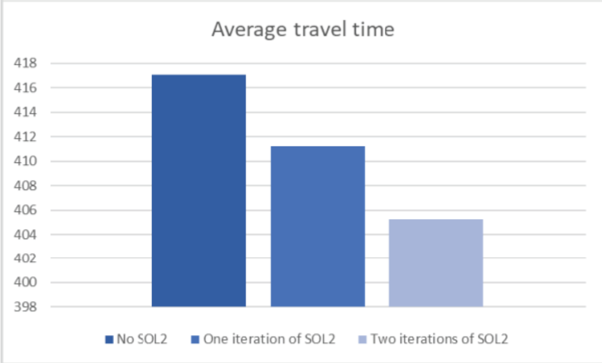

Figure 14. Average travel time on connecting itineraries before and after the application of the Schedule Design Solution

For particular origin and destination pairs, the Schedule Design Solution has a significant impact, drastically reducing travel times, (Table 4), at the expense of significantly increasing travel times in other itineraries (Table 5). At first glance it might seem that this just displaces the "bad" itineraries from one place to another, however, the Schedule Design Solution targets inconvenient and underused services to help connecting more efficiently regions with high demand.

This is clearly shown in Table 6: overall the application of the Schedule Design Solution significantly increases the attractiveness of connecting itineraries, increasing the number of people using these itineraries.

Origin	Destination	Minutes saved
Navarra	A Coruña	185
Murcia	Vizcaya	170
Burgos	Ourense	159
Tenerife	Lugo	153
Girona	Huelva	136

Table 4. Biggest time savings by itinerary after the appli cation of the Schedule Design Solution.

Origin	Destination	Minutes lost
Murcia	Mallorca	193
Melilla	Vizcaya	188
La Rioja	Fuerteventura	171
Vizcaya	Málaga	152
Burgos	Toledo	122

Table 5. Biggest time loss by itinerary after the application of the Schedule Design Solution

Scenario	Number of connecting passengers	difference
Before the application of SOL2	18637	-
After one application of SOL2	19592	+5.12%
After two applications of SOL2	20032	+7.49%

Table 6. Number of connecting passengers before and after the application of the Schedule Design Solution

Another significant impact of the Schedule Design Solution is to modify the catchment area of airports. As we can see in Figure 15, the access time to airports can increase or decrease significantly after the application of the Schedule Design Solution. This highlights the fact that schedule optimisation can have impacts in the infrastructure used, increasing the number of people connecting in some airports by reducing those connecting in other airports. This can be used to decongest heavily congested airports by making secondary airports more accessible but can also divert passengers to smaller airports instead of rail alternatives in the case of a flight ban.

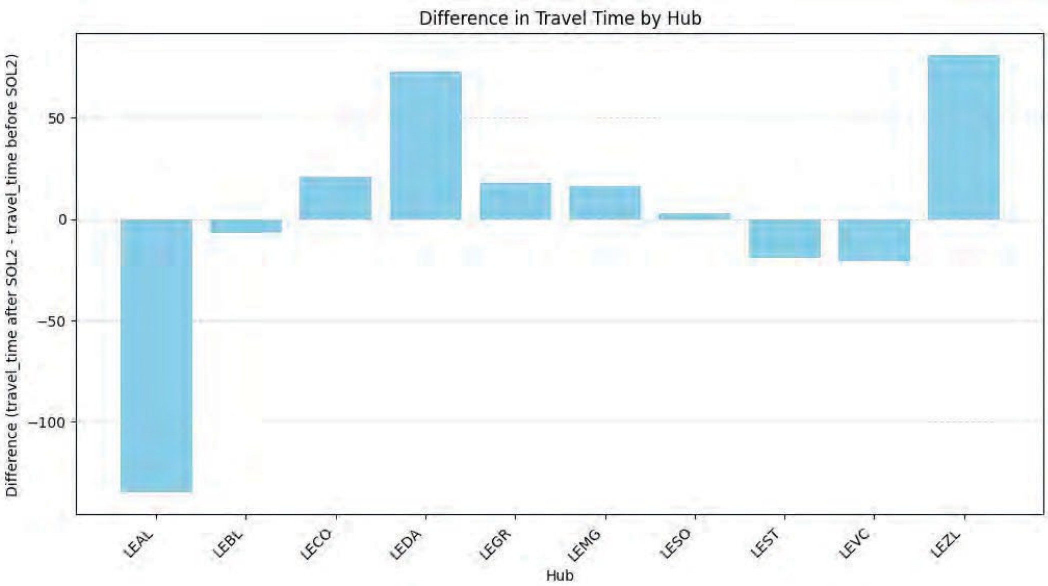

Figure 15. Travel time change to different airports after the application of the Schedule Design Solution

In conclusion, The Schedule Design Solution improves the connections of a given region by improving travel times, reducing buffer times and increasing the number of connecting passengers, fundamentally changing network utilisation in the process.

4.3 The Disruption Management Solution

The performance of SOL401 has been demonstrated on a Spanish airrail network. The results on different disruptions and demand levels show distinct improvements for the decentralised and centralised disruption management, where the centralised disruption management consistently performed better than its decentralised counterpart. Table 7 shows exemplary results for a scenario of a single disruption and nominal air and rail operations used as benchmark.

The decentralised disruption management showed improvements for the number of stranded passengers (up to 6 %), for the service delays (more than 30%). For centralised disruption management nearly all KPIs and PIs improved significantly, showing even greater benefits. Most importantly, the passenger travel times decreased by 20%. Simultaneously, the number of stranded passengers decreased by about 17%. Also the service delays reduced by about 50% for cumulative and average numbers. The resilience also showed promising changes, as the number of replanned passengers increased for all cases. Finally, a smaller number of diversions have been required for the centralised variant.

Scenario	Arrival delay	Avg. journey time	Stranded passengers	Departure delay	No. of diversions	Replanned passengers
Decentralised	35 %	2 %	6 %	33 %	6	+ 8 %
Centralised	53 %	19,6%	17 %	50 %	3	+ 10 %

Table 7. SOL401 results for a scenario with a single disruption and nominal air and rail operations

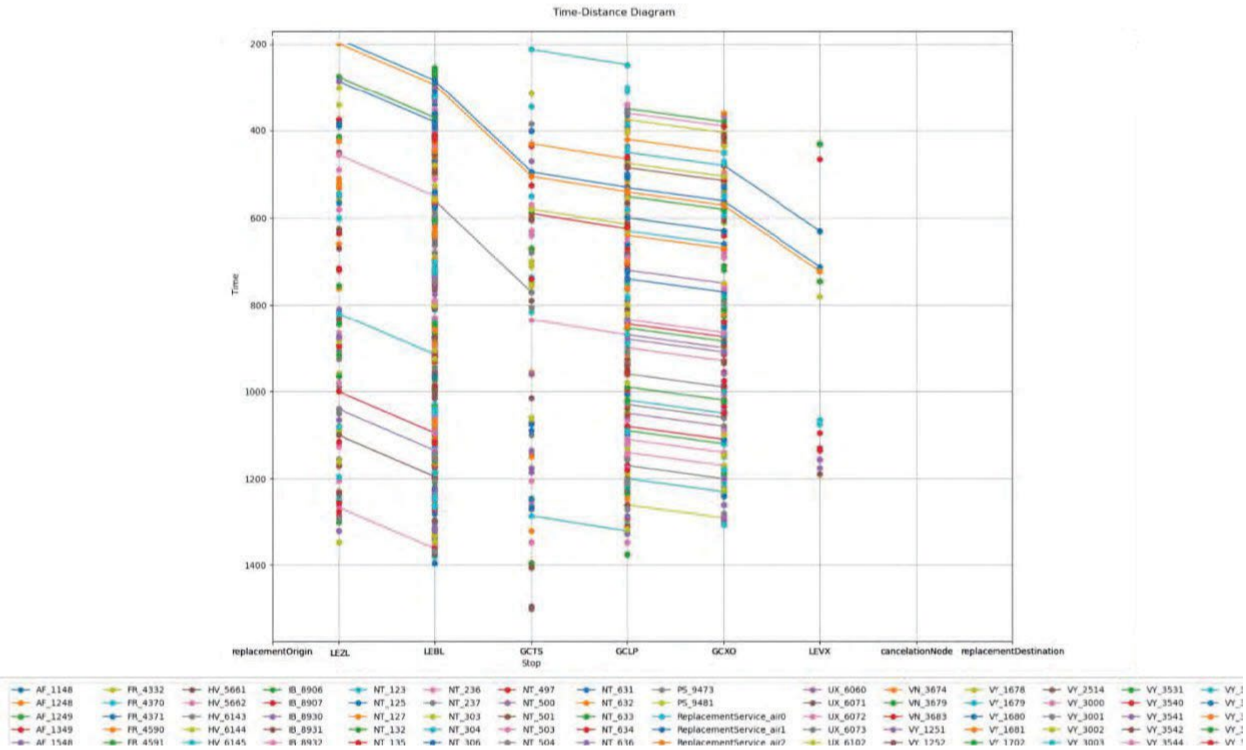

Figure 16. Adjusted timetable for a feasible flight plan along the route of two replacement flight services from LEZL to LEVX

Figure 16 shows an illustrative timetable for multiple airports in a timedistance diagram. Arrivals and departures at airports are marked by circles, scheduled connections are indicated by the timedistance lines.

It can be seen that minimal separation times between the services are respected and no conflicting connections exist. Further, the rotations of two successively schedules replacement services become visible, which sequentially serve the selected airports.

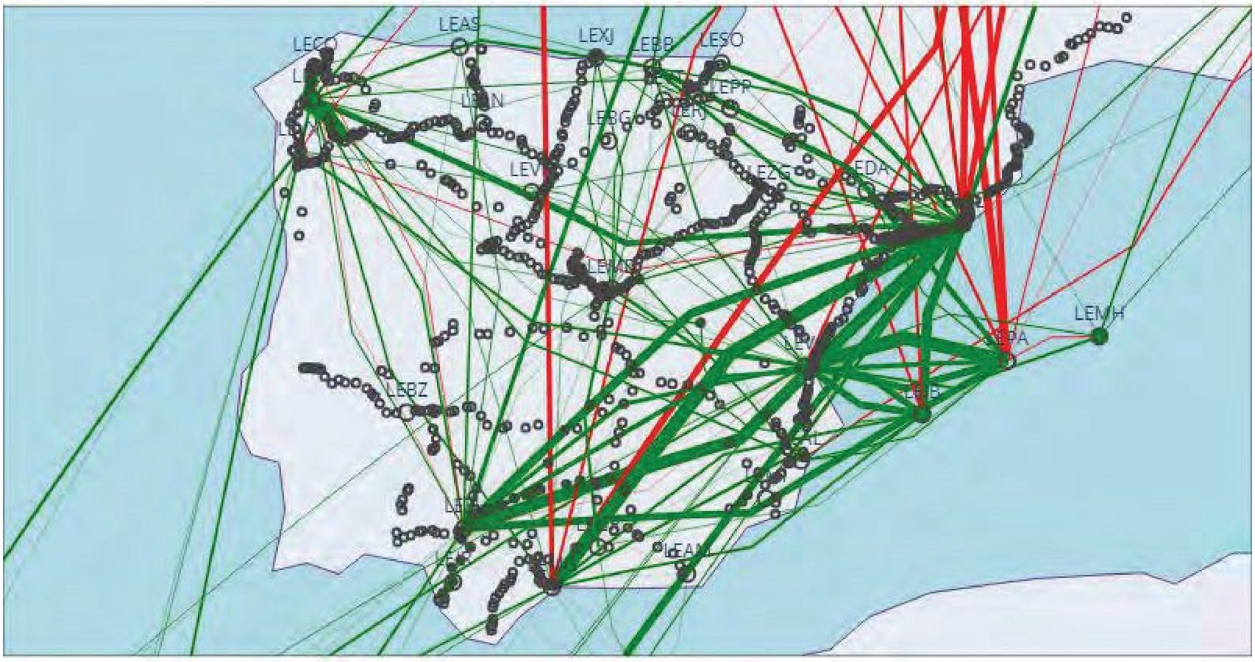

Figure 17. Passenger flow comparison of centralised DM solution with benchmark solution (green: increasing PAXnumbers, red: decreasing PAXnumbers)

Figure 17 shows an exemplary passenger flow comparison of centralised Disruption Management solution with benchmark solution. The centralised Disruption Management strategy demonstrates a clear advantage over the benchmark solution in its ability to maintain and even enhance passenger service levels during disruptions. This is particularly evident in the increased passenger flows observed on key domestic corridors.`

Finally, the disruption management of SOL401 clearly enhances the passenger centric performance significantly. Depending on the degree of centralisation, different levels of improvement are revealed. There, the centralised disruption management shows clear superiority in almost every aspect. Thereby, it suggests that the benefits of multimodality can be leveraged best by managing disruptions in a centralised and coordinated manner.

5 Conclusions and Recommendations

The results of the MultiModX project demonstrate that the integration of air and rail networks through coordinated planning, performance evaluation, and disruption management can substantially enhance the efficiency, resilience, and passenger experience of the European transport system. The Performance Assessment Solution provides a robust and replicable framework for measuring multimodal mobility, offering an unprecedented ability to quantify doortodoor performance through an open digital catalogue of passengercentric indicators and a set of opensource tools for the evaluation of planned and replanned airrail multimodal networks both strategically and tactically. This marks an important advancement beyond traditional modespecific assessments, enabling decisionmakers to evaluate systemwide tradeoffs and synergies between air and rail.

The Schedule Design Solution confirms that relatively minor schedule adjustments can generate significant networkwide improvements. By synchronising flight and rail timetables around passenger flows and operational constraints, travel times are reduced, buffer times optimised, and connectivity between regions strengthened. These outcomes demonstrate that coordination, rather than largescale infrastructural change, can deliver tangible efficiency and environmental benefits, while contributing to the longterm objectives of Flightpath 2050 and the Sustainable and Smart Mobility Strategy.

Similarly, the Disruption Management Solution highlights the operational and passenger benefits of coordinated responses under disrupted conditions. The simulations show that a centralised approach to disruption management outperforms decentralised strategies, leading to marked reductions in delays, missed connections, and stranded passengers. This underlines the importance of realtime data exchange and crossoperator coordination mechanisms for ensuring continuity of multimodal services.

The common analytical foundation of MultiModX – built on passenger archetypes, regional typologies, and multimodal policy environments – provides a transferable framework for scenariobased modelling and policy experimentation. Together, these components enable a deeper understanding of passenger behaviour and system dynamics, offering practical insights for future multimodal governance and regulatory design. multimodal governance and regulatory design.

To maximise the impact of these findings, further efforts should focus on formalising multimodal performance monitoring within European transport policy frameworks, encouraging shared data standards to support coordinated schedule design, and implementing centralised disruptionmanagement protocols across operators. Equally, fostering integrated ticketing, harmonised passenger rights, and open data interoperability will be essential to translate the project's technical outcomes into lasting policy and operational change. Continued collaboration among SESAR initiatives, national authorities, and mobility service providers will be crucial to scaling these solutions and realising the vision of a connected, sustainable, and passengercentric European mobility ecosystem by 2050.

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7 Glossary

AgentBased Modelling (ABM): A simulation approach where individual agents (e.g. passengers, flights, trains) act according to defined behaviours, allowing the emergence of complex system dynamics.

Archetype: A representative model of passengers or regions sharing similar behavioural or structural characteristics used for modelling purposes.

Disruption Management Solution (DMM / SOL401): A decisionsupport tool that optimally adjusts air and rail schedules during disruptions, minimising passenger impact and operational costs.

Doortodoor journey: The full passenger journey from origin to final destination, including access, main travel, transfers, and egress.

Infrastructure node (NIi): A location in the transport network where passengers can access, transfer between, or exit mobility layers (e.g. airports, rail stations).

KerbtoGate / GatetoKerb Time (KS / SK): Time required for passengers to move between the infrastructure kerbside and service gate, including processes such as checkin, security, or baggage collection.

Mobility layer: A modespecific transport network (e.g. air, rail) that can be interconnected to form a multimodal system.

Mode swap: A change in the mode of transport (e.g. from air to rail) during a journey or in response to a disruption or policy measure.

Multimodality: An integrated approach to transport where different modes (e.g. air, rail, bus) work together to optimise efficiency, sustainability, and passenger experience.

Multimodal Performance Framework: A structured set of indicators and methods for assessing the efficiency, resilience, and passengercentricity of multimodal networks.

ParetoEquivalent clusters: Groups of itineraries offering similar levels of performance in terms of key indicators (e.g. time, cost, emissions), representing equally efficient alternatives.

Passengercentric approach: A methodology that prioritises passenger needs, experience, and outcomes when designing and managing transport systems.

Performance indicator (PI): A quantitative measure used to evaluate performance aspects such as travel time, emissions, cost, or connectivity.

Schedule Design Solution (SOL400): A tool that jointly optimises air and rail timetables to improve connectivity, reduce waiting times, and maximise network efficiency.

Strategic Multimodal Evaluator: A model assessing longterm multimodal network performance at planning level, considering schedules, demand, and policy conditions.

Tactical Multimodal Evaluator: A simulation tool that evaluates realtime multimodal operations and passenger outcomes under nominal or disrupted conditions.

Transfer time (TR): The time required to move between two nodes within or across mobility layers.

8 List of Acronyms

ABM	AgentBased Modelling
AOC	Airline Operations Centre
APOC	Airport Operations Centre
ATFM	Air Traffic Flow and Capacity Management
CO2	Carbon Dioxide
DMM	Disruption Management Model / Solution (SOL401)
ECAC	European Civil Aviation Conference
ER	Exploratory Research (SESAR Programme)
GTFS	General Transit Feed Specification
IR	Industrial Research (SESAR Programme)
KPI / PI	Key Performance Indicator / Performance Indicator
KS / SK	KerbtoService / ServicetoKerb time
LEMD	Madrid-Barajas Airport (ICAO code)
LEMG	Málaga Airport (ICAO code)
LEVD	Valladolid Airport (ICAO code)
MaaS	Mobility as a Service
MCT	Minimum Connecting Time
MND	Mobile Network Data
NUTS	Nomenclature of Territorial Units for Statistics
OD	Origin-Destination
OP	Operator
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaking

SOL1 / SOL399 Performance Assessment Solution

SOL2 / SOL400 Schedule Design Solution

SOL3 / SOL401 Disruption Management Solution

UTC Coordinated Universal Time

9 Mode d’emploi: How MultiModX Solutions can be used

This annex provides guidance on how the MultiModX Solutions can be used by different stakeholder groups to support multimodal coordination across Europe’s transport system.

The Performance Assessment (SOL399) (developed as opensource), Schedule Design (SOL400), and Disruption Management (SOL401) Solutions combine data integration, agentbased modelling, and scenario simulation to evaluate and improve air-rail interoperability.

Each solution has been designed to be transferable and scalable, allowing stakeholders – from railway undertakings and infrastructure managers to airlines, airports, and policymakers – to apply the models to their own networks and policy contexts.

The following section outlines how the MultiModX framework operates and how it supports both operational planning and strategic decisionmaking for a more connected, sustainable, and resilient European mobility system.

9.1 The MultiModX Workflow

The MultiModX Solutions operate at three complementary levels: strategic (analysis and policy), pretactical (disruption management), and tactical (realtime management and resilience).

Step	Solution	Function	Output
Strategic Level	SOL399 – Performance Assessment	Integrates multimodal data and indicators to evaluate system performance and policy scenarios. It identifies bottlenecks and improvement areas through Pis such as travel time, CO2 emissions, and connectivity. The open-source models are available at https://github.com/UoW-ATM/ MultiModX, and the Performance Framework at https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY	Provides baseline data and indicators for SOL400. Evaluates planned multimodal networks (including the impact of policies)
	SOL400 – Schedule Design	Uses the insights from SOL399 to generate coordinated air and rail timetables that minimise waiting times and optimise connectivity at multimodal hubs. The model operates within industry-validated constraints (e.g. ±20-minute adjustment thresholds).	Optimised schedules which can be evaluated with SOL399.
Pretactical	SOL399 – Performance Assessment	Evaluates impact of replanned operations (due to disruption management) on passenger itineraries identifying suitable alternatives for them.	Performance indicators on passenger rebooking in case of replanned networks due to disruptions. Can evaluate outcome of SOL401.
	SOL401 – Disruption Management	Using collaborative, passengercentric strategies, it reallocates capacity and passengers dynamically across modes to maintain performance under stress.	Validates system resilience and informs updates to SOL399 performance models.
Tactical	SOL399 – Performance Assessment	Simulate day of operations including disruptions and disturbances in the mobility network.	Indication of robustness of networks considering passengercentric indicators.

9.2 How They Work Together

The three Solutions can work independently but also interlinked and iteratively:

1. SOL399 defines the baseline performance and identifies improvement opportunities.
2. SOL400 designs integrated timetables and tests planning scenarios based on those insights.
3. SOL401 optimises the replanning of networks considering disruptions.
4. SOL399 evaluates the planned networks (strategically), replanned networks (pretactically) and their robustness (tactically)

This cyclical process ensures that policy evaluation, planning, and disruption management are coherent, datadriven, and continuously refined, supporting both strategic planning and tactical operations.

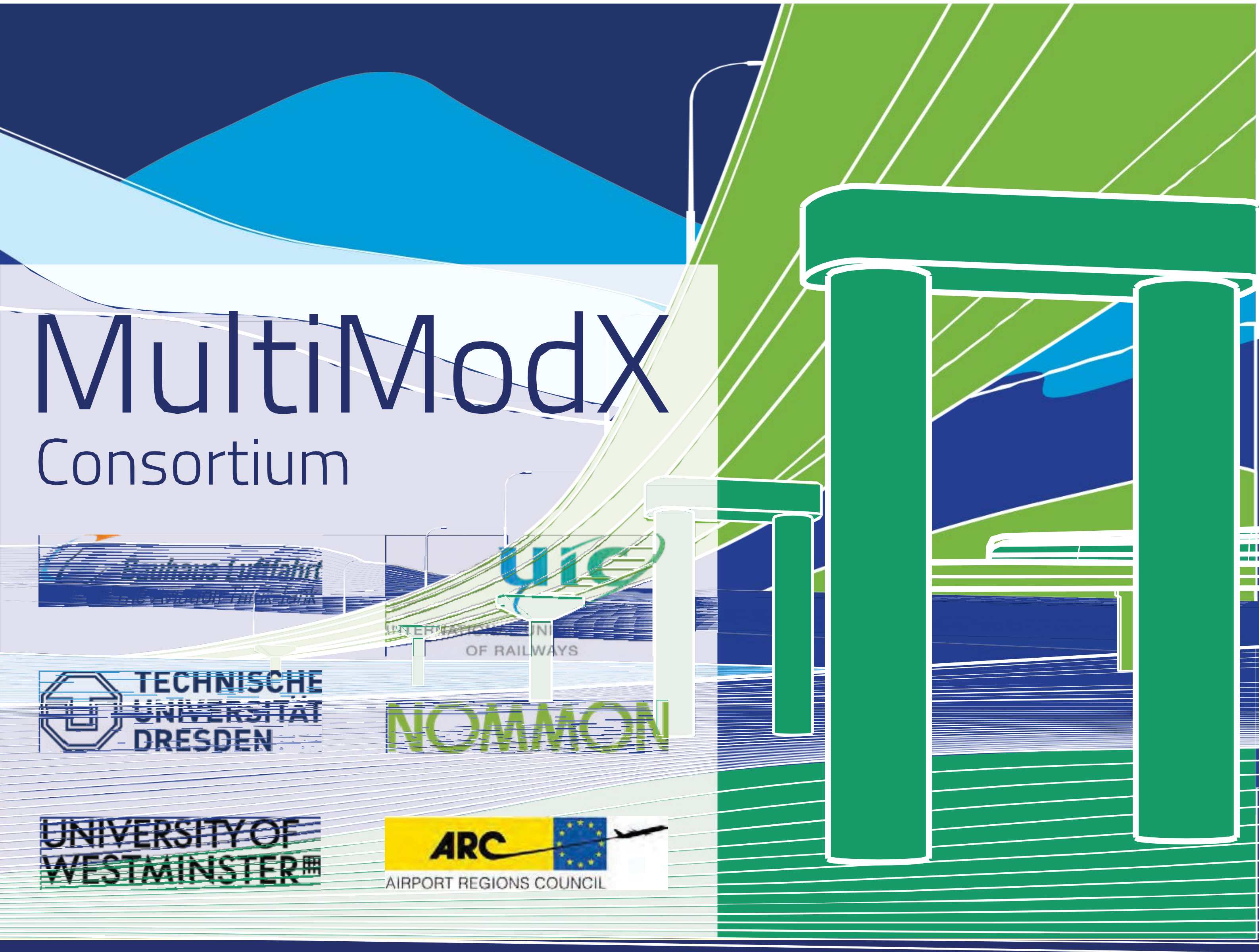
9.3 Who Can Use and How to Apply the MultiModX Solutions

The MultiModX Solutions have been designed to be transferable, scalable, and userfriendly, allowing each stakeholder group to apply them according to their operational or policy needs. Among others:

- Rail stakeholders – can integrate the Schedule Design (SOL400) and Disruption Management (SOL401) Solutions to coordinate train operations with flight schedules, test connectivity scenarios, and assess resilience at multimodal hubs.
- Airlines and airports – can use the Performance Assessment (SOL399) and Schedule Design tools to analyse passenger flows, optimise feeder services, and evaluate how coordinated timetables impact punctuality and CO2 performance.
- Policymakers and planners – can employ the complete MultiModX framework to evaluate policy scenaios such as shorthaul flight restrictions, CO2 cost variations, or integrated ticketing schemes, using the opensource Performance Framework for evidencebased evaluation.
- Researchers and data analysts – can adapt the opensource models to extend the methodology, apply it to other corridors or countries, and contribute to the European knowledge base on multimodal transport.
- Ultimately, passengers and citizens are the final beneficiaries of the MultiModX Solutions. By enabling more reliable, connected, and sustainable journeys, the framework contributes to smoother doortodoor travel, better disruption management, and an overall improvement in the passenger experience across Europe’s multimodal transport system.

9.4 Overall Impact

By connecting performance assessment, planning optimisation, and disruption management within a single modelling ecosystem, the MultiModX Solutions deliver a comprehensive toolkit that supports the design of a connected, resilient, and passengercentred European transport system.



MultiModX official webiste:
https://multimodx.eu/

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