MultiModX

Open Multimodal Performance and Evaluation Tools

Technical Summary

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Abstract

This Technical Summary provides an overview of the open Multimodal Performance Framework and Multimodal Evaluation Tools developed under the SESAR 3 Joint Undertaking's MultiModX project. It complements the open documentation and repositories with more details on the Performance Framework rationale and approach, and on the models inner workings and capabilities for the assessment of planned multimodal networks, replanned networks to consider the impact of disruptions and day of operations execution. Both the Multimodal Performance Framework and the Evaluators take a passenger-centric approach to assess not only the operational aspects (services, load factors, infrastructure usage) but the passengers' door-to-door journey and multimodal network connectivity. This document is not a manual of use but complements the information on the open repositories.

Executive Summary

A Multimodal Performance Framework and a set of Multimodal Evaluation tools have been developed as part of MultiModX SESAR-Horizon Exploratory Research (ER) Project.

The **Multimodal Performance Framework** builds on previous multimodal research projects and extends the work with collaboration with other SESAR Exploratory Research and Industrial Research initiatives.

The modelling and evaluation tools are divided into three distinct capabilities:

- The **strategic multimodal evaluation** of air-rail multimodal networks with a focus on passenger-centric metrics. MultiModX's Strategic Multimodal Evaluator provides mobility metrics at the region, the infrastructure (airport, rail station), the operator and the passenger level, considering flight schedules, rail timetables, infrastructure characteristics and policies. This enables the evaluation of changes to any of these elements (schedules, infrastructure and policies) accounting for passengers' preference over alternative itineraries.

- The **evaluation of replanning of operations under disruption**. Building on some of the functionalities of the Strategic Multimodal Evaluator, the impact of replanning operations (e.g. delays, cancellations, adding services) on planned passenger itineraries can be evaluated. This evaluation provides passenger-centric metrics on the impact of the disruption considering different levels of rebooking flexibility.

- The assessment of the **execution of the operations under uncertainty** and disturbances. MultiModX's **Tactical Multimodal Evaluator** can simulate the operations as they unfold on the day of execution. This model tracks vehicles (flights and trains) and passengers, providing passenger-centric metrics, e.g., missed connections and total delays. The Tactical Multimodal Evaluator can, therefore, assess the robustness of planned (and replanned networks) and how tactical mechanisms (e.g. fast-track at airports for multimodal passengers) could support the multimodal connectivity of passengers.

This document provides a technical overview of the open-source Multimodal Performance Framework and the evaluation tools developed under MultiModX's Solution 1 /SESAR's Solution 399 (Multimodal Performance Evaluation).

The Multimodal Performance Framework at

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

The open-source models are available at

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

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1 Introduction

The multimodal performance framework and assessment tools described in this document are part of MultiModX project . MultiModX is an Exploratory Research (ER) Project from the Single European Sky & Air Traffic Management Research (SESAR) programme.

1.1 Towards European air-rail multimodality

The topics of multimodality, passenger experience and inclusion, and the development of a European seamless mobility system that meets the goals of the Paris Climate Agreement are gaining traction [1] This multimodal vision requires airports to be multimodal nodes of the future, with coordinated planning and collaborative decision-making based on shared information and situational awareness across transport modes [2][3][4]. Railway can help expand airport catchment areas and shift passengers from feeder flights to high-speed rail (HSR) connections, reducing greenhouse gas (GHG) emissions and releasing airport capacity [5][6]. A shift to suitable HSR rail alternatives from air with short-haul bans is being implemented in several European countries, with France at the front [7] and Spain considering a similar policy [8]. Multimodal networks to ensure connectivity would be required for these policies to be impactful.

The interactions between different modes of transport are complex as they can involve substitution due to competition, complementarity of services, and/or supporting each other by covering different segments of a door-to-door journey, as a feeder mode for one another. All these interactions need to consider how passengers are using the networks. Therefore, a passenger-centric vision is required considering total door-to-door (D2D) journeys.

In this regard, the schedule synchronisation between different transport networks can optimise transfer times, significantly reducing D2D travel times [9], [10] Understanding how these multimodal networks perform on the day of operations and managing disruptions and missed connections is crucial when assessing the resilience and feasibility of multimodal trips [11]. Finaly, large disruptions in any of the networks might require, from the passenger perspective, finding suitable alternatives in the remaining replanned network. In this case, the passenger's door-to-door journey needs to be considered [12]. Passengers might use suitable alternatives which could involve using different routes, different modes, and even starting and ending their journey at different infrastructure nodes, if the journey is possible and the total door-to-door time is appropriately considered. passenger's door-to-door journey needs to be considered [12]. Passengers might use suitable alternatives which could involve using different routes, different modes, and even starting and ending their journey at different infrastructure nodes, if the journey is possible and the total door-to-door time is appropriately considered.

Overall, there is a need for a better understanding of the impact on mobility (door-to-door) of multimodal mechanisms (e.g. integrated ticketing, optimised schedules), incentivisation (e.g. taxation of CO2 emissions) and enforcement (e.g. flight bans) policies, infrastructure changes (e.g. minimum connecting times), and other operational aspects (e.g. alliances between operators). These need to be evaluated with a common suitable multimodal performance framework and considering the planning (strategic), replanning (disruptions management) and execution (tactical) perspective.

1.2 Tools for evaluating multimodal air-rail networks

1.2.1 Multimodal Performance Framework

The Multimodal Performance Framework builds on the work from previous multimodal research projects and extends the work with collaboration with other SESAR ER and IR initiatives, providing a catalogue of performance indicators (PI).

The expected evolution of the SESAR Master Plan considers the inclusion of Passenger Experience as a new key performance area (KPA), in need of specific PIs and KPIs. The KPA expands the flight-centric vision of ATM to include the passenger perspective. This would a gradual inclusion of airport and mobility elements. Therefore, a shared multimodal performance framework is needed to define the appropriate multimodal indicators. This should reflect, for the particular case of SESAR, how SESAR KPIs impact multimodality, how multimodality could impact SESAR's indicators and, and critically, how the SESAR Performance Framework could be extended to include some of these passenger-centric (multimodal) aspects.

Besides that, there is a need for a catalogue of more exploratory door-to-door indicators which could be shared among ER projects so that adequate comparisons between mechanisms could be drawn.

1.2.2 Strategic Multimodal Evaluation

MultiModX's Strategic Multimodal Evaluator uses a detailed representation of multimodal transport supply considering flight schedules and rail timetables. The model computes possible itineraries between origin and destination regions subject to infrastructure and policy constraints and disaggregates the underlying demand between the regions on passenger flows and eventually itineraries (accounting for passengers' preferences on total travelling time, cost and emissions, and services capacities).

The Strategic Multimodal Evaluator is, therefore, able to consider the joint operations of air and rail services and compute performance indicators at different level (e.g. region, infrastructure, operator) to assess the effectiveness of the planned operations.

1.2.3 Evaluation of replanned networks under disruptions

The transport network is subject to different disruptions. From day-to-day minor delays, infrastructure issues and congestion to more severe disruptions blocking elements in the system (e.g. weather which closes a rail link) or even system-wide disruptions (e.g. volcanic eruption which closes several airports).

Air and rail operations can be replanned as a reaction to disruptions. These adjustments can include, among others, delays, cancellations, modification of routes (particularly for rail) and addition of new services. These changes can be produced directly by the operators (e.g. airlines deciding to cancel their flights), by a central manager (e.g. issuing air traffic flow management (ATFM) delay by the Network Manager), or from an optimisation process. If the disruptions are known with sufficient look-ahead time, alternative passenger itineraries could be offered.

Building on the capabilities of the Strategic Multimodal Evaluator, a replanning of the network can be evaluated. This evaluation assesses the status of passengers' itineraries after the replanning and finds suitable alternatives under different levels of flexibility for stranded passengers. Once again, passenger-centric performance indicators evaluate the effectiveness of the replanning.

1.2.4 Tactical Multimodal Evaluation

During the day of operations the planned networks can be subject to disruptions of some of their elements (e.g. delays in the link between the rail station and the airport) and disturbances (e.g. day-to-day delays in the air system). It is crucial to evaluate how the multimodal networks perform under these conditions to assess, among other things, their robustness.

In the context of multimodality it is particularly as important to model flights and rail services (with their delays) as passengers and their full itineraries. Passengers experience delays and disruptions differently from airlines (and flights) [13][14][15] and rail operators, simply due to the fact that their journey often involves multiple connections and/or modes of transport.

MultiModX's Tactical Multimodal Evaluator extends the capabilities of Mercury [14], an open-source flight and passenger mobility model developed over 10 years on several SESAR ER projects, to provide this tactical evaluation of the multimodal networks.

1.3 Document objective and intended audience

This document provides a technical summary of the open-source models developed for the multimodal evaluation of air and rail networks. It complements the digital catalogue of multimodal performance indicators and the code of the multimodal evaluators available in GitHub (see Section 1.4) with a more detailed description of the methodology used to develop the performance framework and the inner workings and capabilities of the evaluators.

The document showcases some of the capabilities of the different tools developed. Note that this is not a user guide for the tools and the most up to date information on the models, including manuals are available in the open repositories (see Section 1.4).

The intended audience are stakeholders with interest in mobility, air and rail performance evaluation (e.g. SESAR JU, SESAR ER and IR projects, EU-Rail), and readers with a technical background who want to have a better understanding of the evaluators aiming at using or extending them.

1.4 Open-source catalogue of indicators and multimodal evaluation models

The catalogue of indicators of the multimodal performance framework and the evaluation models are available as open documents and open-source code (under GPL-3.0 license).

The Multimodal Performance Framework at

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

The open-source models are available at

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

1.5 Document structure

The rest of the document is structured as follows. Section 2 describes the Multimodal Performance Framework including the digital catalogue of multimodal indicators. Section 3 details the Strategic Multimodal Evaluator for the evaluation of planned multimodal networks. Section 4 describes how the replanned networks under disruptions can be evaluated. The Tactical Multimodal Evaluator is described in Section 5. Conclusions and recommendations are given in Section 6. The document closes with references in Section 7, glossary in Section 8, a list of acronyms in Section 9, and Appendix A – Performance Indicators in Digital Catalogue.

2 Multimodal Performance Framework

2.1 Methodology

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

1. Indicators at Level 1 are indicators currently part of the SESAR3 (S3) Performance Framework. These indicators have, by their nature, a stronger focus on the gate-to-gate (G2G) 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 SESAR3 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 door-to-door journey. These represent indicators that can be more desirable but currently not feasible due to several limitations, such as data availability.

It is worth noting 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 door-to-door 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.

A workshop on 'Multimodality and passenger experience in the SESAR Performance Framework' was held in January 2025. It was attended by relevant stakeholders (e.g. SESAR Joint Undertaking, EUROCONTROL, ACI Europe) and members of ER and IR projects which relate to multimodality and passenger aspects: MultiModX, PEARL [16], AMPLE3 [17], SIGN-AIR [18], MAIA [19] and Travel Wise [20] projects. This workshop supported the validation of the methodology and the framework, extending its scope from pure multimodality to passenger experience, and from focusing solely on multimodal mobility performance to consider the relationship and integration with the SESAR3 Performance Framework.

2.2 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. A list of PIs in the Digital Catalogue is in Appendix A. These indicators are the basis for the assessment of the multimodal mobility networks.

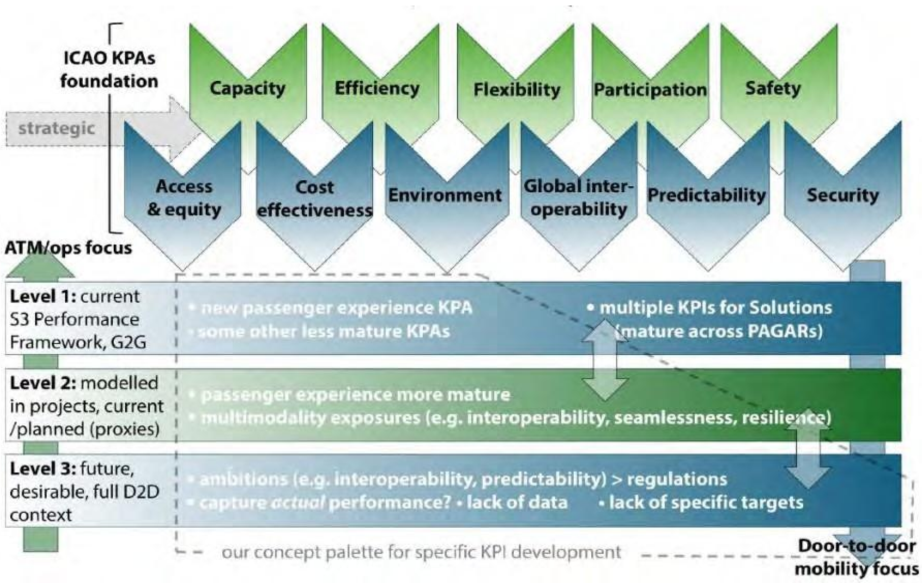

Figure 1 Performance Assessment – Multimodal Performance Framework Concept

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, etc). The catalogue is currently accessible to other stakeholders and projects: MultiModX, SESAR 3 Scientific Committee, SESAR3 Joint Undertaking's Multimodality and Passenger Experience flagship, PEARL [16] , SIGN-AIR [18] and MAIA [19], and has been shared with other projects such as Travel Wise [20].

2.3 Recommendations

The Multimodality and Passenger Experience SESAR flagship should review the indicator catalogue and provide a continuation of the work. A transfer of the catalogue so that it can be maintained beyond MultiModX is recommended, including developing a governance structure for maintenance and updates. Other projects should be encouraged to review and contribute to the definition of the indicators so that these can be as homogenous and compatible across projects as possible. This will minimise redoing work already performed by parallel projects, increase the collaboration across projects, and more importantly, provide a common framework for the comparison of the benefits of different Solutions impacting multimodality and/or passenger experience..

3 Strategic evaluation of networks

3.1 Scope

The Strategic Multimodal Evaluator can assess planned multimodal networks as depicted in Figure 2. From the characteristics of demand (OD demand) and supply (flight and rail schedules and infrastructure aspects), the model computes the materialisation of the supply and demand characteristics in the network. The supply could be any flight and rail schedule: either historical or the outcome of an optimisation, such as the schedules generated by the Scheduling Design Optimiser[1]. Figure 2 presents more details on this element; as shown, possible itineraries along the rail and air network that allow passengers to fulfil their journeys are computed. Then, the demand is disaggregated into flows of passengers who would like to use different services (alternatives). These alternatives can be pure air or rail options or a combination of both (multimodal journeys). Finally, passengers are assigned to services, generating individual passenger itineraries.

The Evaluator finalises with the computation of performance indicators based on the outcome of the passenger assignment to itineraries from those described in the Multimodal Performance Framework.

3.2 Methodology

As shown in Figure 3, the multimodal networks are modelled according to the principle of mobility layers interconnected through temporal multiplexes [21][22], which constitute graphs capturing the time-dependent connectivity between infrastructure nodes, as flight schedules and rail timetables dynamically generate and dissolve edges between them.

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.

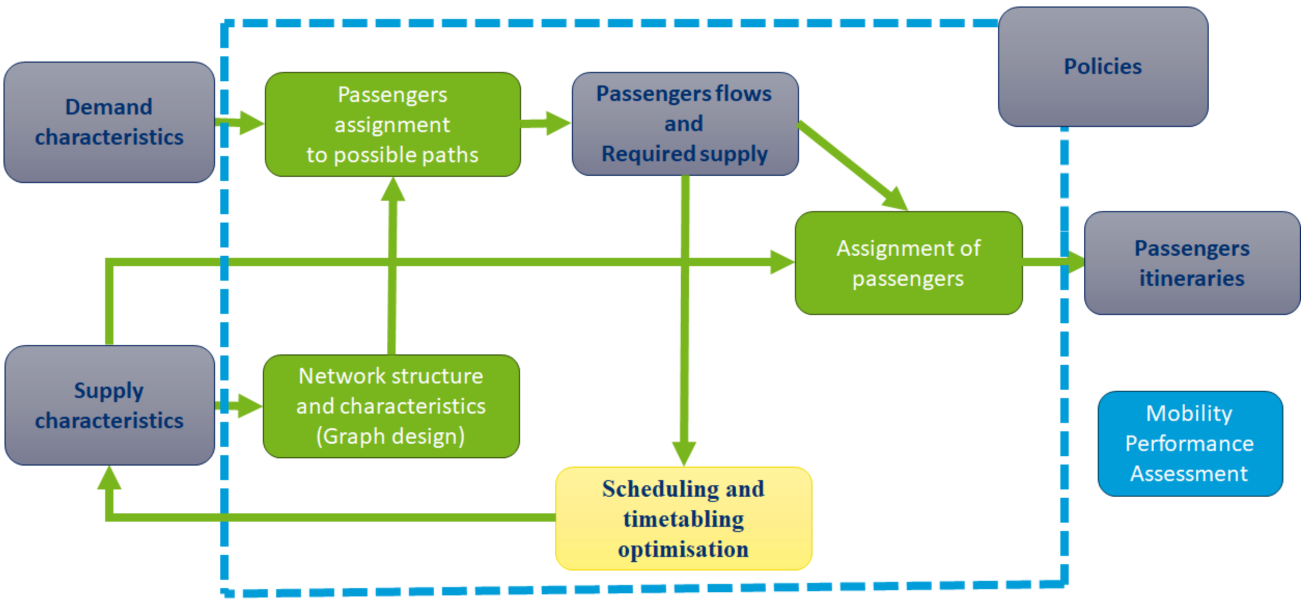

Figure 2 Performance Assessment – Strategic Planned Network Evaluator Concept

[1] MultiModX's SOL400/SOL2 – Schedule Design Solution aims at shifting the services planned operating times (flight schedules and rail timetable) to improve the connectivity between air and rail (reducing waiting time between services).

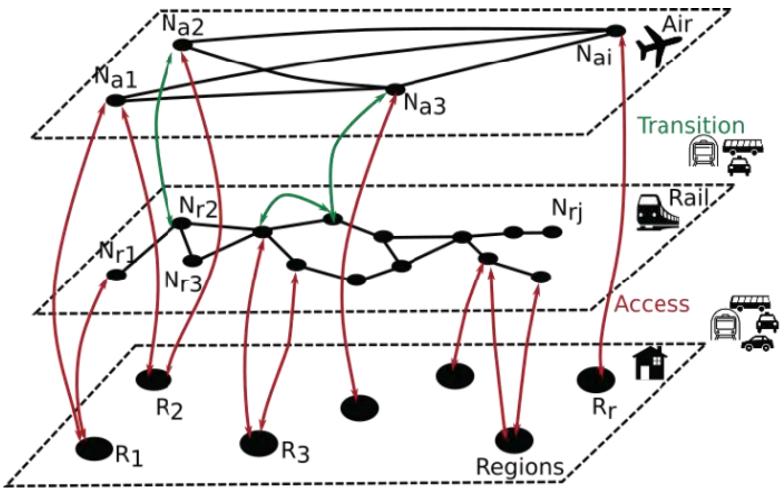

Figure 3 Multilayer modelling approach [22]

3.2.1 Demand

The starting point is the definition of *Regions (Rr)*, and demand between them defined for different passenger archetypes. The archetypes collect passengers in groups that exhibit distinctive characteristics, through sensitivity to mobility factors (total travel time, costs and emissions). *Da(Ri, Rj)* represents the demand between region *Ri* and *Rj* for archetype *a*; *D(Ri, Rj)* would then be the total between regions Ri and Rj for all archetypes. For example, for the case study of intra-Spain mobility, the regions are defined at NUTS-3 level (provinces, islands, Ceuta and Melilla) with six passenger archetypes.

3.2.2 Infrastructure

Each region is connected to one or several infrastructure nodes (airports or rail stations). Only two mobility layers are considered in this research (air and rail), but the model allows the definition of as many complementary layers as desired (e.g. additional rail or air layers, or new layers to consider additional modes, such as bus). The infrastructure node characteristics are explained below.

RA(Ri, Nlj) (RE(Ri, Nlj)) represent the **average access (egress) times** (door-to-kerb, time taken by passengers to arrive to the infrastructure node (airport, rail station) from the point where they start their journey (e.g. home) (kerb-to-door, time taken by passengers from the edge of the infrastructure node (airport, rail station) to reach their final destination (e.g. home)),) from region *Ri* to (from) the infrastructure node (airport or rail station) j of layer *l (Nlj)*. These values allow the model to estimate the total passenger door-to-door travel time when comparing alternatives. Not all infrastructure nodes are accessible from each region, and more than one node could be accessible from the same region even if geographically those nodes could be located at a different region. Passengers in a given region can start and end their journeys at any of the infrastructure nodes accessible from the region.

It is possible to transition between mobility layers using public transport (that is, metro, bus, taxi). *TR(Nli, Nkj)* represents the required **transfer time between two nodes**. These nodes could belong to the same mobility layer (for example to allow transfers between two train stations within the same city using the metro network), or enable multimodal connections between layers.

Some additional processes are considered within the infrastructure nodes*: KS(Nli)* represents the **time required to reach the service** (flight/train) from the kerb of the infrastructure (airport/rail station). This includes processes such as check-in or security. SK(Nli) represents the **time required by the passenger to reach the kerb** from the moment the service arrives at the node (i.e., the flight arrives at the gate or the train to the rail station).

Finally, each node that allows intra-mode transfers has a **minimum connecting time** defined (*MCT(Nli)*). This is the minimum time required to change between flights at an airport or between trains at a given rail station.

3.2.3 Supply and connectivity

Flights and trains define the connectivity within the air and rail mobility layers, respectively. The model transforms the individual connections provided by these into services. A service (*Si*) is defined as a temporal link between two nodes in the same mobility layer. For flights, this is a natural association, train trips (from General Transit Feed Specification (GTFS)[2]) are transformed into individual services between the different stops served . For each service (flight or train service), the model standardises their departing and arrival times, origin and destination and other parameters as:

1. Departure and arrival times in UTC (*SOBT(Si)* (departing time) and *SIBT(Si)* (arrival time));

2. Departure and arrival nodes (*FROM(Si)* and *TO(Si)*). Airports (*Nai*) for flights, rail stations (*Nri*) for trains;

3. Other parameters: mode type (air, rail) (*M(Si)*); operator (or alliance) (OP(Si)); capacity (*CAP(Si)*); cost (*C(Si)*); and emissions per passenger (*CO2(Si)*), provided or estimated by the model [23].

Intralayer connectivity between two services (*Si* and *Sj*) is possible if the subsequent service departs from the same node as the previous one, their operator (or alliance) is the same, and the MCT is respected.

Multilayer connections between two services (*Si* and *Sj*) are valid as long as a transition exists between the arrival node of the first service and the departure node of the subsequent one, and the connecting times are respected.

The approach for the evaluation comprises four functionalities, as shown in Figure 4 and relies on mobility network modelling.

3.2.4 Paths and itineraries computation

Function 1 of Figure 4 will create the mobility network described previously (and depicted in Figure 3) and apply two high-level functionalities to find potential and possible paths between regions.

The (n)-fastest possible itineraries, considering service schedules and respecting MCTs are computed. Each itinerary (*Ii*) is defined as a sequence of services (*Ii = [S1, S2, …, Sn]*), and for a given origin region (Ro) and destination region (Rd), the list of possible itineraries is denoted by (*PIod = [I1, I2, …, Ik]*).

For each itinerary (*Ii* in *PIod*), performance indicators relevant to passenger preferences are computed and listed below:

- Total travel time
- Total CO2 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, i.e. itineraries with similar total travel time, emissions, costs, number of connections and modes used are grouped together. For example, a passenger might have the option of using three different direct flights connecting at two different hubs to reach their destination, if their travel time, costs and emissions are

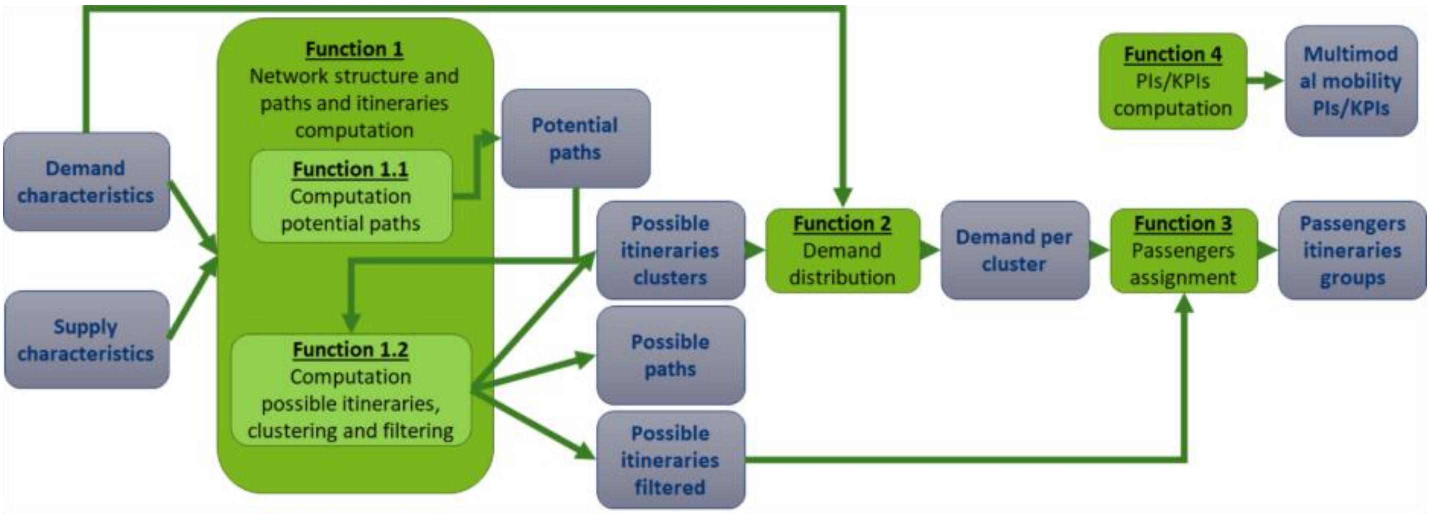

Figure 4 Functional diagram of the Strategic Multimodal Evaluator

[2] GTFS: Open standard for ride-facing transit information widely used to encode train timetables. https://gtfs.org/

similar, these can be considered as equivalent alternatives. The passenger archetype does not have a preference between the individual itineraries within the cluster. Given an origin region (Ro) and destination region (Rd), the list of alternative clusters is denoted by (*Aod = [C1, C2, ..., Cm]*), where each cluster contains itineraries with similar characteristics. The average performance of each cluster is calculated (average total travel time, CO_2 and cost) and used to retain only Pareto-equivalent clusters (with some margins per indicator), reducing the number of alternatives in (*Aod*). For example, if one cluster has an option of a direct train while another cluster requires two train connections taking more time, more emissions and costing more, the first cluster Pareto dominates the second one; and this second cluster would be removed from the list of alternatives.

3.2.5 Demand distribution

The task of assigning passengers to individual services (i.e., itineraries) is a difficult optimisation problem. The problem is divided into the distribution of the demand to the itineraries' clusters, performed by Function 2, and the further assignment of demand to the itineraries within the clusters, performed by Function 3 (see Figure 4).

The demand between regions (D(Ro, Rd)) is distributed among different clusters available between those regions (Aod). The probability of a passenger archetype to select a given alternative (cluster) is computed using a logit model previously calibrated. In the case of MultiModX, where intra-Spain mobility was analysed, both the archetypes and the calibration of the logit model are produced form the analysis of anonymised mobile phone network data (MND) [24]].

The first step is to estimate, as shown in Equation 1, a utility function for each passenger archetype (*a*) and cluster (*Ci*); where:

- traini, flighti and multimodali are binary variables (1 or 0) describing the itinerary type, i.e., only one of them will be 1 depending on the modes used in the itinerary. For example, a multi-leg journey where all modes used are flights (e.g. two flights connecting at LEMD on the route LEBL - LEMD - LECO) will be traini=0, flighti=1 and multimodali= 0; while a journey with one leg being a train and a second leg being a flight would be traini=0, flighti=0 and multimodali= 1.
- travel_timei, costi and CO2i are the total door-to-door expected travelling time, cost (Euros) and CO2 emissions (kg) for alternative i respectivelly. Note that in this context, the alternative is the cluster of equivalent individual itineraries, and therefore, these values are the average of all the itineraries within the clusters.
- alphaa_train, alphaa_flight, and alphaa_multimodal represent the sensitivities of the passenger archetype a toward the modes of transport used; betaa_time, betaa_cost, and betaa_co2 are the sensitivities of the passenger archetype a towards the total travel time, cost and CO2 emissions respectively.

The utility of each alternative, i.e., each cluster, for each passenger archetype is then translated into probabilities with Equation 2.

$$P_a[i] = \frac{e^{u_a[i]}}{\sum_{j=1}^{n} e^{u_a[j]}}$$

Equation 2 Probability of archetype a to select itinerary alternative i

The probability of archetype a selecting the cluster (*Ci*) for a given OD pair depends on the utility of that alternative (ua*[i]*) and the utility of all n alternatives available between the OD pair. Finally, the demand is distributed among the alternatives based on these probabilities, creating a flow of passengers. The attractiveness (i.e. utility) of the alternatives might be increased or reduced as a function of policies (e.g. introducing integrated ticketing or a CO_2 tax).

3.2.6 Passenger assignment

To finalise the network loading, the next step is the assignment of passengers to individual options within each cluster, i.e., to the individual services (flights and trains), while considering their capacity (*CAP(TRIP(Si))*).

$$\begin{aligned} u_a[i] = \alpha_{a\_train} \cdot train_i + \alpha_{a\_flight} \cdot flight_i + \alpha_{a\_multimodal} \cdot multimodal_i \\ + \beta_{a\_time} \cdot travel\_time_i + \beta_{a\_cost} \cdot cost_i + \beta_{a\_co2} \cdot CO2_i \end{aligned}$$

Equation 1. Utility function used in logit model (for archetype a and alternative i)

This is computed with a lexicographic optimisation framework with integer programming with three objectives: 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, as otherwise the optimiser might prioritise single-leg passengers to maximise number of passengers assigned as decrement to multileg itineraries, and that passengers are distributed among different services, avoiding bunching of passengers in services.

3.2.7 PIs computation

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

3.3 Capabilities

The Strategic Evaluator uses as input the supply characteristics, i.e., flight schedules, rail timetable, minimum connecting time between services intra and inter modes connections considered, access and egress times to infrastructures (airports and rail stations), alliances and operators, the demand characteristics (number of aggregated passengers (per passenger archetype) for each origin-destination of interest) and policies (e.g. integrated ticketing, taxation on CO_2 emissions, flight bans). Note that the flight schedules and rail timetable could come from historical data or be the outcome of an optimisation, e.g. MultiModX's Schedule Design Solution.

Many mobility-related changes to the system can be easily evaluated by modifying the Evaluator's input, for example:

- infrastructure changes, like new access and egress times or improved MCTs,
- policies, like removing flights within a threshold (flight-ban),
- increasing cost of services due to taxes (even only for specific archetypes, such as frequent flyer levy)

,

- changes to demand characteristics (e.g. new archetypes or sensitivity towards travel parameters).

3.4 Examples of capabilities for the strategic evaluation of networks

Here we describe examples of use, specifying the data, scenarios and Evaluator outputs, modelling a day of operations of intra-Spain mobility in 2019.

3.4.1 Data: demand, supply and infrastructure

The results presented in this article focus on intra-Spain mobility with demand flows between the 49 biggest cities (considering passengers by train and/or flights, 481K passengers). Authors in [24] analysed anonymised mobile phone network data (MND) for a year of mobility within Spain, inferring six passenger archetypes and estimating the demand between all NUTS-3 regions in Spain for a nominal busy 2019 (pre-COVID) day per archetype.

Flight schedules are obtained from OAG for the 6th September 2019, which has been selected as a nominal busy day of aviation pre-COVID. Due to the recent increment in rail operations, rail timetables, provided by the International Union of Railways (UIC), are from a busy and nominal day from 2023 20th September 2023 (only rail stations that provide connectivity between NUTS-3s are considered).

The centroid of the population of each NUTS is computed using EUROSTAT census data, and used to estimate the access and egress time to the nodes of the networks. The accessibility of nodes from the NUTS is based on MND. MCTs for rail stations are provided by UIC, while the airport ones are based on historically available datasets. The intra-layer connectivity is based on times observed with mobility applications such as Google maps. Finally, processing times (KS and SK) are defined based on expert judgment.

3.4.2 Scenarios: policy packages

Three policy packages are created as defined in Table 1 to create scenarios. These scenarios will represent different mobility status that will be evaluated and compared between them by means of the Strategic Multimodal Evaluator.

The policy packages combine three policies:

1. Integrated ticketing to support multimodality, providing a single ticket for the multimodal journey

and reducing multimodal connecting times (30 and 15 minutes for rail-to-air and air-to-rail connections);

2. Additional CO2 taxation of 0.15 EUR/Kg CO_2;

3. Flight-ban eliminating flights when a high-speed rail (HSR) alternative of up to 3h is available.

3.4.3 Results for different policy packages

3.4.3.1 Demand satisfied and mode of transport usage

In the baseline scenario (PP00), 389K passengers are assigned to services, satisfying 80.9% of the original underlying demand of 481K passengers between NUTS-3 regions in intra-Spain mobility. The average load factor for rail and flights is of 69.8% and 69.5% respectively. Most of the trips are rail itineraries (72.1%), 26.3% are flights, and only 1.6% (6.4K passengers) are multimodal trips. This is to be expected, as limited to intra-Spain mobility. Madrid, Valencia and Barcelona airports are used for most multimodal journeys which tend to start or end in peripheral regions and with a flight to the islands.

In the incentivised case (PP10), similar results are observed. The total demand satisfied is equivalent. The volume of multimodal journeys increases slightly but remains at 2.0%. The load factor of rail also increases slightly to 70.1%.

The enforced case (PP20) with the flight ban removes 104 flights out of 1,253 flights; mainly affecting flights between Madrid (LEMD) and Malaga (LEMG), Alicante (LEAL), Barcelona (LEBL), Pamplona (LEPP), Seville (LEZL), Valencia (LEVC). In this case, there is a small reduction in air share (23.8%), a slight increment of multimodal journeys (2.1%), but mainly an increase in rail trips (74.1%). This is reflected in a higher load factor for rail (71.3%). In some corridors the capacity might be fully utilised, as in the Barcelona-Madrid case where only 3.9K passengers are assigned in PP20 when close to 6K are assigned in PP00 and PP10. This leads to a slightly smaller total satisfaction of 381K passengers (79.2%).

If we focus on region-pairs that in PP00 use any of the 104 flights banned in PP20, we can see that in PP00 between those regions, the mode share was 18.1%, 80.7%, and 1.2% for air, rail and multimodal, respectively, while in PP20 we observe 7.8%, 90.6% and 1.5%. So, passengers are mostly shifted to rail instead of multimodal journeys. In most cases, the multimodal alternative is significantly longer in time (on average 533 minutes instead of 220 and 320 minutes for rail and air, respectively). So, the average travel time between these regions does not change significantly due to the flight ban. However, the total demand served is reduced: from 94.5K passengers in PP00 to 86.6K passengers in PP20.

3.4.3.2 Travel patterns and infrastructure

The volume of passengers directly affected by the flight ban (scenario PP20) is low: only 104 flights are removed and, as in this case, only intra-Spain mobility is considered, direct rail alternatives are available. However, some origin-destination pairs generate new travel patterns even if they are not directly impacted by the flight ban.

Examples of these newly formed paths are observed in the routes between Valencia and Barcelona to Madrid. With the flight ban, the direct flight to Madrid is no longer possible, but an alternative of connecting in Palma de Mallorca (LEPA) or Ibiza (LEIB) to then fly to Madrid (LEMD) appears. Only 5 passengers (0.2% of the assigned demand) are assigned to use the LEVC -- LEPA -- LEMD route (flying from Valencia to Madrid via Mallorca); and 152 passengers (3.9% of the assigned demand) use the

Code	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 1 Policy packages

route LEBL -- LEIB -- LEMD, that is, flying from Barcelona to Madrid via Ibiza. In both cases, it is a minority, as the rail option remains the most suitable (96.1% of the passengers between Barcelona and Madrid are assigned to the HSR). However, it is interesting to see this pattern, as overall there is a lack of capacity in the rail system (1.9K fewer passengers are served between Barcelona and Madrid in the PP20 scenario with respect to the baseline (PP00)).

The flight-ban policy does not affect some airports, increasing their relevance as connectivity nodes. In particular, the airports of the Balearic Islands increase the number of connecting passengers from 93 to 190 for Palma de Mallorca (LEPA), from 22 to 546 for Ibiza (LEIB) and from 0 to 28 for Menorca (LEMH).

Some regional airports also gain relevance as part of multimodal journeys due to the flight ban. When the ban is not present, larger airports, which are also located in cities with better rail links, capture the demand. With the flight ban, alternatives that are less appealing are used, and regional airports can provide connectivity to adjacent regions. Valladolid (LEVD) is an example of this: with the flight ban, the number of multimodal journeys using the infrastructure grows (166.1% higher than in PP00 and a 105.4% increase with respect to PP10), as shown in Table 2. In absolute value, the number of multimodal passengers is still small, but it is worth noting that there are only 2 arrivals and 2 departures for LEVD in the day. This means that of a combined 369 seats arriving at LEVD, 202 (54.7%) continue their journey multimodally, and 104 (28.2% of the flight seating capacity) arrive at the airport as part of a multimodal journey in the PP20 scenario.

Table 2 provides the number of multimodal connecting passengers at Madrid airport (LEMD). As shown, when the incentivised policies are in place (PP10), both airports increase the number of multimodal passengers in a similar way: 27.6% increase for LEMD and 29.6% for LEVD. This shows the impact of reducing the multimodal connecting times due to integrated ticketing.

In contrast, for Madrid, when the flight ban is implemented, the number of multimodal passengers is reduced with respect to the incentivised case (from 4,330 to 3,907 passengers). This could be expected as international connections are not considered, and flights to main destinations within Spain are banned, making the rail services potential feeders for international destinations. The intra-Spain flows are rerouted to other alternatives. It is expected that with international connections, hubs like Madrid will significantly increase their multimodal journeys as the long-distance flights will be fed by rail alternatives; even if some spillage to other hubs can also occur (as now is the case with regional airports).

Figure 5 shows for LEVD the rail stations from which (and to which) multimodal journeys connect in LEVD for the three scenarios.

As depicted, when multimodality is incentivised (PP10) and the flight ban is applied (PP20), the number of regions (and passengers) that use LEVD as their local regional connector increases.

Airport	Scenario	Onward multimodal journey	From multimodal journey	Total
Madrid (LEMD)	PP00	1735	1658	3393
	PP10	2,015 (16.1%)	2,315 (39.6%)	4,330 (27.6%)
	PP20	1,872 (7.9%)	2,035 (22.7%)	3,907 (15.1%)
Valladolid (LEVD)	PP00	78	37	115
	PP10	95 (21.8%)	54 (45.9%)	149 (29.6%)
	PP20	202 (159%)	104 (181.1%)	306 (166.1%)

Table 2 Number of passengers with multimodal journeys from/to the airports for the different scenarios. (% Variation with respect baseline)

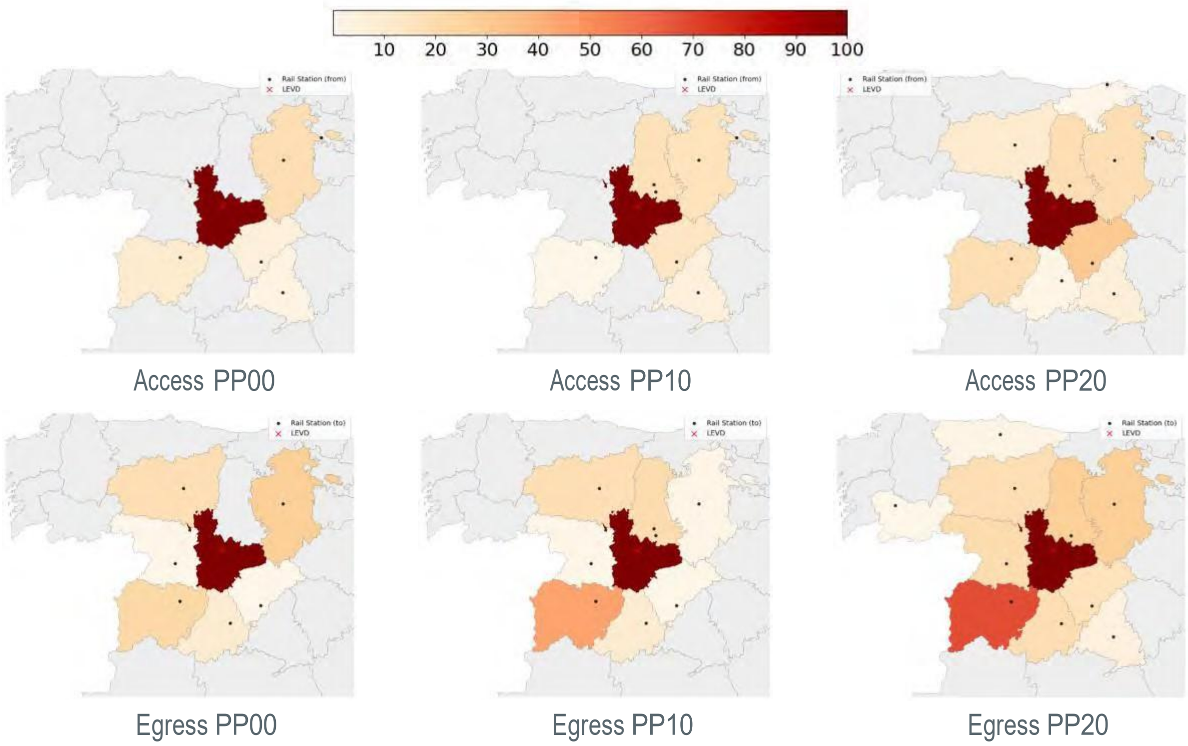

Figure 5 Access and egress (including from/to multimodal journeys) for Valladolid airport (LEVD) for three scenarios

3.4.4 Travel time and regions connectivity

The final example of results that can be obtained with the Strategic Multimodal Evaluator is the estimation of travel times and the connectivity of the regions. Figure 6 shows the average travel time (door-to-door) from the Catalonia region (North-East Spain) (NUTS-2 ES51) to the rest of the regions in Spain (Canary Islands not shown). This is calculated by averaging the travel time from the four NUTS-3 areas which compose ES51. As shown, it is easy to identify the regions that are part of the HSR line, the connectivity with Madrid (by direct HSR services) and regions well connected by air services such as the Balearic Islands.

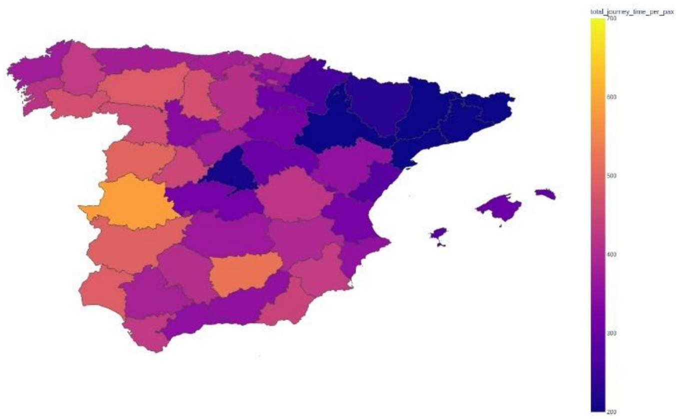

Figure 6 Total mobility time from ES51 (Catalonia) to NUTS 3 regions for PP00 scenario

3.5 Future evolution of the Strategic Evolution of Networks

Future work should focus on consider adding costs and emissions associated with the access and egress phases, as for those journey segments only time are currently considered. For air transport it would be important considering international hub competition for long-distance trips and include in the modelling the possible use of long-distance bus routes.

4 Evaluation of replanned networks (under disruptions)

4.1 Scope

When disruptions impact the network in a significant manner, the air and rail operators will modify their services (e.g. cancelling flights, delaying services). This replanning of operations can be done reactively (just to adjust to the disruption, e.g. by shifting the schedules by the planned ATFM delay), or proactively, for example, by replanning operations to maximise the supplied demand to fulfil passengers' itineraries. This optimised replanning is the objective of MultiModX's Disruption Management Solution[3], the outcome of which is a set of new flight schedules and rail timetables, which modify some of the originally planned operations.

The strategic evaluation of network presented in the previous section (Section 3) provides a set of capabilities which enables the assessment of the impact on passengers of replanning operations due to large disruptions. In particular, replanned networks can be evaluated utilising the capabilities of modelling air-rail multimodal networks as multiplexes to being able to compute potential itineraries between given origin and destination, and the possibility to assign passengers to itineraries considering the available capacity of the services.

4.2 Methodology

The evaluation of the impact of replanned operations on passengers' itineraries is performed in the following steps:

1. Network modification
2. Identification of status of passengers' itineraries
3. Estimation of available capacity
4. Computation of possible itineraries in replanned network
5. Reassigning passengers
6. PIs computation

4.2.1 Network modifications

Firstly, the planned (prior to disruption) network's supply (flight schedules and rail timetables) is modified. When disruptions impact the network in a significant manner, the air and rail operators will modify their services (e.g. cancelling flights, delaying services, rerouting).

These modifications are applied on the planned network to create a replanned network.

The first step, is therefore to create a new representation of the multimodal mobility network with the updated schedules.

4.2.2 Identification status of passengers' itineraries

The next step is to identify the status of passenger itineraries in the replanned network. Some itineraries might still be feasible (not affected or delayed) while others might need to be reassigned. These are passengers whose service has been cancelled or whose connection is no longer possible due to delay.

4.2.3 Estimation of available capacity

The passengers with still feasible trips in the replanned network follow their original itineraries and therefore still utilise the capacity of their planned services. The passengers who cannot perform their planned itineraries in the replanned network are removed from all their original services and the spare capacity is then computed.

4.2.4 Computation of possible itineraries in replanned network

For each origin and destination pair for the passengers needing reallocation, possible itineraries are computed in the replanned network using the services which still have some capacity available.

Different alternatives are possible for this computation, as a function of the flexibility that is allowed for reallocating passengers: from restrictive conditions when passengers can only us very similar itineraries as originally planned (e.g. using the same operators and path originally considered), to full flexibility where even departing before initially planned is available.

These levels of flexibility can be adjusted in the evaluator (i.e., allowing or not the use of different paths, modes, starting and ending infrastructure node and departing earlier than originally planned or not). For simplicity, these alternatives are grouped into five meaningful alternatives shown in Table 3.

[3] Disruption management solutions can optimize the flight and rail services to account for the disruption, and the passenger flows needs, such as in SOL401/SOL3 of MultiModX

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 3 Passengers replanning alternatives

4.2.5 Reassigning passengers

Once the possible itineraries for each origin-destination which has passengers that need to be reallocated are computed, the next step is to assign passengers to individual possible itineraries, i.e., to the individual services (flights and trains), taking the capacity into account.

A lexicographic optimisation is used to perform the reassignment of passengers to potentially suitable itineraries. How this optimisation is performed could be adjusted if desired. 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.

4.2.6 PIs computation

The final step is the computation of performance indicators which reflect the impact of the replanning of the network with a passenger-centric view. Example of indicators that are computed are number of stranded passengers, mismatch between capacity and demand per origin-destination impacted by the replanning (i.e., by the disruption), passengers delay (arrival and departure), etc.

4.3 Capabilities

As presented in Section 4.1, any network which has been replanned could be evaluated with the methodology described in Section 4.2. This means that a wide range of disruptions can be assessed, such as:

- closure of rail link, by cancelling trains using the affected link,
- closure of an airport, by cancelling flights operating in the affected airport,
- ATFM regulations at an airport e.g. due to industrial action, which include some flights cancelled while other delayed,
- reduction of capacity at an airport, which would imply different cancellation rates.
- All these disruptions can be directly evaluated by modelling their impact on the operations (i.e., without needing to optimise the remaining services).

4.4 Examples of capabilities for the evaluation of replanned networks

4.4.1 Closure of LEMG airport

In this scenario the closure of Malaga airport (LEMG) in the intra-Spain mobility case is considered. All flights departing and arriving to LEMG are cancelled.

Figure 7 shows the status of the disrupted passengers. With PA01 alternative, a total of 9,525 passengers are stranded, but as the passengers need to keep their mode, path and operators, no alternatives are possible (as the airport is closed). Therefore, no passengers are reaccommodated.

In PA02, when alternate paths are possible, e.g., a different intermediate airport can be used, 15.7% of disrupted passengers- are reassigned. This is because passengers can find alternative routes with the same mode and operator by flying to and from different airports or connecting at a different node.

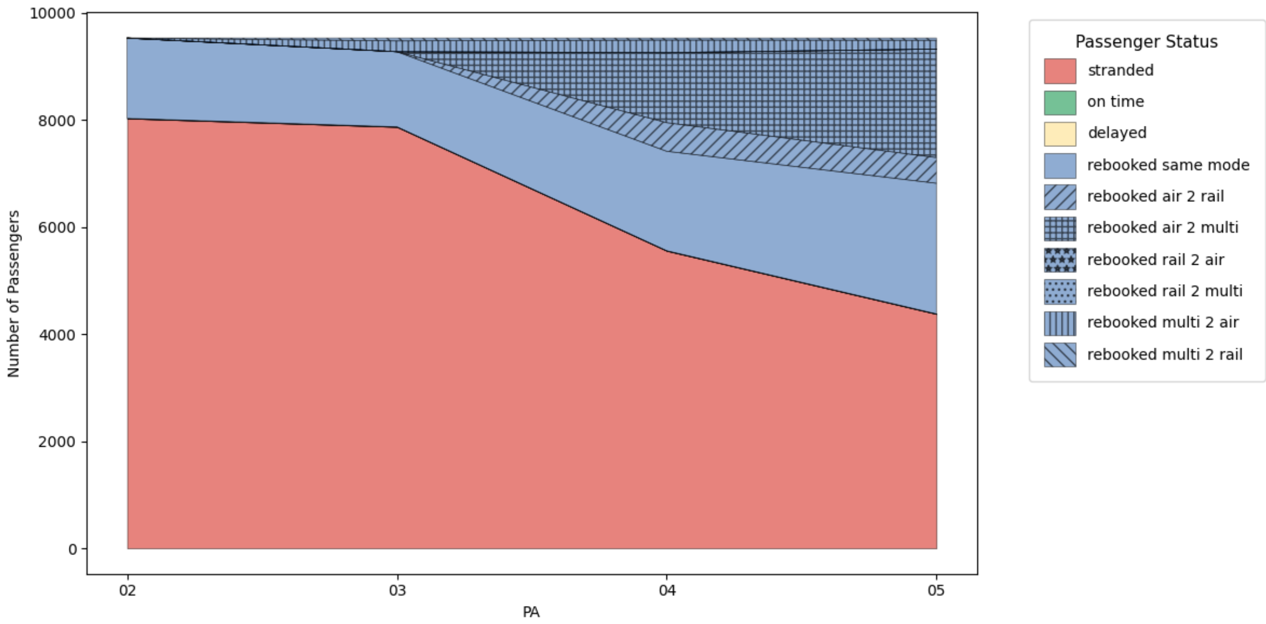

Figure 7 Passengers impacted by closure of Malaga airport (LEMG) across the replanning alternatives

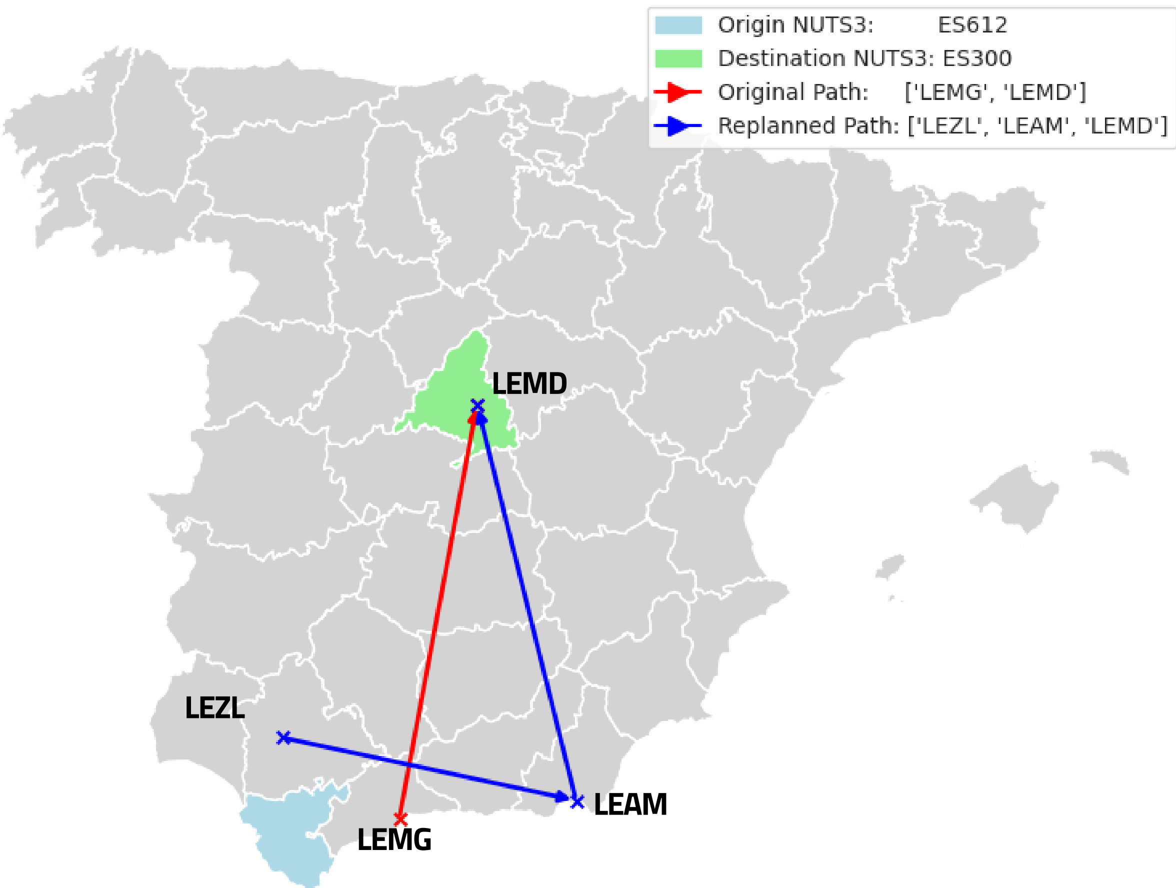

Figure 8 Example of itinerary replanned in closure of Malaga airport (LEMG)

Figure 8 shows an example of this possibility of finding alternative airports to use. The passengers were originally planning to travel from Malaga (LEMG) to Madrid (LEMD). However, as shown, the NUTS of origin is ES612 (Cádiz); therefore, the alternative found is to travel to Seville airport (LEZL), instead of Malaga, and to fly to Madrid via Almeria (LEAM). The total trip is longer than the initially planned one (connecting itinerary instead of direct flight), but it is possible and the passenger is no longer stranded.

Allowing operator change (PA04) increases the number of reaccommodated passengers significantly to 41.7%.

Malaga airport (LEMG) closure	PA01	PA02	PA03	PA04	PA05
Mean departure delay	N/A	185.2	178.2	90.7	-295.2
Mean arrival delay	N/A	215.1	189.6	190.7	-141.5
Mean total travel time deviation	N/A	29.9	11.4	100.0	153.8

Table 4 Mean departure, arrival delay and travel time deviation of replanned journeys for Malaga airport closure

Finally, enabling earlier than originally planned departure (PA05) ensures that 1,179 additional passengers are served (with a total of 54.1% of disrupted passengers reaccommodated).

As shown in Table 4, the possibility to change mode represents a larger increment in the total travel time of disrupted passengers, as slower and multi-leg alternatives could be used.

Figure 9 shows an interesting example from PA05 where, in the original itinerary, passengers were flying from Malaga airport (LEMG) to Asturias (LEAS). However, the passengers were, in reality, travelling from ES611 (Almeria). Therefore, an alternative route is fly from Alicante (LEAL) to Madrid (LEMD) and connect to Asturias (LEAS). The passenger has a different itinerary and access as the origin airport is changing from Malaga to Alicante and then needs to connect in Madrid. This might mean an earlier than originally planned departure, as allowed by PA05. The example is illustrative of the effect of airport access/egress connectivity.

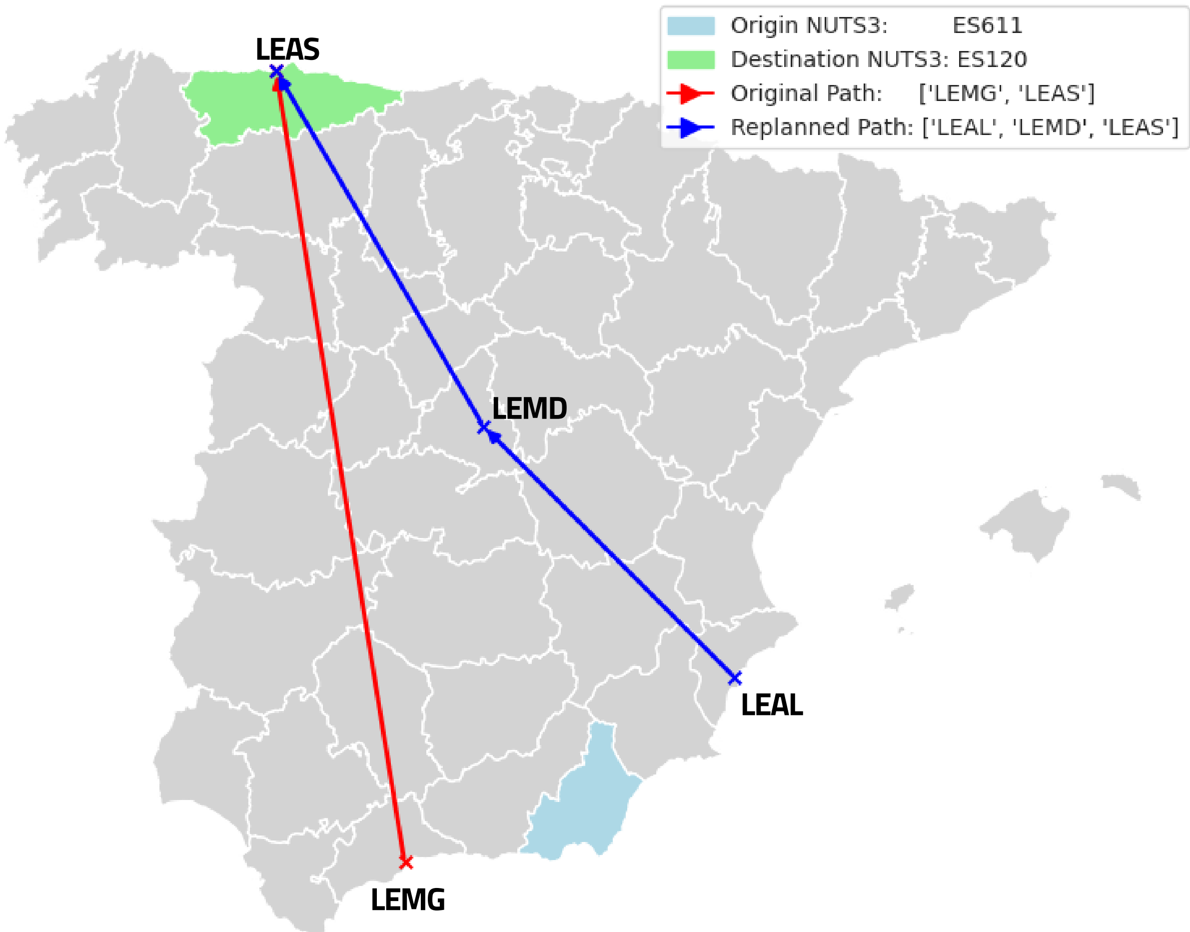

Figure 9 Example of itinerary replanned in PA05 change of infrastructure nodes with closure of Malaga airport (LEMG)

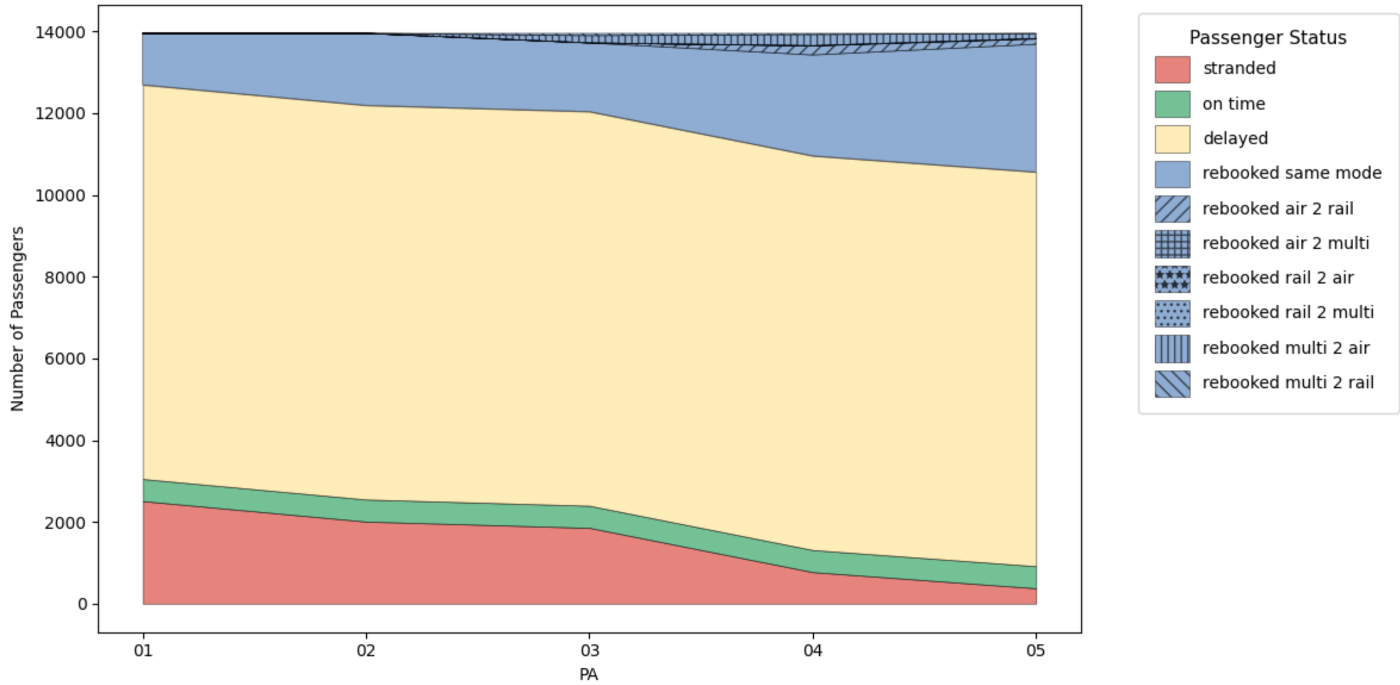

Figure 10 Passengers impacted by industrial action in LEMD

4.4.2 ATFM due to industrial action in Madrid Barajas (LEMD)

This scenario is illustrative of the replanning of a network for a significant, expected, reduction in capacity due to industrial action. This is modelled by simulating a cancellation for flights departing arriving to Madrid of 7.5% and applying a probability and amount of delay due to ATFM to the remaining flights following an analysis of historic ATFM regulations due to industrial action.

A total of 13,953 passengers are affected by the replanning of operations due to the ATFM regulation. As shown in Figure 10, most of them are due to delays on their flights (9,644, or 69.1% of affected passengers). These are passengers who are delayed on arrival at their final destination. Interestingly, 541 passengers (3.9% of affected ones) are impacted by the regulation (some of their flights are delayed) but still arrive on time to their destination. These are most likely connecting passengers whose inbound flight is delayed but they still made the connection (either to another on-time flight or rail service).

In PA01, when the same operator, mode and path must be maintained, 1,258 (9.0% of affected passengers) can be rebooked on alternative flights. Enabling the use of alternative paths (PA02) has a small improvement (12.6% of passengers are reassigned), enabling the mode swap but maintaining the operator as originally planned (PA03) only improves a few multimodal passengers who can be allocated just to rail. When changes between modes are allowed for all passengers (PA04) 21.5% of affected passengers are replanned and only 5.5% remain stranded. See, however in Figure 10 how the number of passengers rebooked across modes is still very limited. Finally, if the disturbance is known enough ahead of time, passengers can be reaccommodated into earlier than originally planned services, in this case (PA05), only 376 passengers end up stranded (2.7% of the originally affected ones). As depicted in Figure 10, most of these replannings are achieved by ensuring that air connections are still possible by selecting earlier flights.

Figure 11 represents for PA04 and PA05 the status of different itineraries affected. Once again, as the flexibility to re-accommodate passengers increases, the number of stranded passengers decreases. Passengers are rebooked mostly by keeping their initial intended mode, even if there is flexibility to change it (if needed) in PA05. Interestingly in PA04 from the 2,996 rebooked passengers, 2,466 (82.3%) maintain their initial mode and the 530 remaining (17.7%) change mode; however, when the flexibility to depart before originally planned is introduced in PA05, more passengers are rebooked overall (3,392) but only 268 (7.9%) change mode. Departing earlier allows passengers to use an earlier service maintaining their connection without having to change mode.

Figure 12 contrasts the delays per type of impact on passengers for PA01 and PA05. As previously discussed,

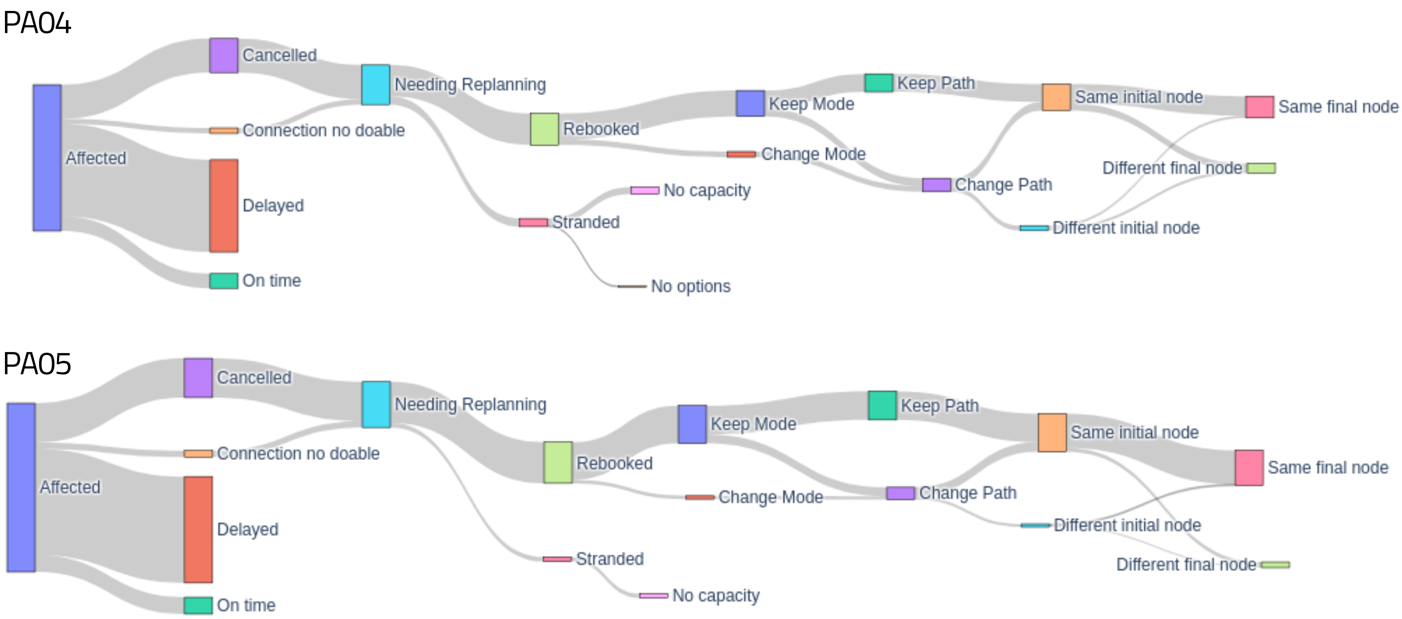

Figure 11 Distribution of itineraries status for PA04 and PA05 for industrial action in Madrid (LEMD)

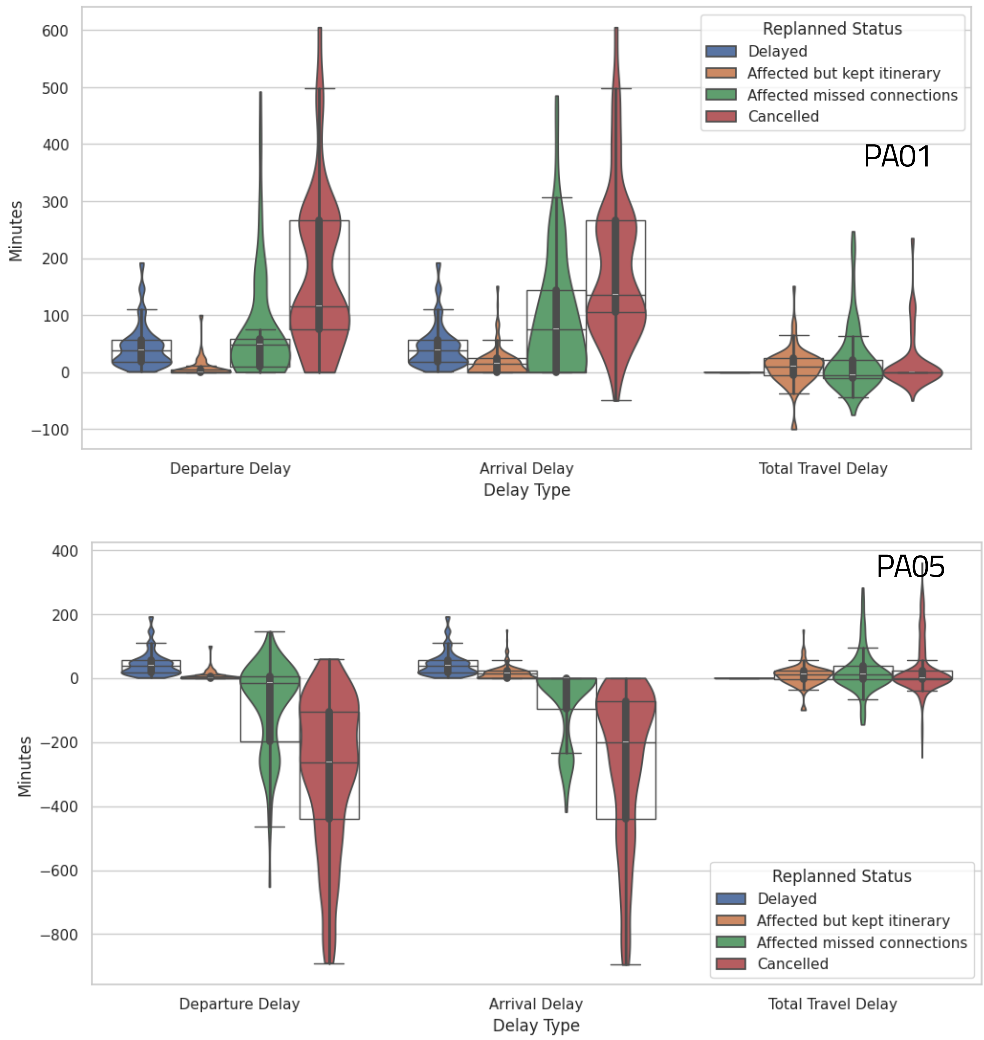

Figure 12 Distribution of departure and arrival delays, and travel deviation for PA01 and PA05 for industrial action in Madrid (LEMD)

passengers with cancellations and those with missed connections are the ones with higher variations with respect to their original plan. Passengers with single flights (delayed) kept their originally planned total travel time, and passengers who can keep their connection increase their travelling time but overall present low departing and arrival delays. This Figure showcases once again the difference between flight and passenger-centric metrics that can be estimated.

Finally, Figure 13 presents for PA01 and PA05 the number of passengers affected that can make their journey, and those who got stranded (either because there were no alternative options for them or because there was no spare capacity). As shown, in PA01, as the most restrictive replanning, passengers must maintain their operator, mode and path. Therefore, a significant number of passengers are stranded due to a lack of alternatives. In the PA05 case, as passengers can use different operators, modes and even depart earlier than planned (possibly using a previous service that ensures their connection), all affected passengers have potentially an alternative option. The lack of capacity is the only reason that some passengers still remain stranded.

4.5 Future evolution of the evaluation of replanned networks

The capabilities presented open the door to the possibility of planning ahead the impact of significant disruptions to assess the effect of these on passenger itineraries and accommodate them accordingly in a preventive manner.

Future work could incorporate passenger agency, conduct parametric sensitivity analysis.

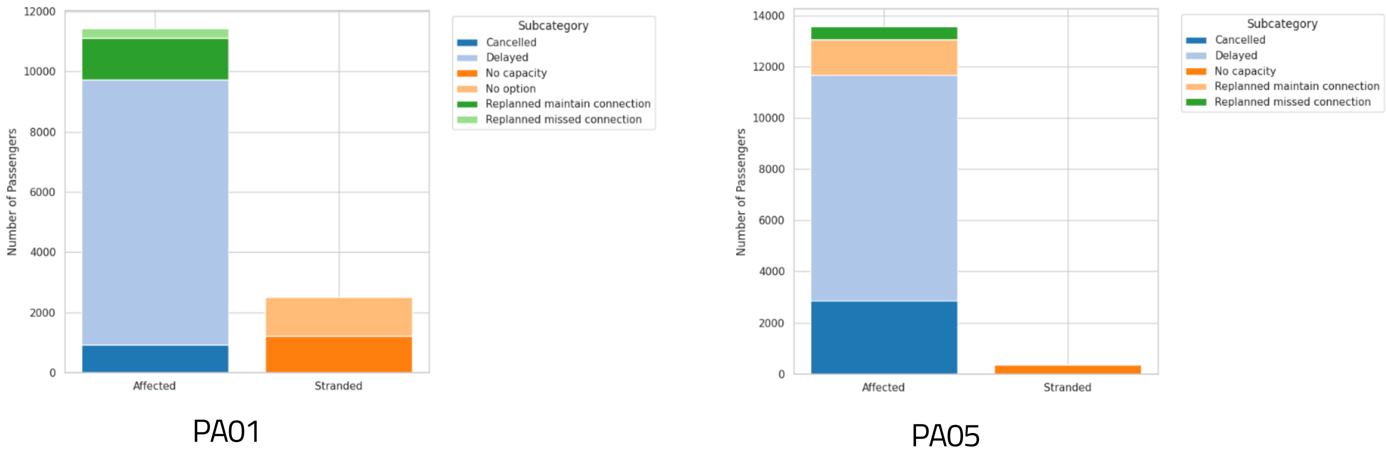

Figure 13 Passengers affected by the disruption and their status for PA01 and PA05 in case of industrial action in Madrid (LEMD)

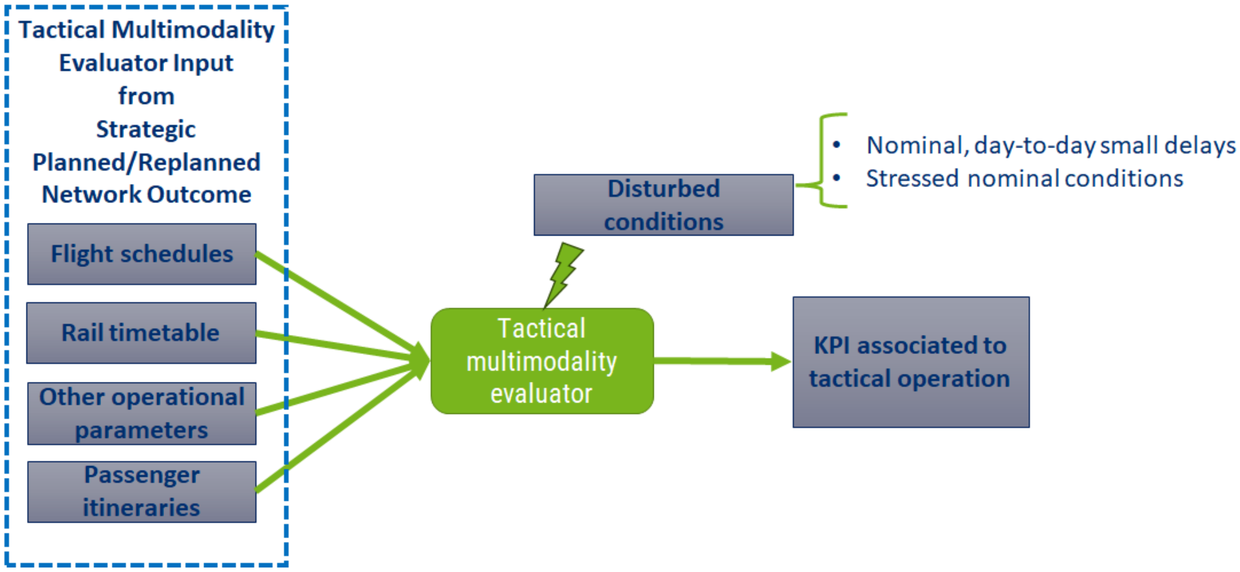

Figure 14 Tactical Multimodal Evaluator input and output

5 Tactical evaluation of networks

5.1 Scope

The Tactical Multimodal Evaluator of the Performance Assessment Solution focuses on simulating stochastically a day of operations in the network, tracking individual flights and passengers. As shown in Figure 14, the input to the tactical evaluator consists of individual flight schedules, rail timetables, passenger itineraries and any other tactical, operational parameters (e.g. probability of ATFM regulation, turnaround times, etc.).

5.2 Methodology

The Tactical Multimodal Evaluator extends Mercury Agent-Based Modelling platform (https://github.com/UoW-ATM/Mercury) developed over several SESAR ER projects from a gate-to-gate simulator to a full multimodal evaluator [14][25]. Mercury is, therefore, the Tactical Multimodal Evaluator. The platform can track individual flights, trains and passengers. This facilitates the computation of very low-level passenger-centric indicators, such as missed connections, waiting times, total journey times, etc.

The Evaluator follows an Agent-Based approach describing via agent and roles the main components of ATM. Mercury uses an event-driven engine to simulate the main processes. A full day of ECAC[4] -wide operations (around 27K flights and 3M pax) can be simulated in under 25 minutes.

As presented in Figure 15, 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 kerb-to-gate and gate-to-kerb 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 transfer times between air and rail infrastructure.
4. The Pax Handler agent proactively captures the decision-making process of passengers (or travel companions) to rebook passengers for subsequent flights or train services.

The model's by-default version represents 'basic' multimodal operations. Mercury is very flexible as it enables the extensions by creating Modules (which can change the behaviour of Roles), as shown in [25]. This allows, for example, the evaluation of multimodal supporting mechanisms by modifying the default behaviour of the agents. For example, modifying the Airport

[4] European Civil Aviation Conference with 44 members including all 27 EU, 31 of the 32 European Aviation Safety Agency member states, and all 41 EUROCONTROL member states.

Terminal Agent to enable modelling of fast track for delayed multimodal passengers [26].

In the current version, Mercury can model air-to-air, rail-to-air and air-to-rail connections. Therefore it enables the evaluation of multimodal connections even if rail-to-rail connections are not simulated but evaluated as post-processing.

5.3 Capabilities

Mercury can simulate daily operations, including small day-to-day delays, stressed nominal conditions (e.g. ATFM regulations or delays on the ground system linking the rail stations with the airports) and large disturbances. 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. fast-track at airports for delayed multimodal passengers). Finally, if larger network-wide disruptions, which require some replanning of operations instead of a reactive approach when managing passengers and services, are experienced, the network would be replanned (as presented in the Section 4), and the Tactical Multimodal Evaluator could then assess this new network.

5.4 Examples of capabilities for the tactical evaluation of networks

5.4.1 Evaluation of robustness of networks

In this experiment, the baseline scenario was run with the Tactical Multimodal Evaluator. These simulations are performed considering a background noise in the system operations. These are modelled as:

- delay for trains using a normal distribution centred at 0 minutes with a standard deviation of 10 minutes,
- the time for passengers to travel between modes (from the train stations to the airports and from the airports to the train stations) is modelled as a normal distribution with a standard deviation of 5 minutes,
- for the air system, nominal amount of delay (e.g. ATFM) and uncertainty (e.g. taxiing, turnaround) as from historical datasets is used [14].

The objective of this experiment is to show how the Tactical Multimodal Evaluator can instantiate the planned network evaluating passenger-centric metrics. The assessment of the robustness of the planned networks with respect to larger disturbances (e.g. higher delays in the ground mobility) and the potential benefit of tactical mechanisms to support multimodality (e.g. passengers' fast processing track at the airport) are reported in Section 5.4.2.

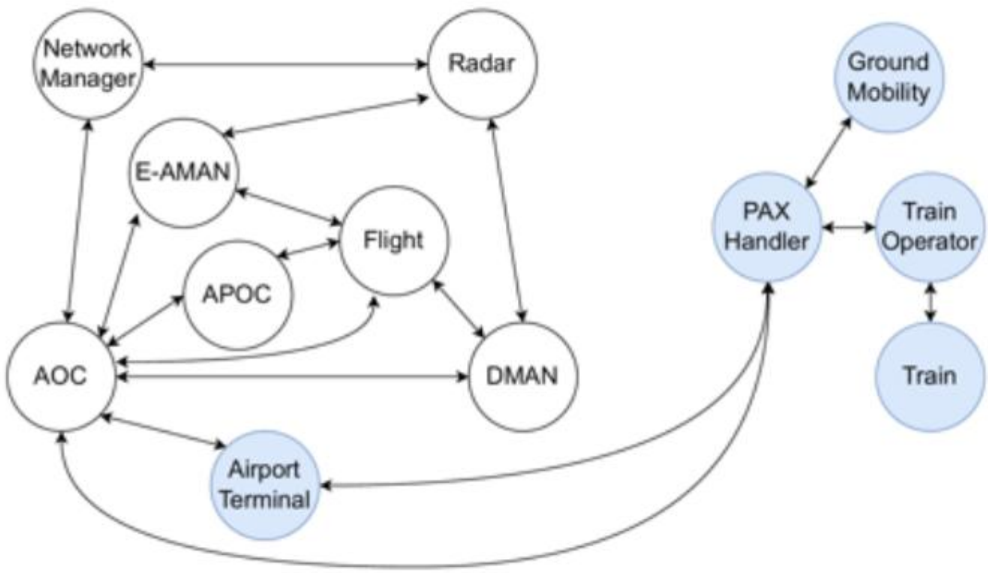

Figure 15 Tactical Multimodal Evaluator model – agent architecture

Table 5 shows the values of the most relevant indicators related to the dynamic nature of the tactical operations. Other indicators, such as kerb-to-gate time, are not listed as their change is small due to the additional noise.

Firstly, the total journey time has decreased compared to the strategic results. However, this indicator only considers passengers who reached their destinations. 0.4 % of passengers (1,445.9 passengers in total) missed their connection, and less than 0.1% of passengers (72.3 passengers in total) were stranded. These results suggest that the itineraries are robust in baseline conditions. Out of all passengers with missed connections, almost 5% become stranded. Out of all stranded passengers, almost 54% missed their onward flight connection when coming from rail. As flight frequencies are much lower than rail, missing a flight likely results in being stranded.

Table 6 shows the ratio of delayed flights, 73% of flight had some delay and 37% had a delay of 15 minutes or more; and how these relate to the ratio of delayed passengers.

The average arrival delay for passengers was 3.69 minutes. As can be seen in Table 6, 55% of passengers arrived with some delay, however only 9% of passengers had a delay of 15 minutes or more. The average arrival delay for passengers with missed connections (not stranded) is much larger, more than 276 minutes. These results confirm findings from previous research, which indicate that passenger and service delays (in particular flights) can be different and highlight the need for dedicated passenger-centric metrics.

Indicator	variant	Value
total arrival delay	average	3.7 (min)
	average for passengers missing connections	275.7 (min)
stranded passengers	percentage of stranded passengers over the total number of passengers	<0.1%
	percentage of stranded passengers with air-to-rail connections over total number of stranded passengers	<0.1%
	percentage of stranded passengers with rail-to-air connections over total number of stranded passengers	54%
	total number of stranded passengers	72.30
	percentage of stranded passengers over the total number of passengers with missed connections	4.8%
missed connections	percentage of passengers with missed connections over the total number of passengers	total 0.4% air-to-air 0.31% air-to-rail 0.05% rail-to-air 0.01%
	total number of passengers missing connections	total 1,446 air-to-air 1,216 air-to-rail 176 rail-to-air 54
total journey time	Addition of the total journey time of all passengers	87,335,386.04 (min)

Table 5 Tactical indicators for the baseline scenario (PP00) in intra-Spain mobility

Threshold (min.)	Percentage delayed flights	Percentage delayed passengers
0	73%	55%
15	37%	9%
30	15%	4%
45	6%	2%
60	3%	1%

Table 6 Delayed flights and passengers with arrival delay larger or equal to the threshold for baseline (PP00) intra-Spain mobility

These capabilities can be used to assess the robustness of a planned network, supporting the assessment of optimised networks, such as after applying a Scheduler Optimiser.

5.4.2 Evaluation of mechanisms to support multimodality

In this experiment, a fast-track to process passengers at the airport pre-departure is used as a tactical disruption management mechanism. The principle of this mechanism is to support delayed multimodal passengers by facilitating their journey through the airport to reduce the time they need to reach the gate aiming at minimising missed connections [27].

The fast-track mechanism is implemented in Mercury as a module of the Airport Terminal agent, which replaces the Wait for move kerb2gate times request role. The Airport Terminal agent returns by default the average time for the passengers' processes to reach the gate from the kerb of the airport; if the fast-track is activated, then it provides a faster time according to a speed-up coefficient.

This experiment is applied over the intra-Spain scenario with multimodality enforced (including a flight ban), PP20, see Section 3.4.2. To the planned operations, 30 minutes of delay is assumed between the rail station and the airport impacting multimodal connections.

Figure 16 shows the number of missed connections for a 30-minute disruption with varying fast-track through airport processes for delayed multimodal passengers speed-up coefficient. As expected, a larger coefficient and thus smaller kerb-to-gate time for delayed passengers reduced the metric. The largest improvement is obtained by fast-track speed-up coefficient of 0.1 and 0.2, where the number of passengers with missed connections is reduced by 20% and 14%, respectively. After 0.3 coefficient, the number of passengers with missed connections stays almost the same with slight decrease. As the mechanism only affects the kerb-to-gate times and,

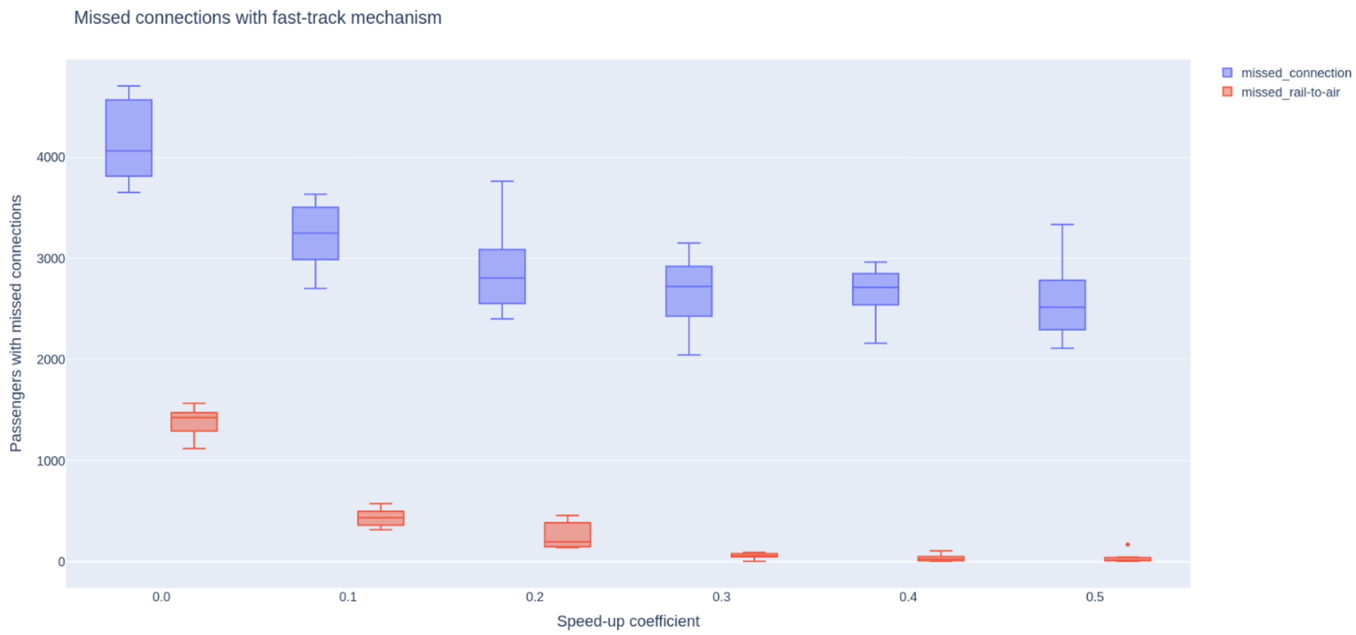

Figure 16 Passengers with missed connections with fast-track mechanism at airport as a function of speed-up coefficient

therefore, does impact only rail-to-air connections and not air-to-rail or air-to-air connections. There is a diminishing number of rail-to-air passengers that can benefit from further reduction of kerb-to-gate times in accordance with the shape of the distribution of itinerary buffers, as can be seen the graph below. The number of missed rail-to-air passengers approaches 0, and after the coefficient 0.3 cannot be further improved.

The air-to-rail or air-to-air connections could be positively affected by employing other mechanisms such as improved ground mobility (a dedicated bus line) or flights waiting for passengers. Some of these mechanisms have been explored in [26]. As can be seen from the results, the mechanism can reduce the number of missed connections and thus improve the robustness of itineraries.

5.5 Future evolution of tactical evaluation of networks

Future work could focus on the integration of external disruption management solutions for rebooking of passengers who miss their connections, linking passengers' archetypes to transfer times between modes and within the infrastructures, directly including the rail-to-rail connections in the simulation.

6 Conclusions

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 Framework and tools described provide a robust and replicable framework for measuring multimodal mobility, offering an unprecedented ability to quantify door-to-door performance through an open digital catalogue of passenger-centric indicators and a set of open-source tools for the evaluation of planned and replanned air-rail multimodal networks both strategically and tactically. This marks an important advancement beyond traditional mode-specific assessments, enabling decision-makers to evaluate system-wide trade-offs and synergies between air and rail.

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8 Glossary

Agent Based 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 decision support tool that optimally adjusts air and rail schedules during disruptions, minimising passenger impact and operational costs.

Door-to-door 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).

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

Mobility layer: A mode specific 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 passenger- centricity of multimodal networks.

Pareto Equivalent clusters: Groups of itineraries offering similar levels of performance in terms of key indicators (e.g. time, cost, emissions), representing equally efficient alter- natives.

Passenger-centric approach: A methodology that prioritises passenger needs, experience, and outcomes when designing and manag ing 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 long term multimodal network performance at pl0anning level, considering schedules, demand, and policy conditions.

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

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

9 List of acronyms

ABM	Agent Based Modelling
AOC	Airline Operations Centre
APOC	Airport Operations Centre
ATFM	Air Traffic Flow and Capacity Management
CO_2	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	Kerb-to-Service / Service-to-Kerb time
LEMD	Madrid–Barajas Airport (ICAO code)
LEMG	Málaga Airport (ICAO code)
LEVD	Valladolid Airport (ICAO code)
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

Appendix A – Performance Indicators in Digital Catalogue

This annex provides a table with the PIs in the digital catalogue. Note on the KPAs: All indicators could be considered part of the 'Passenger Experience' KPA. However, as indicated in this table, they can be further disaggregated into different, more specific KPAs.

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

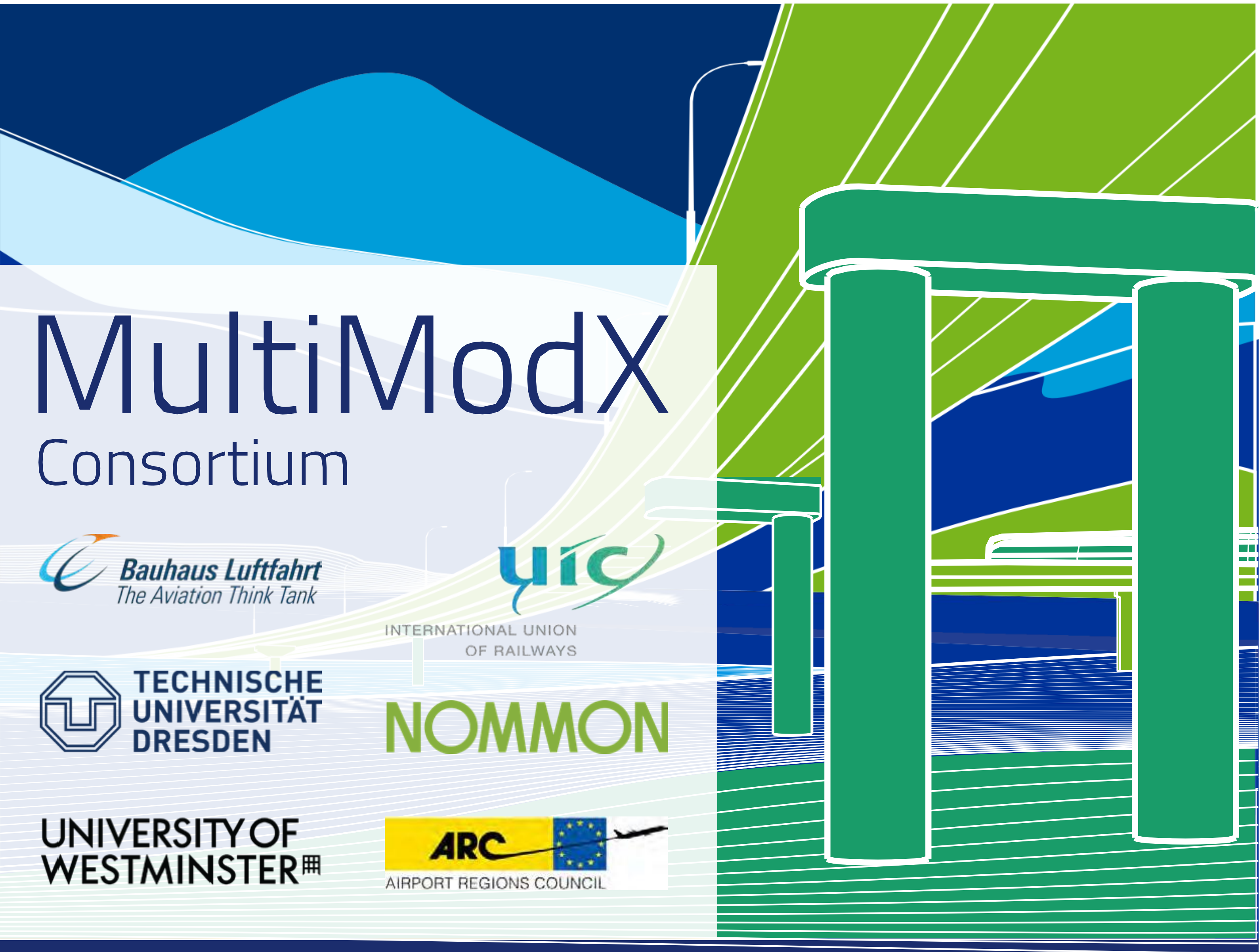
Table 7 Digital catalogue of indicators

KPA	PI Id	PI short name	PI Definition	Type	Highest Maturity Level	Source	Subpage - Indicator definition
Operational Efficiency (OPS)	OPS_PE1	Passengers processing time at infrastructure	Minutes taken to do the process from the kerb to the gate at the airport. The same opposite indicator should be considered 'Gate to kerb' and 'Gate to gate' for connecting passengers.	Strategic	L2.2	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/NjkxZGM1NGJkYjBjNDhhYjlkMWIxMGQzNDFkMjJmMmM
	OPS_PE2	Total journey time	Strategic based on published schedules, actual based on the recorded performance on the day of operations.	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/OGU0OTk2M2ZjYWQ0NGRlYzk3OGUzM2UzNmJiMDBmZDE
	OPS_PE3	Passengers time efficiency	Best possible journey time (from schedules)/actual time travel (from actual operations) [percentage]	Strategic	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/MTU2MTcxNzVjOWJiNDlkYjkyZjEyMjYyZWJiMWYxZDQ
	OPS_PE4	Buffers in itineraries	Amount of time used as buffers in connections in itineraries.	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/ZTRkNTJkN2Q4MzMzNGU4MTg3YTQ1ZmU4NjFkZWI3MjA
	OPS_PE5.1	Arrival delay (flights)	Arrival delay (at thresholds 15, 30, 45 and 60 min).	Tactical	L2.1	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/NmNhMzNhZTNiOTkwNDQyMmI0NjI0ZGVhYjU0YzUxZmY
	OPS_PE5.2	Total arrival delay at final destination	Difference between planned and actual arrival time at final destination. Could be disaggregated (all passengers, passengers who	Tactical	L3	'Multimodality and passenger experience in the SESAR Performance	https://nommon.atlassian.net/wiki/external/NDE1MjZlZTdhNzY2NDI0OWEwY2ViMzdiOWQ4MzAyMzk

		missed connections, passengers rerouted, etc.).			Framework' workshop	
OPS_PE6	Cancellations due to ATFM	Percentage rate.	Tactical	L2.1	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/YmRlOTMxMGRkMTEzNDk2MzgwNzRiMmZiMGFlMzgwODc
OPS_PE7	Reactionary delay	Minutes of delay of reactionary delay due to ATFM.	Tactical	L2.1	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/NWI0MmI3MmE2MzQzNGRiYTgxNGVjZTA5NjE1MThmNzk
OPS_PE8.1	Stranded passengers	Percent of pax not reaching their destination.	Tactical	L2.2	MultimodX	https://nommon.atlassian.net/wiki/external/YmVmNTI5YzYwYTIzNDU2MTkyYzRmMGJkZmNmODQ1MTA
OPS_PE8.2	Ratio of stranded passengers	Ratio of passengers stranded over number of passengers missing their connection.	Tactical	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/MjMzZGViY2QxMjQ5NGExMGFjMzYzZGNiN2ZlMjM5NDE
OPS_PE8.3	Stranded passengers	Percentage of passengers not reaching their destination due to replanning.	Replanning	L3	MultimodX	https://nommon.atlassian.net/wiki/external/MjY4YjdiYWIxODViNGRlZWJjMGQ3ZThiZTI3MTU1MGE
OPS_PE9	Missed connections	Percent of pax with missed connection (can be disaggregated by type of connection inter/intra-mode)	Tactical	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/MDExYzEyYTEyNzM3NDAyYWIzYzk5MmRlNjgxN2RlMTc

Interoperability (INT)	INT_PE1	Modal share	Share of transport modes in passenger itineraries on a specific origin-destination pair [percentage per mode(s)]	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/ZTU4ZGRlMTk2MTkxNDgxZmE1MDU4ZWZlOWE4MjBmYTg
	INT_PE2	Seamless of travel (time)	Journey transition time (between modes and stops) [mins]	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/NWYyNGE3OWVjNTdlNGY0ZTg5ODc2MmUzNWQ1NGMyZjM
	INT_PE3	Infrastructure connectivity	Volume of passengers that are connecting at a given infrastructure node	Strategic	L2.2	MultimodX	https://nommon.atlassian.net/wiki/external/NGQxM2Y3MDI0NTNmNDUwYzk0YTlhYjZhYTIyZDU0YWQ
Flexibility (FLX)	FLX_PE1.1	Resilience alternatives	Number of strategic (planned) and tactical (actual) alternatives available for a given origin-destination pair.	Strategic	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/NTBlMzQ5NmQ4ZDFmNDQyMzk1YWRhMzg5ODc5ZjFlZTU
	FLX_PE1.2	Passenger Resilience replanned	Difference between planned and replanned itineraries	Replanning	L3	MultimodX	https://nommon.atlassian.net/wiki/external/NWY5MzExZWM4N2JhNGExNmJiZTg5NDc5MDRlZTUzMWU
	FLX_PE2	Diversity of destinations	Number and type of destinations which can be reached from an origin	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/YmJiNzYyNDJlMDJhNGFjZDk5MzgyNTVhMjE5YzU2MTI
	FLX_PE3	Resilience replanned	Captures applied changes/adaptations in the replanned schedules: -rerouted train services -diverted flights -replacement services -retimed/delayed services	Replanning	L3	MultimodX	https://nommon.atlassian.net/wiki/external/NTkxMjBiN2ZmM2Y5NDYxNDlmN2Y5Y2RmOWI1MzhlOTg
Cost-Efficienc	CEF_PE1	Direct operating cost per user	Operating cost per trip per user [Euros]	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/MGI2ZmFjMzllZmUxNGFjZGE0ZmI3NWFkOTE1YTRmNWM

	CEF_PE2	Load factor	Number of passengers over number of seats per operator / mode / total	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/OGIzMDc4ZTJmY2YwNDEwMmI4YWRmY2JlYWM2ZGY0NTc
Capacity (CAP)	CAP_PE1	Demand served	Number of passengers that are assigned to itineraries over the total number of passengers who want to travel between a given origin-destination pair.	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/YjYxYjcwZmFhYzUyNGQ2MmE5MTYyMTE0YzE3MjBmZTc
	CAP_PE2	Catchment area of airports	Distance of ground mobility (e.g. rail) from which an airport captures demand. Could be normalised by passengers using that distance.	Strategic	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop	https://nommon.atlassian.net/wiki/external/ZDUxMDljMjUxYWMzNGYxNDliMWZhZDhlN2ZiZDc1YWU
	CAP_PE3	Capacity available	Number of seats available between a given origin-destination pair.	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/ODFhMmYwZGFmOTNkNDIwOWFiMjEzOTM1YzA0YWU0NGM
Environment (ENV)	ENV_PE1	CO_2 emissions	Total emissions of services used (could be normalised by passenger-km considering the demand served)	Strategic	L3	MultimodX	https://nommon.atlassian.net/wiki/external/MWFiZWY2Yjc1ZDc5NGFlMWE5ZmY2OWY2ZDczMWJlNTU
Predictability (PRED)	PRED_PE1	Variability	Share of passengers arriving late (within pre-defined time slot) [percentage]	Tactical	L3	MultimodX	https://nommon.atlassian.net/wiki/external/Mzk1Mzg1MWRlZTFjNDNmYWEyOGRjYTVhZWUyMTIzYmQ



MultiModX

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UIC – International Union of Railways

Technische Universität Dresden

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