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Abstract

The Multimodal Performance Framework has been validated with exchanges with relevant stakeholders and other exploratory and industrial research projects. The Strategic Multimodal Evaluator and Tactical Multimodal Evaluator have been validated assessing a planned multimodal mobility network, including the integration of optimised schedules (i.e., from SOL400/SOL2). The Strategic Multimodal Evaluator has been validated assessing a replanned multimodal mobility network subject to different types of disruptions (e.g. rail link closure, airport closure, airport capacity reduction, industrial action) and flexibility to reaccommodate passengers and management actions (such as the replanning of operations by SOL401/SOL3). Finally, the Tactical Multimodal Evaluator has shown to simulate multimodal (air-rail, rail-air) connections. This facilitates the evaluation of the robustness of planned networks but also the assessment of mechanisms (and Solutions) which could impact passenger connectivity. The inclusion of internal and external experiments, along with the Maturity Self-Assessments, supports that the Solution reaches TRL2.

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Nominative authoring compliance

The beneficiaries/consortium confirm(s) the correct application of the Grant Agreement, which includes data protection provisions, and compliance with GDPR or the applicable legal framework with an equivalent level of protection, in the frame of the Action. In particular, beneficiaries/consortium confirm(s) to be up to date with their consent management system. The beneficiaries/consortium has obtained the explicit, freely given, informed and unambiguous consent from the author(s) when indicated nominatively, otherwise, anonymous (using the name of the participating entity) is used in the Authoring and approval tables.

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MultiModX

INTEGRATED PASSENGER-CENTRIC PLANNING OF MULTIMODAL NETWORKS

MultiModX

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1 Executive summary

The Experimental Research Report (ERR) presents the results of the validations outlined in the Experimental Research Plan (ERP). This document contains a summary of the SESAR Solution and the ERP, a summary of each validation exercise, the detailed results of each validation exercise, and the conclusion of each validation exercise and on the maturity of the Solution along with some final recommendations.

The Exploratory Research Report (ERR) is the document that consolidates the results obtained by SOL399/SOL1 of the MultiModX's project once the validation activities, experiments, and analysis are concluded. This document is the final version of the report, which includes all the results of the activities finished at this moment and preliminary results of the ongoing activities. This document includes a self-assessment of the achieved TRL.

2 Introduction

2.1 Purpose of the document

The Exploratory Research Report (ERR) is the document that consolidates the results obtained by SOL399/SOL1 of the MultiModX's project once the validation activities, experiments, and analysis are concluded. This document is the final version of the report, which includes all the results of the activities finished at this moment and preliminary results of the ongoing activities. This document includes a self-assessment of the achieved TRL.

2.2 Intended readership

The readers of this document would typically include a range of stakeholders involved in the rail and aviation industry, transportation planning, and policymaking. These may include SESAR JU, SESAR IR and ER projects, EU-Rail, airlines, airports, rail operators, train stations, transportation planners, policymakers, urban planners, researchers and academics, consultants and advisory firms, technology developers, and environmental organisations.

2.3 Background

Multimodal Performance Framework

Previous work has focused on computing ad-hoc PIs to capture multimodal aspects of mobility. Noteworthy are the works conducted by previous SESAR ER projects Modus and TRANSIT [1, 2], which already reviewed the current ICAO [3] and SESAR performance schemes [4]. Both projects developed multimodal indicators that account for aspects such as door-to-door travel time, travel time reliability, monetary cost for the passenger, regional connectivity and accessibility, environmental impact, and resilience.

When considering the multimodal aspect of transport, the focus naturally shifts from vehicle-centric to passenger-centric indicators. Foundation work on passenger-centric metrics in Europe was led by the University of Westminster in the POEM project (Passenger-Oriented Enhanced Metrics), putting the passenger at the centre of monetised KPIs with corresponding policy implications.

The expected evolution of the SESAR Master Plan considers the inclusion of Passenger Experience as one of the areas where PIs and KPIs will be developed. This contributes to the focus on passengers, extending the flight-centric vision of the ATM system. Other current research projects are working on these aspects and will coordinate some of their activities with the work to be conducted as part of SOL399/SOL1, namely, SIGN-AIR [11], MAIA [14], PEARL [9], AMPLE3 [10] and Travel Wise [12]. The Passenger Experience and Multimodality Flagship will further develop these activities.

Strategic Multimodal Evaluator

The detailed representation of multimodal transport supply as a layered network (multiplex) enables the evaluation of coordination mechanisms, but it is computationally challenging given the high number of alternatives that may be available for performing a trip. Previous research conducted by

TRANSIT [5] has already shown how considering schedules and low-level demand data are required to understand passengers' alternatives and their preferences when using the network.

Tactical Multimodal Evaluator

The transport network is subject to different types of disruption during its operation, from day-to-day minor delays, infrastructure issues, and congestion to more severe disruptions blocking elements in the system (e.g. weather which closes an airport) or significantly dropping the capacity (e.g. runway closure) and system-wide disruptions (e.g. volcanic eruption). It is therefore important to model the realisation of the planned mobility network as passengers' experience can be significantly negatively impacted, and mechanisms (and Solutions) could be put in place to alleviate these.

In the context of multimodality, it is important not only to focus on the modelling of flights (or rail services) but also on the passengers and their full itineraries. Previous research has shown that passengers might experience disruptions very differently than airlines (and flights) [6]. In the context of multimodality, these discrepancies are expected to increase, particularly when considering missed connections in the multi-modal context. Moreover, airlines' operational decisions tend to be underpinned by their expected operating costs, which might vary as a function of passenger experience.

Mercury, is a gate-to-gate (extended to door-to-door) flight and passenger mobility simulator specifically developed to tackle these considerations in many previous research projects [6, 23]. Mercury has been successfully used for the evaluation of door-to-door mobility considering intra-airport processes (kerb-to-gate, gate-to-kerb) and first-last mile [6].

2.4 Structure of the document

Chapter 2 of the document serves as an introduction, providing general information about the Exploratory Research Report. Chapter 3 is a summary of the context of the Exploratory Research Plan and contains the information needed to understand the Exploratory Research Report. In Chapter 4, a summary of the results of the validation exercises is presented. The conclusions regarding the validation exercises, along with some general recommendations, are provided in Chapter 5. The detailed results of each validation exercise are presented in Appendices A, B and C.

2.5 Glossary of terms

Term	Definition	Source of the definition
Air network disruption	Significant ATFM regulations or closures at airports.	Own elaboration
Case Study	Geographical context in which the Solution will be applied, i.e., trains, flights considered, demand and infrastructure.	Own elaboration
Disruption	Rail or air network disruptions, which are known in advance and produce a significant reduction in supply on the infrastructure of the networks.	Own elaboration

Disruption package	Set of disruptions that are applied at the same time to the planned network.	Own elaboration
Disturbance	Delays in the system which do not require a replanning of operations (e.g. ‘nominal’ background delay)	Own elaboration
Experiment	A succession of steps within a validation exercise that are analysed together. Instantiation of Scenario with specific parameters.	Own elaboration
Itinerary	A succession of services (flights or trains) which represent a possible trip for a passenger.	Own elaboration
Multimodal supporting mechanisms	Mechanisms that tactically support passengers through their multimodal journey, e.g. fast-track at airports dedicated to multimodal passengers to reduce potential missed connections. These mechanisms modify the default behaviour of elements in the system.	Own elaboration
[infrastructure] Node	Airport or rail station	Own elaboration
OD pair	Origin and Destination pair. Refers to the start and end points of each passenger's journey. The number of O&Ds also indicates the size and complexity of a network.	ATPCO Glossary
Planned network	Instantiation of a strategic experiment computed by the Strategic Performance Evaluator consisting of: supply (flight schedules and rail timetable), demand (passenger itineraries) and infrastructure (access/egress times, minimum connecting times, inter-modes connecting times, passenger processing times).	Own elaboration
Policy package	Set of policies to be considered/applied to the network: short-haul bans, frequent flyer levy, rail incentivisation, CO2 costs, and level of integrated ticketing. These policies are grouped meaningfully.	Own elaboration
Rail network disruption	Reduced throughput at nodes (rail stations) and/or links, and/or closure of links.	Own elaboration
Replanned network	A planned network for which flight operations and rail timetables are adjusted to consider the impact of disruptions (cancellations, shifts in schedules (delays) and the addition of new services).	Own elaboration
Scenario	The specific socio-economical context in which the Solution will be applied within a case study (case study with policy package).	Own elaboration
Service	Flight or specific train between two stations	Own elaboration

Strategic experiment	A specific network defined by supply (flight schedules, rail timetable), demand (origin-destination demand matrix per passenger archetype), infrastructure (access/egress times, minimum connecting times, inter-modes connecting times, passengers processing times), configuration parameters (for the Strategic Evaluator, e.g., clustering thresholds) and policy package (set of policies to be considered by the network). See Annex A of FRD for information on format and parameters [20].	Own elaboration
Tactical experiment	A planned tactical network (supply (flight schedules, rail timetable), demand (passenger itineraries) and infrastructure (access/egress times, minimum connecting ties, inter-modes connecting times, passenger processing times)) in the format required by the Tactical Evaluator (see Annex A from FRD [20]) and any other additional required data by the Tactical Evaluator to simulate the network (e.g. disruptions, flight plans).	Own elaboration
Use Case	A potential situation in which a system receives an external request (such as user input) and responds to it.	Wikipedia (use case definition)
Validation exercise	Set of experiments done in order to validate the utility of a Solution	ERP document

Table 1: Glossary of terms

2.6 List of acronyms

Term	Definition
ABM	Agent-Based Model
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BIM	Benefit Impact Mechanism
CAP	Capacity
CEF	Cost-Efficiency
ECAC	European Civil Aviation Conference region
ENV	Environment
ER	Exploratory Research
ERP	Exploratory research plan
ERR	Exploratory Research Report

EWGT	Euro Working Group on Transportation
FLX	Flexibility
FRD	Functional Requirements Document
GA	Grant Agreement
HSR	High-Speed Rail
IB	Industry Board
ID	Identifier
INT	Interoperability
IR	Industrial Research
KPA	Key Performance Area
KPI	Key Performance Indicator
MND	Mobile Network Data
NUTS	Nomenclature of Territorial Units for Statistics
OPS	Operational Efficiency
OSED	Operational Service and Environment Description
PI	Performance Indicator
PRED	Predictability
SESAR	Single European Sky ATM Research
SESAR 3 JU / S3JU	SESAR 3 Joint Undertaking
TRL	Technology Readiness Level

Table 2:List of acronyms

Context of the exploratory research report

Project / SESAR solution 1: a summary

SOL399/SOL1 a system enabler that supports external solutions. It provides a multimodal performance framework and a set of tools to evaluate multimodality and solutions applied in this context. In the scope of MultiModX, SOL399/SOL1 is, therefore, an optional enabler for SOL400/SOL2 (Scheduling Design Optimiser) and SOL401/SOL3 (Disruption Management Solution). Those solutions can be evaluated independently, but SOL399/SOL1 provides a framework and tools for their assessment. In addition SOL399/SOL1, as a standalone Solution, can be applied across diverse operational environments and evaluate the performance of SESAR Solutions, mechanisms and other more broad elements such as policies considering a full multimodal performance framework, developed with a mobility and passenger-centric approach.

Note that as a performance framework and a set of tools to evaluate other Solutions, the models developed within SOL399/SOL1 could be considered to have achieved operational capabilities (i.e., some aspects of TRL8); in a more broad context of evaluating multimodality (including during its deployment) there are still elements to improve, and therefore we consider SOL399/SOL1 to have achieved the targeted TLR2 as for the validations presented in this report.

SOL399/SOL1 is composed of three main components:

- Multimodal Performance Framework: describing performance indicators and a methodology to analyse and further develop them.
- Strategic Multimodal Evaluator: focused on the analysis of planned (and replanned) multimodal networks.
- Tactical Multimodal Evaluator: aiming at modelling the realisation of the planned networks on the day of operations.

Multimodal Performance Framework

The multimodal performance framework developed as part of SOL399/SOL1 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:

- Level 1 are indicators currently part of the SESAR3 Performance Framework. These indicators will have, by their nature, a stronger focus on the gate-to-gate component of the passenger journey. Work will be conducted to identify how multimodality could impact the SESAR Performance Framework's currently considered PIs and KPIs.
- Level 2 comprises indicators that are currently (or are planned) to be at least modelled by research projects. These will mature some aspects of passenger experience and focus on multimodal considerations such as reliability.

- Level 3 contains more ambitious indicators that aim to capture the total experience of passengers in their door-to-door journey. These will represent indicators that can be more desirable but currently not feasible due to several limitations, such as data availability.

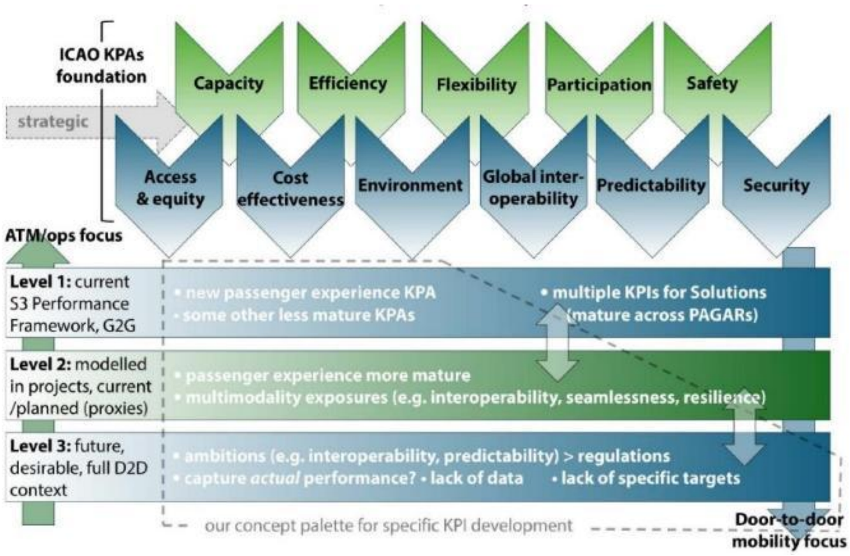

Figure 1: Multimodal Performance Framework approach.

MultiModX provides a first identification of indicators and establishes the required collaborations across different European Exploratory and Industrial Research projects and stakeholders so that an open-access digital catalogue of indicators with an assessment of their development level could be set up in the context of the Passenger Experience and Multimodality Flagship.

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Strategic Multimodal Evaluator

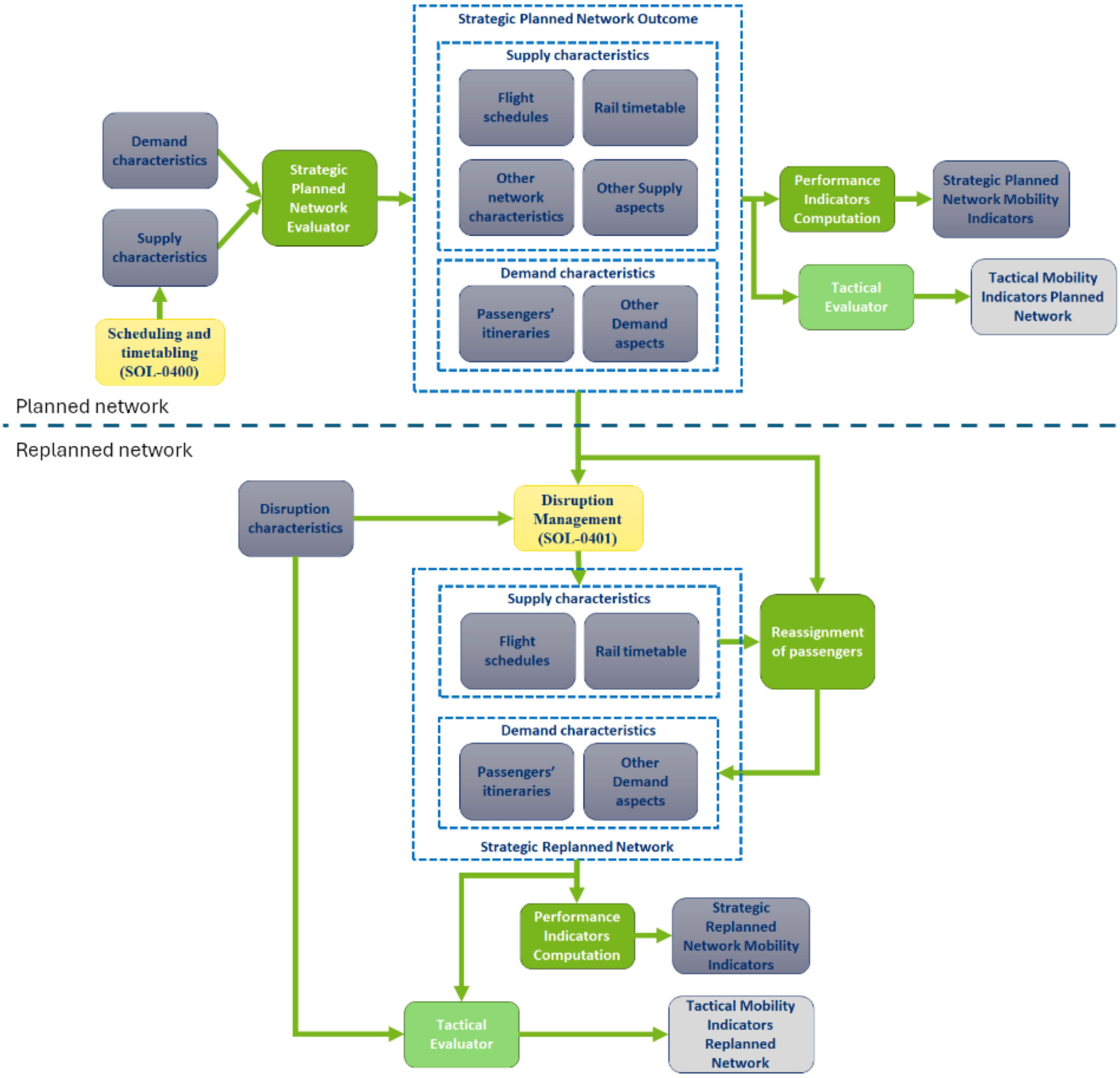

Figure 2: Strategic Multimodal Evaluator framework.

As shown in Figure 2, the Strategic Multimodal Evaluator is responsible for building and analysing the planned (and replanned) network. It comprised of three main elements:

- **Strategic Planned Network Evaluator**, which, from the characteristics of demand (OD demand) and supply (flight and rail schedules) and infrastructure aspects, computes the materialisation of the supply and demand characteristics in the network.

The supply could be any flight and rail schedules, including the outcome of the Scheduling Design Optimiser (MultiModX's SOL400/SOL2) aiming to improve the connectivity between air and rail layers.

- **Passenger Reassignment on Replanned Network**, which 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). 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). As shown in Figure 2, the Strategic Evaluator can then reassign the demand of passengers impacted by these changes. The overall process is similar to the Strategic Planned Network evaluation, but the passenger demand is already in the form of passenger itineraries, and only passengers impacted by the replanned operations are considered.
- **Performance Indicators Computation**, which computes mobility performance indicators when considering the outcome of the Strategic Planned Network Evaluator. These computations are part of the general model and implemented in ad-hoc libraries.

Tactical Multimodal Evaluator

The Tactical Multimodal Evaluator simulates a day of operations in the network, tracking individual flights and passengers. As shown in Figure 3, the input to the Tactical Evaluator is the individual flight schedules, rail timetables, passenger itineraries and any other tactical, operational parameters (e.g. probability of ATFM regulation, turnaround times).

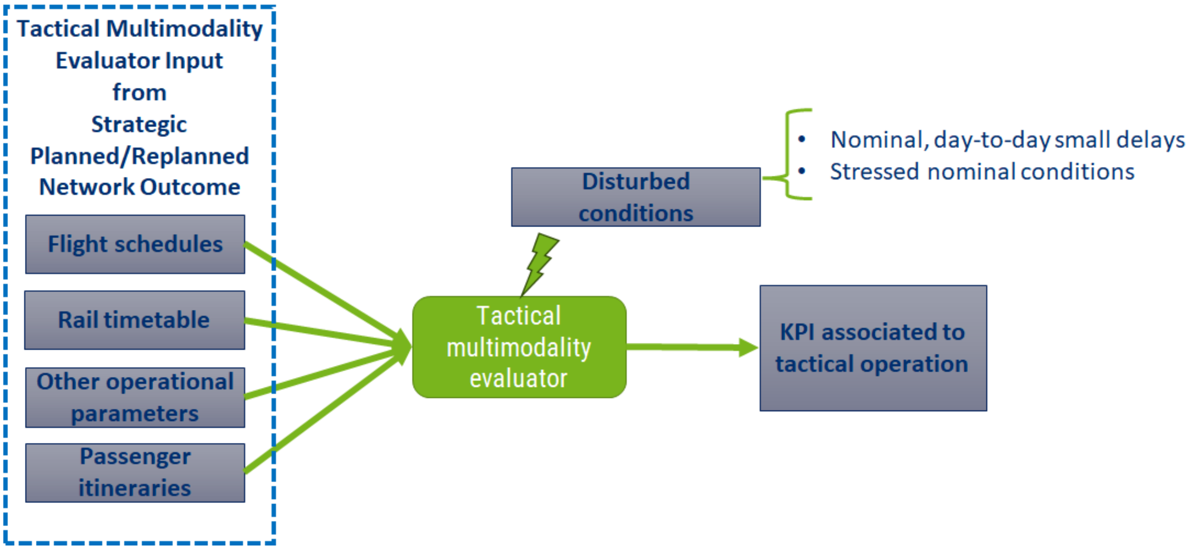

Figure 3: Tactical Multimodal Evaluator framework.

The model can simulate disturbed conditions, such as day-to-day *nominal* delays, and stressed nominal conditions (e.g. ATFM regulations or 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.

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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).

As the Tactical Multimodal Evaluator can track individual services and passenger itineraries, very low-level passenger-centric indicators (e.g. missed connections) can then be estimated by the execution of the Tactical Performance Indicator Computation module.

Summary of the exploratory research plan

Exploratory research plan purpose

Three validation exercises are planned to **ensure the assessment of the capabilities of SOL399/SOL1**:

- '*Validation of the multimodal performance framework*' relies on interactions with MultiModX's Industry Board and relevant stakeholders and experts. It supports the validation of the indicators and the approach for their validation.
- '*Strategic and Tactical evaluation of planned multimodal mobility network*' to show the capabilities to assess the planned multimodal networks, including the integration of optimised flight schedules and rail timetables from the Schedule Design Solution (SOL400/SOL2). These validation activities rely on modelling and quantitative analysis along with interaction with relevant experts to gather feedback on the modelling approach and assumptions.
- '*Assessment of the impact of disruptions on a multimodal mobility network and mechanisms to support multimodality*' is the final validation exercise. This exercise focuses on the replanning of the network considering disruptions (with and without the use of Disruption Management Solution (SOL401/SOL3)) and the computation of ad-hoc indicators. Moreover, the assessment of mechanisms to support multimodality for different levels of disturbance will be assessed.

In terms of the operational environment, the validation exercises focus on the intra-Spain case study, as this comprises all the different mobility region archetypes and all relevant passenger archetypes identified in the project. Policy packages are considered to create different potential futures where operations are similar to nowadays or where multimodality is encouraged, for example, by means of flight bans. Likewise, disruption packages are used to assess the impact of the network being replanning. The case of Spain mobility, including international destinations, is considered but not required for the validation of SOL399/SOL1 and therefore still under development at the moment of producing this report.

2.6.1 Summary of validation objectives and success criteria

The summary of the validation objectives and success criteria has been done in Section 4.3 of the ERP.

2.6.2 Validation assumptions

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Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A1	Stakeholders representativeness	The validation of the performance framework relies on the interaction with stakeholders. It is assumed that the pool of stakeholders is representative of the European-wide system and captures all their needs.	The Industry Board and panel of stakeholders approached to validate the performance framework is large (at least 20 members) and comprises stakeholders of the different elements of multimodality: airlines, rail operators, airports, etc. Feedback from other research projects (e.g. PEARL, AMPLE3, SIGN-AIR, MAIA, Travel Wise) is also envisioned.	Low
A2	Case studies coverage	It is assumed that the three case studies defined in the ERP provide an interesting variety in terms of regional specificities and situations of multimodal transport (national case study and international corridor with an integrated HSR station in an airport) [18] to cover the different operational environments described in the OSED [15]. This will impact the validation and calibration of the performance assessment of the Strategic and Tactical Evaluators.	Regional archetypes have been studied, and the case studies cover national and international cases.	Medium
A3	Passenger archetypes coverage	It is assumed that the set of passenger archetypes considered represents the entirety of travellers, as required for the disaggregation of demand by the Strategic Evaluator.	Extensive research has been conducted to ensure that those passenger archetypes represent the variety of travellers.	Medium

A4	Data availability	It is assumed that the required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, distribution of delays and disruptions, etc.) are available in the regions under study. Appendix A of the FRD summarises the different data sources considered. For the multimodal consideration the main datasets considered include: - Demand between regions by archetype. - From an infrastructure accessibility perspective: average door-to-airport, airport-to-door, door-to-rail_station, rail_station-to-door, which infrastructure nodes are accessible from which region (NUTS). - From an infrastructure management perspective: minimum connecting times, passenger processing times (kerb-to-gate, gate-to-kerb, kerb-to-platform, platform-to-kerb). From providers perspective: flight schedules, rail timetable, seats available per service, alliances between modes which allow the connection of passengers between them, itineraries costs and emissions.	Data are required to execute the Strategic and Tactical Evaluators, but modelling assumptions can be established if needed.	Medium

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A5	Existence of multimodal governance	It is assumed that a multimodal performance scheme and multimodal governance are in place, allowing cooperation between modes of transport in particular between rail and air operators. This includes the sharing of data: - between modes: flight schedules, rail timetable, seats available per service, alliances between modes which allow the connection of passengers between them, itineraries costs and emissions. - if integrated ticketing in place, then by how much connecting time are reduced.	The project is interested in studying the impact of a multimodal and collaborative framework. Therefore the requirements on data exchanges and availability are out of scope of MultiModX. It is assumed that all the required agreements between parties for data sharing and implementation of ticketing are in place.	High
A6	Fixed demand per OD pair	It is assumed that the demand for each OD pair is fixed, meaning that the choice of passengers to travel is independent of the schedules (there will be no more or less demand). Their destination will not change as a result of the schedule optimisation for the Strategic Evaluator.	It is considered sufficiently precise to have demand flows per OD pair and archetype for each scenario (including the impact of policies). The reaction of demand to the supply is considered to have a potential small impact only.	Medium
A7	Coordination between air and rail	The Strategic Evaluator considers the rail and air network, leaving aside other long-distance ground transportation modes such as long-distance buses.	The scope and focus of the project are on air and rail collaboration. For future projects, it would be interesting to include road transport.	Medium

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A8	Fixed prices	It is assumed that the prices of the different paths are fixed as an input of the solution and will not be updated within the solution in the Strategic Evaluator.	The price reaction to the demand through an economic model is considered out of the scope and interest of the project. Price variations may come from the policies defined in the scenarios.	Low
A9	Considered times	Scenarios, case studies, experiments and use cases are constructed to be representative of a nominal day in 2030.	First, it is assumed that maturation of the solution from TRL 1 to TRL 2 can be sufficiently performed by using. Second, flight data is based on a busy day in 2019, which, according to [27], would be slightly higher than the average expected day in 2030. Similar behaviour is expected by selecting a busy and nominal day in 2023 for rail; and passenger demand from MND of a busy day in September 2022.	Medium
A10	Disruption knowledge	It is assumed to have information on the disruption impacting the operations. This assumption can be relaxed as required.	The Evaluators need to know the information on the external disruption and disturbances for their evaluation.	Low

A11	Close system evaluation	It is assumed that paths, itineraries and strategic and tactical alternatives are considered within the schedules, timetables and paths available in the case study model.	The input of the Strategic and the Tactical Evaluator will consider the network defined in the case studies. Therefore, the scope to compute alternatives and to assess the performance is limited by the scope of these networks.	Medium
A12	Itineraries performance equivalence	It is assumed that itineraries with similar total travel time, total cost, total emissions, number of connections and modes are equivalent.	The passenger archetypes are considered sensitive only to these parameters and, therefore, not impacted by other factors (see A13).	Medium
A13	Passenger archetype sensitivity	It is considered that passenger archetypes are sensitive when selecting an itinerary to total travel time, total cost, total emissions and modes of transport (air, rail, multimodal); and possibly to number of connections, total waiting time and buffers and modes.	Total travel time, total cost, total emissions and mode of transport are the key factors influencing the passenger preference for the different alternatives. This is subject to be reviewed and improved in further versions.	Medium
A14	Equivalence of alternatives when planning network	All itineraries within a given cluster (equivalent as defined by A12) are considered equivalent, and passengers are assigned to individual services with the objective of maximising the total number of passengers served.	As per A12 and A13, the passengers are considered not sensitive to parameters not considered in the cluster definition. Therefore, any itinerary within the cluster of equivalent itineraries is considered usable by the passengers from the flow assigned to that cluster.	Low

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A15	Equivalence of alternatives when replanning itineraries	For passengers impacted by a disruption, it is assumed that they no longer consider their preferences in terms of cost, emissions and travel time. All alternatives which take them to their final destination are valid as long as they meet the constraints imposed in the replanning (e.g. maintain (or not) the mode, path, etc.). The objective is to assign the maximum volume of passengers so they can reach their final destination, with the possibility of considering the minimisation of the difference with respect to their initially planned arrival time.	When reassigning passengers being impacted by a disruption in updated flight schedules and rail timetables, the passenger is already on the day of travel (or close). Their preferences were considered when planning the network (before the disruption), but now they just want to get to their final destination as close to their planned time as possible.	Medium
A16	Stock availability	When assigning passengers to itineraries (either in A14 or A15), it is assumed that the stock of seats available per service is accessible through the system. Any required data sharing and coordination are in place (see A5).	When planning the network, the system assumes that multimodal governance exists (e.g. integrated ticketing (see A5)). So, it is assumed that the ticketing system can access seat stocks from all required operators. When replacing the operations due to disruptions, it is assumed that a coordinated approach is performed between operators. Therefore, the required governance should be in place (see A5).	Medium

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A17	Passengers rebooking is feasible	When reassigning passengers to itineraries, it is assumed that there is enough time available to notify and rebook the impacted passengers and that the required data and governance infrastructure are in place. This means that some time is expected to exist since the identification of the disruption (or its forecast) and the implementation of the reallocation of passengers into the modified schedules and timetables.	The Disruption Management Solution can replan the flight and rail operations considering the impact of a current (or forecast) disruption in the system. Passengers impacted by the modified services are rebooked into the available seats by the Strategic Evaluator (A15). The data and governance required are already assumed to be in place (see A5, A16); therefore, the technology required to notify passengers impacted is assumed to be in place. If some time is required, this might impact the look-ahead required to replan operations but not necessarily its outcome.	Low

Table 3: Validation assumptions overview

2.6.3 Validation exercises list

Identifier	TVAL.01.1-MultiModX-0399-TRL2
Title	Validation of the Multimodal Performance Framework
Description	The exercise will consist of: • Presenting the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the relevance and level of the indicators. • Gain insight into the validity of the approach to further develop the indicators beyond the scope of MultiModX.
KPA/TA addressed	• Capacity • Operational Efficiency • Cost Effectiveness • Environment • Interoperability • Passenger Experience
Addressed expected performance contribution(s)	Obtain relevant information from the industry board, stakeholders and experts about the multimodality performance framework.
Maturity level	TRL-2
Use cases	Review Multimodal Performance Indicators, Suggest modifications Multimodal Performance Indicators
Validation technique	Feedback gathering from the stakeholders and experts
Validation platform	Presentation, Open Questions, Voting, Collaborative platform
Validation location	Paris, Rome, London

Start date	• First round:
	  ○ Start date: 01/01/2024
	• Second round:
	  ○ Start date: 01/12/2025

End date	• First round:
	  ○ End date: 30/11/2024
	• Second round:
	  ○ End date: 28/02/2025

Validation coordinator	UoW
Status	Completed
Dependencies	–

Table 4: TVAL.01.1-MultiModX-0399-TRL2 validation summary list

Identifier	TVAL.02.1-MultiModX-0399-TRL2
Title	Simulations of SOL399/SOL1 Strategic and Tactical evaluation of a planned multimodal mobility network
Description	The exercise will consist of: • Executing the model of the strategic and tactical evaluator. • The modelling assumptions will be presented to relevant experts for their validation. • The overall framework will be executed for calibration purposes, and performance computation will be considered. • A full network is to be evaluated both strategically and tactically to show the capabilities of the models to estimate strategic and tactical indicators. • A Schedule Design Solution (SOL400/SOL2) is to be evaluated strategically using the developed pipeline.
KPA/TA addressed	• Capacity • Operational Efficiency • Cost Effectiveness • Environment • Interoperability • Passenger Experience
Addressed expected performance contribution(s)	Provide a platform able to evaluate strategic and tactical multimodal networks, including the usage of Schedule Design Solutions to optimise the coordination of air and rail services.
Maturity level	TRL2
Use cases	Create strategic experiment (with Optimise schedules with Scheduler Designer Solution extension), Execute Strategic Evaluator with strategic experiment, Compute PIs of strategic experiment, Compare strategic experiments performance, Create tactical experiment, Execute Tactical Evaluator with tactical experiment, Compute PIs of tactical experiment, Compare tactical experiments performance.
Validation technique	PIs and KPIs calculation and comparison. Feedback gathering from the stakeholders and experts.
Validation platform	Software, Presentation and Open Questions
Validation location	Rome and online.

Start date	• First round:
	    ○ Start date: 01/04/2024
	• Second round:
	    ○ Start date: 01/12/2024

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End date	• First round:
	  ○ End date: 30/11/2024
	• Second round:
	  ○ End date: 30/04/2025

Validation coordinator	UoW
Status	Completed
Dependencies	The evaluation of Schedule Design Solution (SOL400/SOL2) requires this to be available.

Table 5: TVAL.02.1-MultiModX-0399-TRL2 validation summary list

Identifier	TVAL.03.1-MultiModX-0399-TRL2
Title	Assessment of the impact disruptions on a multimodal mobility network and mechanisms to support multimodality
Description	The exercise will consist of: • Replanning a network considering disruptions with and without the use of a Disruption Management Solution (e.g. SOL401/SOL3) and the computation of replanning indicators. • The possible tactical modelling of the replanned networks to assess tactical multimodal indicators. • The assess of the benefits of Disruption Management Solution (SOL401/SOL3) by comparing the replanning indicators (and the tactical ones if available). • Integration of a mechanism to support multimodality (fast track at airports) into the Tactical Multimodal Evaluator and its assessment by means of a parametric study with different levels of disturbances.
KPA/TA addressed	• Capacity • Operational Efficiency • Cost Effectiveness • Environment • Interoperability • Passenger Experience
Addressed expected performance contribution(s)	Provide a platform able to evaluate the Disruption Managemnt Solutions and the replanning of networks along with the possibility to modify the behaviour of the Tactical Multimodal Evaluator to integrate mechanisms that support multimodality.
Maturity level	TRL2

Use cases	Replan network in case of disruption (including the extension of Replan network with Disruption Management Solution), Compute PIs of the replanned network, Compare replanned networks performance, Create tactical experiment (including the extension Integrate tactical mechanism supporting multimodality), Execute Tactical Evaluator with tactical experiment, Compute PIs of tactical experiment and Compare tactical experiments performance.
Validation technique	PIs and KPIs calculation and comparison
Validation platform	Software
Validation location	N/A

Start date	• First round:
	  ○ Start date: 01/04/2024
	• Second round:
	  ○ Start date: 01/12/2024

End date	• First round:
	  ○ End date: 30/11/2024
	• Second round:
	  ○ End date: 30/04/2025

Validation coordinator	UoW
Status	Completed
Dependencies	The evaluation of Disruption Management Solution (SOL401/SOL3) requires this to be available.

Table 6: TVAL.03.1-MultiModX-0399-TRL2 validation summary list

2.7 Deviations

2.7.1 Deviations with respect to the S3JU project handbook

There are no deviations from the S3JU project handbook

2.7.2 Deviations with respect to the exploratory research plan (ERP)

TVAL.01.1-MultiModX-0399-TRL2

Besides the presentation of the indicators and the framework to MultiModX's Industry Board to validate their definition and gather feedback (as defined in the ERP), SOL399/SOL1 has sought a collaborative process to define and validate the framework in a range of conferences and dedicated workshops.

It is expected that the `Multimodality and Passenger Experience flagship' could continue the development and maintenance of these indicators.

Therefore, the validation has gone beyond a simple consultation with the Industry Board by encompassing a range of relevant stakeholders and supporting a continuous development of the framework.

TVAL.02.1-MultiModX-0399-TRL2

No major deviations have been encountered with respect to the planned activities in the ERP [20]. Some experiments have been adjusted to provide a broader representation of the capabilities of SOL399/SOL1 to assess planned networks. These deviations are as follows:

- Validation of modelling assumptions of the Strategic and Tactical Evaluator - relies on the feedback obtained from the Industry Board (which includes modelling experts), review meetings with the SESAR Joint Undertaking and presentation of the models to relevant research communities and events, such as the SESAR Innovation Days rather than a formal review. All modelling assumptions and improvements are documented.
- Strategic and Tactical evaluation of a mobility network - To fully present the capabilities to analyse strategic planned networks, instead of one, three networks are evaluated (with different policy packages) and compared among them.
- Evaluation of SOL400/SOL2 Schedule Optimiser - focuses on presenting how SOL399/SOL1 is able to compute the performance indicators on the planned network updated with the outcome of the optimisation of schedules performed by SOL400/SOL2. However, the analysis of the potential benefits of SOL400/SOL2 itself is presented in its associated ERR [19].

In terms of technical capabilities, the simulation environment of the Tactical Multimodal Evaluator covers multimodal connections (rail-air) and (air-rail), and on aviation-related connections (air-air). Rail-rail connections are not included in the simulation due to computational and time constraints. These connections have been considered in a post-processing manner.

TVAL.03.1-MultiModX-0399-TRL2

The main deviation with respect to the planned activities is that the replanning of passenger itineraries in case of disruption provided by SOL399/SOL1 can already evaluate different alternatives to manage disruptions without the introduction of SOL401/SOL3. Therefore, the assessment of the replanning capabilities focuses on different types of representative disruptions. The combined disruption of air and rail in the network is not presented, but the capabilities of the model to evaluate both are discussed.

Finally, Experiment 2 has not been executed for this Validation Exercise. Note that this was already considered as a possibility in the original plan (see ERP [18]), and it is not a limitation on the validation of SOL399/SOL1 overall.

Validation results

Summary of project / SESAR Solution 1 validation results

Project / SESAR solution validation objective ID	Project / SESAR solution validation objective title	Project / SESAR solution success criterion ID	Project / SESAR solution success criterion	Project / SESAR solution validation results	Project / SESAR solution validation objective status
OBJ-0399-TRL2-ERP-010	Provide a set of PIs/KPIs for multimodality that capture the system's passenger experience.	**CRT-0399-ERP-010.1**	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the relevance of the indicators by means of PIs prioritisation.	• Performance framework presented to Industry Board and relevant ER and IR projects. • Performance framework partially developed with input from Industry Board and relevant ER and IR projects.	OK
OBJ-0399-TRL2-ERP-020	Categorise the proposed PIs/KPIs suggested in MultiModX's Performance Framework into three levels of development of potential multimodal indicators.	**CRT-0399-ERP-020.1**	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the level of the indicators.	• Categorisation of PIs presented to Industry Board and relevant ER and IR projects.	OK
OBJ-0399-TRL2-ERP-030	Given the input supply, demand, infrastructure, strategic/tactical configuration parameters, and policy packages, compute multimodality strategic and tactical performance indicators.	**CRT-0399-ERP-030.1**	• Modelling assumptions are peer-reviewed and validated by a panel of at least five transport modelling experts. • Key modelling assumptions shall be clearly identified and documented.	• Modelling assumptions for Strategic and Tactical Evaluator presented to relevant experts (Industry Board, scientific community). • Modelling assumptions identified and documented.	OK
		CRT-0399-ERP-	Strategic and Tactical Evaluators calibrated.	• Components of the Strategic Evaluator subject to	OK

		030.2		calibration have been analysed and reviewed. • Tactical Evaluator ground mobility calibrated, and gate-to-gate mobility previously calibrated.	
		CRT-0399-ERP-030.3	A strategic experiment (without the Schedule Design Solution (SOL400/SOL2) is set up and executed with the Strategic Multimodality Evaluator, and strategic multimodality-related PIs are measured.	• Baseline (cs10.pp00.nd00.so00.00), incentivised policies (cs10.pp10.nd00.so00.00), and enforced policies (cs10.pp20.nd00.so00.00) executed, PIs computed with focus on different aspects (regions, infrastructure, passenger mobility, etc).	OK
		CRT-0399-ERP-030.4	A tactical experiment is set up and executed with the Tactical Multimodality Evaluator, and tactical multimodality-related PIs are measured.	• The baseline scenario has been executed tactically (cs10.pp00.nd00.so00.00) with a focus on multimodal connectivity indicators.	OK
OBJ-0399-TRL2-ERP-040	Evaluate the performance of the Schedule Design Solution (SOL400/SOL2).	**CRT-0399-ERP-040.1**	• Set an experiment without Schedule Design Solution (SOL400/SOL2), and execute it to generate the inputs that SOL400/SOL2 requires and to compute multimodality-rated	• Scenario for baseline policies (pp00) and enforced policies (pp20) have been executed without and with SOL400/SOL2 (cs10.pp00.nd02.so00.00,	OK

			PIs with a focus on strategic multimodality-related PIs, as these are the ones required to validate SOL400/SOL2, see [21]; the experiment could be evaluated by the Tactical Multimodality Evaluator to assess tactical PIs to assess how the network would materialise, but this is not required for the validation of SOL400/SOL2 and therefore not a strict requirement to meet this criteria. • Generate updated flight schedules and rail timetables computed with Schedule Design Solution (SOL400/SOL2) (see [21]). • Update the experiment with the updated flight schedules and rail timetables, execute it and compute multimodality-rated PIs as for the experiment without the Schedule Design Solution (SOL400/SOL2). • The performance of the Schedule Design Solution (SOL400/SOL2) is evaluated by	cs10.,pp20.nd02.so00.00, and cs10.pp00.nd02.so10.02, cs10.,pp20.nd02.so10.01). • Strategic PIs have been computed and compared across the experiments. • In addition, these four scenarios have been executed tactically with a sensitivity analysis on passenger missing connections as a function of ground mobility delay for the case with enforced policies (pp20). • A comparison of the results between strategic and tactical indicators is also provided.	

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			comparing PIs for the two experiments.		
OBJ-0399-TRL2-ERP-050	Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries.	**CRT-0399-ERP-050.1**	• Set two experiments to replan the network considering the disruptions, with and without the use of a Disruption Management Solution (e.g. SOL401/SOL3) and use the replanning capabilities of the Multimodal Evaluator to reassign passengers in the network. • Compute PIs on the replanned networks with a focus on replanned multimodal indicators. This computation is to be done on the replanned network obtained from the previous step. The replanned network could be further evaluated tactically computing tactical multimodal indicators by means of the Tactical Multimodal Evaluator. This will allow us to assess how the replan network materialises. However, this is not a requirement for the	• Scenarios with different type of disruptions: rail links and airport closures, industrial actions, and reduced capacity have been evaluated by SOL399/SOL1. • Different replanning of passengers alternatives are considered. • Disruption management initiatives by introducing new services and by applying SOL401/SOL3 have been assessed. • Mobility PIs with a focus on passenger-centric are estimated for the different scenarios enabling the comparison of alternatives.	OK

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			satisfaction of this criteria as the replanned network can already be assessed, and the capabilities of SOL399/SOL1 to evaluate the tactical materialisation of a (re)planned network is already covered by CRT-0399-ERP-030.04. • Compare the results of the PIs of the two related networks to assess the benefit of the Disruption Management Solution.		
OBJ-0399-TRL2-ERP-060	A mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports is evaluated by the Tactical Evaluator.	**CRT-0399-ERP-060.1**	• Two tactical experiments are set up, one with and one without the mechanism activated, and are executed with the Tactical Evaluator and tactical multimodality-related PIs computed. • The performance of the system, with a focus on passenger-centric metrics, is compared across the two experiments to assess the benefit of the mechanism.	• Scenario cs10.pp20.nd02.so10.01 with 30 minute ground mobility delay executed with an airport pre-departure fast-track mechanism. • PIs for passengers with missed connections have been calculated to assess the benefit of the mechanism.	OK

Table 7: Summary of validation exercises results

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Detailed analysis of project / SESAR solution validation results per validation objective

OBJ-XX-TRLx-ERP-001 results

Objective: Provide a set of PIs/KPIs for multimodality that capture the system's passenger experience.

Validation: Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the relevance of the indicators by means of PIs prioritisation

The multimodal performance framework has been developed by MultiModX in continuous collaboration with relevant stakeholders, ER and IR projects. This has ensured that EXE01-CRT-0399-ERP-010.1 is satisfied, as the involvement of these relevant actors goes beyond the presentation of the KPAs/KPIs/PIs to at least 20 relevant stakeholders from the Industry Board to gain feedback and identify the relevance of the indicators by means of PIs prioritisation as done at different stages in the project (First and Second Industry Board meetings).

OBJ-0399-TRL2-ERP-020 Results

Objective: Categorise the proposed PIs/KPIs suggested in MultiModX's Performance Framework into three levels of development of potential multimodal indicators.

Validation: Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the level of the indicators.

The indicators have been presented to the Industry Board and relevant stakeholders to help identify their development level. Note that the framework, in some aspects, goes beyond multimodality to include elements of passenger experience and support other ER and IR projects. All these activities are compiled in the performance indicator digital catalogue, which is publicly accessible at https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY (Accessed November 2025).

OBJ-0399-TRL2-ERP-030 Results

Objective: Given the input supply, demand, infrastructure, strategic/tactical configuration parameters, and policy packages, compute multimodality strategic and tactical performance indicators.

Validation: The experiments carried out in the validation exercise address the SESAR solution success criteria in the following manner:

- Experiment 1: EXE02-CRT-0399-ERP-030.1 (modelling assumptions),
- Experiment 2: EXE02-CRT-0399-ERP-030.2 (models calibrated),
- Experiment 3: EXE02-CRT-0399-ERP-030.3 (strategic evaluation of network without SOL400/SOL2) and EXE02-CRT-0399-ERP-030.4 (tactical evaluation of network without SOL400/SOL2)

The activities performed in Exercise 1 aimed at satisfying the success criteria EXE02-CRT-0399-ERP-030.1. This required that modelling assumptions were peer-reviewed and validated by a panel of at least five transport modelling experts and for key modelling assumptions to be clearly identified and documented. We consider that this has been achieved as more than five transport modelling have been presented with the modelling approach and methodology and feedback obtained. This has been performed by a set of continuous verification and validation activities. Moreover, one could consider this to be an ongoing process with further presentation of the modelling to relevant experts (e.g. at the Euro Working Group on Transportation (EWGT) and SESAR Innovation Days (SIDs) conferences), and with the identification of mobility aspects to be improved in the future.

The activities conducted in Experiment 2 satisfy the criteria EXE02-CRT-0399-ERP-030.2 as both the Strategic and Tactical Evaluators have been calibrated for nominal conditions.

The activities conducted in Experiment 3 satisfy the criteria EXE02-CRT-0399-ERP-030.3 as the Strategic Multimodal Evaluator has been executed successfully for baseline (cs10.pp00.nd00.so00.00), incentivised policies (cs10.pp10.nd00.so00.00), and enforced policies (cs10.pp20.nd00.so00.00) together with a range of PIs computed.

The Tactical Multimodal Evaluator has been executed with the baseline (cs10.pp00.nd00.so00.00) scenario thus satisfying the criteria EXE02-CRT-0399-ERP-030.4.

The Multimodal Evaluators enable the estimation of a range of indicators which can be disaggregated (or analysed) at different levels. When indicators are considered at network-level, the vision tends to be partial, but by combining the findings of different indicators, it is possible to capture the impact of policies (and different planned networks) from a mobility, passenger, service (flight and rail), infrastructure (airports and rail stations) and regions perspective.

OBJ-0399-TRL2-ERP-040 Results

Objective: Evaluate the performance of the Schedule Design Solution (SOL400/SOL2).

Validation: The validation of this Objective is achieved through the implementation of Experiment 4, described in Section B.1.1. of the Annex B.

The activities conducted in the experiment satisfy the criteria EXE02-CRT-0399-ERP-040.1 as the scenarios for baseline policies (pp00) and enforced policies (pp20) have been executed without and with SOL400/SOL2 (cs10.pp00.nd02.so00.00, cs10.,pp20.nd02.so00.00, and cs10.pp00.nd02.so10.02, cs10.,pp20.nd02.so10.01). The scenarios have been compared in terms of both strategic and tactical performance.

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OBJ-0399-TRL2-ERP-050 Results

Objective: Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries.

Validation criteria:

The activities conducted in the experiment satisfy the criteria EXE02-CRT-0399-ERP-050.1. It has been shown how SOL399/SOL1 can evaluate scenarios with different types of disruptions: rail links and airport closures, industrial actions, and reduced capacity. Different replanning of passenger alternatives have been considered by SOL399/SOL1. The replanning of operations by SOL401/SOL3 has been assessed by SOL399/SOL1. The different scenarios have been compared by calculating passenger-centric mobility PIs.

OBJ-0399-TRL2-ERP-060 Results

Objective: A mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports is evaluated by the Tactical Evaluator.

Validation criteria:

The activities conducted in the experiment satisfy the criteria EXE02-CRT-0399-ERP-060.1 as a fast-track to process passengers at the airport pre-departure has been used as a tactical disruption management mechanism for scenario cs10.pp20.nd02.so10.01 with 30 minute ground mobility delay. The scenario with and without the mechanism have been compared in terms of passengers with missed connections to assess the benefit of the mechanism.

Confidence in validation results

Limitations of validation results

We acknowledge that the Spanish air and rail networks offer some limitations in showcasing multimodality. Due to the size of the country and the availability of options, most trips are single-mode with a strong prevalence of rail itineraries. This is mitigated by the use of policy packages that force multimodality, e.g. with the ban of short-haul flights and with the consideration of longer distance trips such as to-from the Canary Islands from the peninsular regions in Spain.

The capacity of the indicators to capture the effect of multimodality is, therefore, limited in some aspects. However, interesting trends and patterns emerge that can be captured by the model (e.g. the relevance of regional airports as connecting nodes when flight bans are in place). The inclusion of international trips will support a deeper analysis of the impact of multimodality, showcasing the relevance of international hubs. This is, therefore, a priority for future work. However, the cases analysed are sufficient to show the capabilities of SOL399/SOL1 to analyse the mobility scenarios both strategically and tactically.

Besides the validation of SOL399/SOL1 to assess replanned networks produced by SOL401/SOL3, some further work could be done to ensure the full compatibility of the assumptions modelled within

SOL401/SOL3. That would allow a deeper analysis of the benefits of SOL401/SOL3. In its current form, we have been able to validate SOL399/SOL1 to assess the outcome of SOL401/SOL3, but the benefits of the solution are left to the ERR of SOL401/SOL3, see [26].

The re-evaluation of the replanned network by the Tactical Multimodal Evaluator would allow us to assess the robustness of the replanning and could provide a better insight into the benefits of the replanning with respect to the baseline of doing nothing. This, however, could be partially limited due to the non-modelling of rail-rail disruptions within the Tactical Multimodal Evaluator, which focuses on the air-air and multimodal connections and relies on already modified rail inputs.

Finally, an overall improved baseline of the operations disrupted if no disruption management is used could be considered as in the current version it is assumed that the impact of the disruption in terms of replanning of the network is available (or provided by SOL401/SOL3).

Quality of validation results

The quality of the results for the validation of the performance framework is influenced by the number of stakeholders involved. We consider that key relevant actors have been involved with an adequate cross-section. Further work could be done to extend the framework with other modes.

We consider that there are no issues regarding the quality and accuracy of the results.

Some of the results show that further work might be required to adjust some of the model input parameters. For example, the unsatisfied demand between selected origin-destination pairs seems too high; this could be due to the use of a subset of trains available (Renfe) or an overestimation of the demand between the regions. Likewise, as shown, the logit model might select in high numbers an option with limited capacity (leading to unsatisfied demand), while extra capacity is provided by different alternatives which are not used. This could be considered by SOL400/SOL2 to adjust the supply with additional services (or reallocation of services) on those over-demanded paths; a different iterative approach to assign demand to alternatives could also be explored in the future.

The Tactical Multimodal Evaluator could be extended to include rail-rail connections, even though the current focus is on air and multimodal mobility.

These highlighted aspects are not significant to, once again, show how SOL399/SOL1 is able to assess a planned network (with and without SOL400/SOL2) both strategically and tactically.

The quality of the replanning relies on the planned network; therefore, some of the limitations observed above could also apply here. For example, some of the model input parameters when building the planned network could be reviewed. The results found in this exercise show the importance of the access/egress areas of airports when considering alternative routes. This could be reviewed in the future, and the model could penalise changes in departing and arrival nodes if they require significant ground access/egress change (in distance and/or time) with respect to the originally planned itinerary, even if feasible.

With the maximum flexibility to reaccommodate passengers evaluated, passengers depart from their origin much earlier than initially planned to reach their destination. A parametric analysis by limiting this maximum earlier departure time could provide interesting insight into the required look-ahead notification to passengers to reroute their itineraries. This is not a limitation on the quality of the results but a highlight of possible future analysis that could be done with the current model.

These aspects are not significant to, once again, show how SOL399/SOL1 is able to assess a replanned network under different levels of flexibility to reaccommodate impacted passengers.

When evaluating the recurrent output of SOL401/SOL3, the replanning of rail operations can lead to a significantly high number of accommodated passengers who might be delayed instead. This however, should not impact in a significant way the results in terms of passenger-centric metrics (delays, number of stranded passengers, etc.).

Significance of validation results

The different maturity levels of the indicators accounts for different capabilities to measure and estimate them.

Operational significance has already been discussed in section B.3.4.1. (Level of significance/limitations of validation exercise results).

Conclusions and recommendations

Conclusions

Conclusions on project/ SESAR solution maturity

All the validation criteria have been met showcasing the effort put into the maturity of the Solution. SOL399/SOL1 provides three distinct but complementary elements: a performance framework, a Strategic Multimodal Evaluator and a Tactical Multimodal Evaluator. All these elements have been improved from previous projects.

The multimodal performance framework has been built on previous literature but has also been developed partially in a collaborative approach involving relevant stakeholders and ER and IR projects. It can hopefully become a base for a permanent digital catalogue of indicators.

The Strategic Multimodality Evaluator has shown its capabilities to assess both planned and replanned multimodal networks. It provides an open platform able to assess from schedules and timetable changes (as produced by SOL400/SOL2) to policies (such as flight bans or integrated ticketing), infrastructure improvements (access and degrees or minimum connecting time modifications), or even the impact of disruption on passenger itineraries and, potentially the adjustment of the network to minimise their impact (as produced by SOL401/SOL3). This mobility-network-wide analysis is an advancement with respect to previous tools available to the community.

Finally, the Tactical Multimodal Evaluator has shown how the ABM Mercury is now able to simulate multimodal (air-rail, rail-air) connections even when infrastructure nodes are not collocated. This facilitates the evaluation of the robustness of planned networks but also the assessment of mechanisms (and Solutions) which could impact passenger connectivity. Mercury has already been validated in the past as a useful tool to assess SESAR Solutions, now it extends those capabilities to kerb-to-kerb and multimodal aspects.

The inclusion of internal and external experiments, along with the Maturity Self-Assessments, supports that the Solution reaches TRL2.

SOL399/SOL1 provides, therefore, a standalone Solution for the transversal evaluation of multimodality. The performance framework can be used for different SESAR projects enabling the comparison of results across research activities and Solutions. The Strategic and the Tactical Multimodal Evaluators are tools which support external Solutions on their evaluation with more advanced performance evaluation capabilities that those Solutions could have on their own. As such, these evaluation tools are already functional.

2.7.3 Conclusions on concept clarification

SOL399/SOL1 matured the concept of the multimodal performance framework. The developed data catalogue is a starting point for future work on aspects of multimodality and passenger experience performance assessment which can, hopefully, be reused and further extended by subsequent projects.

The Strategic Multimodal Evaluator and Tactical Multimodal Evaluator for Strategic Multimodal Evaluation and Tactical Multimodal Evaluation have been validated when assessing a planned multimodal mobility network, including the integration of optimised schedules (i.e., from SOL400/SOL2). The experiments showed that the proposed framework is capable of a performance assessment of a Schedule Optimiser solution.

The Strategic Multimodal Evaluator has been validated when assessing a replanned multimodal mobility network subject to different types of disruptions and flexibility to reaccommodate passengers and management actions (such as the replanning of operations by SOL401/SOL3). Moreover, it has been shown how the Tactical Multimodal Evaluator is able to assess mechanisms to support multimodality, evaluating their benefits when applied on a given (re)planned network.

Conclusions on technical aspects

This validation exercise confirmed the functional requirements indicated in the Functional Requirements Document (FRD).

Conclusions on performance assessments

As discussed in the ECO-EVAL, the Performance Assessment Solution (SOL399/SOL1) aims to evaluate the performance of a planned multimodal mobility network and other multimodal Solutions (such as SOL400/SOL2). This was demonstrated through PIs of the multimodal performance framework, which showed the performance in the KPAs such as a positive impact of SOL400/SOL2 on efficiency, reducing buffer times and total journey times.

The exercise shows how SOL399/SOL1 can provide estimations of the indicators defined in the multimodal performance framework.

Finally, it is worth reminding the reader that results show the importance of disaggregating the indicators on specific cases to fully understand the impact of mechanisms (e.g. policies, schedulers (such as SOL400/SO2)). Otherwise, network-wise indicators tend not to vary in a significant way while mobility patterns are actually emerging in selected sub-operational environments (e.g. hub airports, airports affected by flight bans, and regional airports).

As discussed in the ECO-EVAL, the Performance Assessment Solution (SOL399/SOL1) can assess replanned networks from a passenger-centric perspective and, in particular, replanned networks considering disruptions and optimised by disruption management Solutions (such as SOL401/SOL3). This has been demonstrated through the use of the Strategic Multimodal Evaluator capabilities to assess a range of disruptions under different replanning of passengers assumptions, and considering also the replanned network by SOL401/SOL3.

Moreover, this exercise has validated the capabilities of SOL399/SOL1 to assess the performance of multimodal mechanisms to support these types of connections with the Tactical Multimodal Evaluator.

The exercise shows how SOL399/SOL1 can provide estimations of the indicators defined in the multimodal performance framework in particular those that are passenger-centric and passenger-experience related.

It is worth reminding the reader that results show the importance of disaggregating the indicators on specific cases to fully understand the impact of the replanned operations, particularly looking at specific origin-destination 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 sub-operational environments (e.g. islands, hubs) can (or not) support the disrupted passengers.

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), but as previously discussed, further potential considerations could be analysed.

Recommendations

Recommendations for next R&I phase

The Multimodality and Passenger Experience 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. 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.

If some of the indicators defined in the Multimodality Performance Framework are promoted to the SESAR Performance Framework, particular focus will be required to identify the data sources that will be used for their evaluation. In the case of MultiModX (and other research projects and validation activities for Solutions), these indicators can be estimated from the modelled (and simulated) data. However, in real operations, new datasets will be required, particularly with respect to passenger-centric metrics (e.g. missed connections between modes). There is a need to address data gaps in multimodal journeys, particularly where direct input from transport operators is limited and some modelling might be required.

SOL399/SOL1 provides a set of tools for the evaluation of Solutions, mechanism and even policies in a full air-rail multimodal context considering the strategic (planning and replanning) and tactical (execution) phases. Due to the nature of multimodality, the key indicators impacted by these Solutions are passenger centric. Therefore, the modelling of passenger itineraries is critical to obtain results that are relevant. For this reason, there is a need for enhancing datasets available for external Solutions who want to be evaluated in the context of multimodality. This will be required if the benefits of those Solutions are to be compared in a standardised manner, i.e., they need to consider not only similar traffic but also similar passenger itineraries during their validation.

As discussed, the Strategic Multimodal Evaluator and the Tactical Multimodal Evaluator have already proven their capabilities to support the validation of external Solutions, reaching, therefore an operational TRL. However, there are improvements that could be further developed to produce more accurate results as captured in Section 5.2.2.

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Finally, some elements of the Evaluators could independently evolve to be developed as new Solutions. For example, the replanning capabilities of the Strategic Multimodal Evaluator to identify suitable alternatives for passengers impacted by disruptions could be the base for new Solutions which support disruption management (e.g. identifying the criticality of flights with respect to the impact on passengers journeys if cancelled, or assessing the suitability of alternative airports for diversions considering passengers needs to fulfil their journey potentially in a complementary network, such as rail); the Tactical Multimodal Evaluator could further be developed to support operational decision making processes, such as being integrated within a digital twin of airports to provide advice to the Airport Operation Centre (APOC) on how to manage their resources to minimise passengers missing their multimodal connections.

Recommendations for future R&I activities

The different recommendations for future R&I activities are presented per component of SOL399/SOL1:

- **Multimodal Performance Framework:** A governance and procedure for maintaining and updating the framework should be developed. It is encouraged for the `Multimodality and Passenger Experience flagship' to take the role of caretaker and continue the development and maintenance of these indicators. 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. These could then be used for current and future ER and IR projects. This catalogue should help to 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.
- **Strategic Multimodal Performance Evaluator:** There are different aspects that could be considered as future lines of research to be conducted by the Strategic Multimodal Performance Evaluator. Here a few key aspects are highlighted:
  - Some general improvements could be considered:
    - More accurate emissions and costs associated with access and egress.
    - The replanned rail services from SOL401/SOL3 could be processed so that the affected passengers can be identified as delayed instead of replanned
    - Improved inputs for the models (e.g. adjusting the demand and supply for some particular origin-destination pairs).
  - For the analysis of planned networks:
    - Not only developing international flight cases (which is a change on the input in the current model) but also considering how competition within international hubs can drive passengers in the case of long-haul distance mobility.
    - Additional modes could be incorporated, such as long-distance buses. This will provide a more comprehensive view of the mobility in the region under study.
  - For the analysis of replanned networks:
    - The model could be extended to consider the actions of stakeholders in case of disruptions beyond the cancellation and delay (as planned by the

disruption). This would provide a better baseline to compare any possible replanning alternative.
        - Not only the possibility of replanning passengers subject to some constraints should be considered (as is currently the case), but some agency on the passenger to select those alternatives could also be incorporated, i.e., adding the preference of passengers to alternatives.
        - Parametric analysis could be performed to assess the sensitivity of these factors when reallocating passengers in the disrupted network. Examples of such parameters could include how much earlier a passenger is allowed to depart their origin or how much spare capacity is available in the system.
- **Tactical Multimodal Performance Evaluator:** The different aspects that could be considered as future lines of research to be conducted by the Tactical Multimodal Performance Evaluator include:
    - Some general improvements on the current model such as:
        - Including rail-rail connections in the simulation instead of using post-processing for these.
    - Rebooking of passengers during simulation through external disruption management solutions.
    - Passenger archetypes could be linked to different ground mobility transport modes. This will enable the selection of ground mobility transport mode as a function of the passenger characteristics, supporting the multimodal connections, as in the case of the disruption management mechanism.
    - Finally, Mercury incorporates the behaviour of air stakeholders to manage delays (e.g. airlines might decide to wait for inbound delayed passengers or to adjust their flight to recover delay with dynamic cost indexing). Similarly, a degree of agency could be provided to the rail operator to manage the rail network dynamically. This would produce a richer view of the whole mobility network.

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Applicable documents

This ERR complies with the requirements set out in the following documents:

SESAR solution pack

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Content integration

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Validation

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System engineering

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[10] AMPLE3 -- SESAR3 ATM Master Planning and Monitoring -- https://cordis.europa.eu/project/id/101114738https://cordis.europa.eu/project/id/101114738

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Appendix A Validation exercise #01 report

Appendix B Summary of the validation exercise #01 plan

The validation exercise follows in its principles the one presented in the ERP SESAR Solution SOL399/SOL1.

Appendix C Validation exercise description and scope

This validation exercise presented the results of the multimodal performance framework to a board of at least 20 stakeholders and experts (including exchanges with other relevant research projects (e.g. AMPLE3, PEARL)) to assess:

- the relevance of the multimodal KPAs, KPIs and PIs defined.
- the feasibility of computation and estimation, as modelling and monitoring, whilst differentiating between the strategic and the tactical phases.

The validation techniques included a presentation and gathering feedback from the Industry Board, stakeholders, and experts. In addition, a collaborative space set up within Confluence (a wiki-type collaborative site) was created together with other research projects (e.g. SIGN-AIR, MAIA).

It is worth noting that MultiModX is defining a framework to define the indicators and that this is partially a collaborative effort across projects involved in multimodality and passenger experience. For this, not only are indicators defined but a digital catalogue and methodology to manage the indicators is developed.

Appendix D Summary of validation exercise #01 validation objectives and success criteria

SESAR Solution validation objective	SESAR Solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
EXE01-OBJ-0399-TRL2-ERP-010	EXE01-CRT-0399-ERP-010.1	Fully covered	Provide a set of PIs/KPIs for multimodality that capture the system's passenger experience.	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 stakeholders to gain feedback and identify the relevance of the indicators by means of PIs prioritisation.

EXE01-OBJ-0399-TRL2-ERP-020	EXE01-CRT-0399-ERP-020.1	Fully covered	Categorise the proposed PIs/KPIs suggested in MultiModX's Performance Framework into three levels of development of potential multimodal indicators.	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 stakeholders to gain feedback and identify the level of the indicators.

Table A1 Validation objectives for the exercise #01

Appendix E Summary of validation exercise #01 validation scenarios

For the multimodality performance framework, the experts were encouraged to consider multimodal operations in 2035.

In this case, the Solution scenario assumes that the multimodal performance framework is available, i.e., indicators defined, indicators catalogue available, etc. and that research projects can use these definitions for the validation of their Solutions.

The scope of application for the performance framework is European mobility.

Appendix F Summary of validation exercise #01 validation assumptions

No extra assumptions are needed for this exercise.

Appendix G Deviation from the planned activities

Besides the presentation of the indicators and the framework to MultiModX's Industry Board to validate their definition and gather feedback (as defined in the ERP), SOL399/SOL1 has sought a collaborative process to define and validate the framework.

This means that two Industry Board workshops have been held, but also:

- A poster presentation with a survey at the SESAR Innovation Days (2024) [8].
- A workshop on 'Multimodality and passenger experience in the SESAR Performance Framework', 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 [9], AMPLE3 [10], SIGN-AIR [11] and Travel Wise [12] projects. This extended the scope of the performance framework from purely multimodality to passenger experience, and from focusing solely on multimodal mobility performance to consider the relationship and integration with the SESAR3 Performance Framework.
- A summary of findings from the workshop in a document: 'Multimodality and passenger experience in the SESAR performance Framework' [13],

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- A digital catalogue describing the different indicators and accessible to other stakeholders and projects, currently: MultiModX, SESAR 3 Scientific Committee, PEARL, SESAR3 Joint Undertaking Multimodality and Passenger Experience flagship, SIGN-AIR and MAIA.

It is expected that the `Multimodality and Passenger Experience flagship' could continue the development and maintenance of these indicators.

Therefore, the validation has gone beyond a simple consultation with the Industry Board by encompassing a range of relevant stakeholders and supporting a continuous development of the framework.

Appendix H Validation exercise #01 results

Appendix ISummary of validation exercise #01 results

Exercise #01 validation objective ID	**Exercise #01 validation objective title**	**Exercise #01 success criterion ID**	**Exercise #01 success criterion**	**Sub-operating environment**	**Exercise #01 validation results**	**Exercise #01 validation objective status**
EXE01-OBJ-0399-TRL2-ERP-010	Provide a set of PIs/KPIs for multimodality that capture the system's passenger experience.	EXE01-CRT-0399-ERP-010.1	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the relevance of the indicators by means of PIs prioritisation.	N/A	• Performance framework presented to Industry Board and relevant ER and IR projects. • Performance framework partially developed with input from Industry Board and relevant ER and IR projects.	OK
EXE01-OBJ-0399-TRL2-ERP-020	Categorise the proposed PIs/KPIs suggested in MultiModX's Performance Framework into three levels of development of potential multimodal indicators.	EXE01-CRT-0399-ERP-020.1	Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the level of the indicators.	N/A	• Categorisation of PIs presented to Industry Board and relevant ER and IR projects.	OK

Table A2 Validation exercise #01 results

Appendix J Analysis of validation exercise #01 results per validation objective

A.3.2.1 OBJ-0399-TRL2-ERP-010 Results

Objective: Provide a set of PIs/KPIs for multimodality that capture the system's passenger experience.

Validation: Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the relevance of the indicators by means of PIs prioritisation.

MultiModX has conducted a set of workshops, meetings and activities to support the definition of a methodology to define performance indicators in the framework of multimodality and passenger experience (as supported by the Passenger Experience and Multimodality Flagship).

A.3.2.1.1. Activities performed for the definition of performance indicators

The first Industry Board workshop was held in Paris on the 20th of February 2024 to discuss and prioritise the candidate performance indicators. A follow-up workshop was held in Rome on the 12th of November 2024, where the capabilities of the models to capture indicators were presented and, therefore, the indicators and their benefits were reviewed.

In order to support the definition of the methodology for the performance framework and to gather feedback on the indicators, a poster was displayed at the SESAR Innovation Days (2024) in Rome (November 2024) with a survey, and a follow-up workshop on 'Multimodality and passenger experience in the SESAR Performance Framework' was held on the 15th of January 2025 (at the University of Westminster, London). This workshop was attended by relevant stakeholders (e.g. SESAR Joint Undertaking, EUROCONTROL) and members of ER and IR projects which relate to multimodality and passenger aspects: MultiModX, PEARL, AMPLE3 and SIGN-AIR projects. Besides the classification of the indicators at different levels (as shown in Section A.3.2.2), the workshop also helped to define relevant performance indicators.

A digital catalogue of indicators has been set up in a space in Confluence managed by Nommon, a wiki-like collaborative site (https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY). Note that currently, members of MultiModX, SESAR 3 Scientific Committee, PEARL, SESAR3 Joint Undertaking Multimodality and Passenger Experience flagship, SIGN-AIR and MAIA have access as contributors to the collaborative site, while the catalogue is accessible via the link publicly in view mode. This digital catalogue defines, therefore, a live document which is expected to evolve as different projects define and re-utilise the performance indicators. Finally, it is worth mentioning that the code of MultiModX Evaluators (which includes the implementation of the indicators) will be made public in the project GitHub repository (https://github.com/UoW-ATM/MultiModX).

In the subsequent section we present the outcome of some of the activities performed with the framework. The indicators themselves are described as part of A.3.2.2., as they include their classification between the different levels.

A.3.2.1.2. Results of activities and methodology

KPA	PI	Votes
Interoperability Interoperability	Seamless of travel (time)	4
	Seamless of travel (number of legs)	6
	Modal share	4
Environment	CO_2 emissions	1
	Non-CO_2 emissions	1
Flexibility	Diversity of destinations	2
	Resilience	11
Predictability	Variability	6
Capacity	Average en-routue ATFM delay	0
	Average airport ATFM delay	0
	Number of cancellation	1
	Minutes of delay	1
	Number of passengers per route	2
	Peak runway throughput	0
Cost effectiveness	Direct air navigation services costs	0
	Direct operating cost per user	6
Efficiency	Journey duration	15
	Passengers time efficiency	11

Table A3 Indicators considered during the First Industry Board workshop

Table A3 presents the preliminary list of indicators considered during the First Industry Board workshop. As shown, the most relevant PIs focus on identifying how the passengers experience the journey. It is worth noting that some already-adopted indicators (e.g. Average en-route ATFM delay) received zero votes ***in this context.***

The workshop also highlighted that no PI captures multimodality from an ATM perspective and that there should be a focus on *Efficiency* with *Passenger satisfaction* as a focus (Predictability, Resilience (passengers reaching their destination as seamlessly as possible), door-to-door time).

In order to align the performance framework with the SESAR3 Performance Framework a methodology composed of three levels was defined:

- Indicators at Level 1 are indicators currently part of the SESAR3 Performance Framework. These indicators have, by their nature, a stronger focus on the gate-to-gate component of the passenger journey.
- 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.
- 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.

Note that a given indicator could have different variations which could be at different levels.

The resulting performance indicators developed in MultiModX are a combination of those defined by the project (with the input and validation of the Industry Board) and the ones developed collaboratively in the 'Multimodality and passenger experience in the SESAR Performance Framework'. The details on these are provided in A3.2.2.2. along with their classification in the different levels.

A.3.2.1.3. Conclusions on OBJ-0399-TRL2-ERP-010

The multimodal performance framework has been developed by MultiModX in continuous collaboration with relevant stakeholders, ER and IR projects. This has ensured that EXE01-CRT-0399-ERP-010.1 is satisfied, as the involvement of these relevant actors goes beyond the presentation of the KPAs/KPIs/PIs to at least 20 relevant stakeholders from the Industry Board to gain feedback and identify the relevance of the indicators by means of PIs prioritisation as done at different stages in the project (First and Second Industry Board meetings).

A.3.2.2. OBJ-0399-TRL2-ERP-020 Results

Objective: Categorise the proposed PIs/KPIs suggested in MultiModX's Performance Framework into three levels of development of potential multimodal indicators.

Validation: Present the KPAs/KPIs/PIs to the Industry Board of at least 20 relevant stakeholders to gain feedback and identify the level of the indicators.

A.3.2.2.1. Activities performed for the categorisation of the performance indicators

The 'Multimodality and passenger experience in the SESAR Performance Framework' workshop was held on 15 January 2025 (at the University of Westminster, London), attended by members of the MultiModX, PEARL, AMPLE3, SIGN-AIR and Travel Wise projects and relevant stakeholders.

Besides the classification of the indicators at different levels (as shown in Section A.3.2.2), the workshop also helped to define relevant performance indicators by describing them based on:

- indicator name,

- level of maturity,
- why they are relevant to passengers,
- why they are relevant to ATM,
- data sources needed to compute/estimate them,
- their scope and how to develop them further.

Note that the multimodal performance catalogue is a live document and that not all the indicators discussed in the workshop are relevant (or can be implemented) by the Multimodal Performance Evaluator framework of MultiModX (as some of them relate to the more broad 'Passenger experience' KPA and are beyond the scope of MultiModX).

The 'Multimodality and passenger experience in the SESAR Performance Framework' workshop described in Section A.3.3.1.1 also supported the classification of indicators in different maturity levels. Beyond this, the indicators with their levels are compiled in the performance indicators digital catalogue, as presented in Section A3.2.1.1.

As introduced in Section A.3.2.1.2, Level 1 is a selection of indicators from the current SESAR3 Performance Framework with an indication of the potential impact of multimodality on them.

Level 2 is divided into two categories: Level 2.1, with the indicators selected in the above-mentioned workshop as candidates to be promoted to Level 1; and Level 2.2, which contains indicators currently modelled/considered by different SESAR Solutions (and projects).

Finally, Level 3 is reserved for more ambitious indicators that aim to capture the total experience of passengers in their door-to-door journey.

It is worth noting that from the workshop, it was established that the difference between Level 2.2 and Level 3 is not entirely well-defined for individual indicators. For example, the number of missed connections can be Level 2.2 if we consider air-to-air connections, as it can readily computed from the existing data available; while multimodal connections (rail-to-air and air-to-rail) require additional data sources, which are usually not available in operational data but can be modelled and, as such, represent Level 3. These differences are captured in the catalogue via sub-variants of the indicators.

It was flagged that further consideration needed to be given to which of these indicators were essentially describing potential connectivity, etc., and were thus actually 'capability' descriptors rather than performance metrics *per se*.

Most of these indicators rely on modelling (as data are not available) and, ideally, estimation of passenger itineraries. Some concepts still need further development and more specific definitions, such as 'origin' and 'destination'. The scope of what is considered inside the system and the corresponding assessment needs further consideration. Furthermore, the measurement of passenger experience should ideally be based on passenger surveys rather than proxy measures of assumed utility. All these aspects are under continuous review in the digital catalogue of indicators.

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A.3.2.2.2. Results of categorisation

Level 1

The analysis of the SESAR3 Performance Framework indicators is available in the digital catalogue. These indicators have, by their nature, a focus on the gate-to-gate component of the passenger journey. The analysis performed in MultiModX focuses on identifying how multimodality could impact the SESAR Performance Framework's currently considered PIs and KPIs either directly or by impacting some of the Influence Factors of the indicators.

The potential impacts of multimodality on the KPAs/KPIs/PIs defined in the Performance Framework are qualitatively classified as:

- N/A: Not applicable (no impact expected on this KPA/KPI/PI due to multimodal operations);
- Weak: There could be some impact but in an indirect way (usually due to changes in operations to account for changes in demand/supply);
- Medium: Some impact could be expected (in some cases, depending on how multimodality is implemented);
- High: It is expected that multimodality would impact this KPA/KPI/PI

Overall, for the majority of indicators, multimodality is *not applicable* (77), or *weak* (11 indicators). 12 indicators are considered with a *medium* possible impact. Note that this might depend on how multimodality is implemented. For example, if flights actively wait for delayed multimodal connecting passengers, that could have an impact on PUN1 (Departure punctuality). Most of these impacts are expected in the KPA of Operational Efficiency affecting the predictability of operations if flights are managed considering multimodality.

Finally, 10 indicators might be impacted in a *high* manner by multimodality. Most of them (7) are in the Cost-Effectiveness area, as it is expected that managing multimodal passengers will result in a cost for the operators, including the cost of rebooking and managing connections. This is the case, for example, of AUC3 – Direct operating costs for an airspace user.

It is worth noting that in the current SESAR Performance Framework, the indicators do not describe/capture multimodality, but some of them could be affected by it.

Level 2 and 3 – Digital catalogue of indicators

In Level 2 and Level 3, the objective is to define indicators which capture multimodality and/or passenger experience. These indicators are defined in the digital catalogue, as previously explained. The catalogue includes a table, as can be seen in Fig. A1, with information on all the indicators, including their KPA, type (strategic/tactical), the highest level achieved by any of its variants, brief description, source for the indicator, and link to their detailed definition page.

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	OPS_PE1 - Passengers processing time at infrastructure
	OPS_PE2	Total journey time	Strategic based on published schedules, actual based on the recorded performance on the day of operations.	Strategic	L3	MultimodX	OPS_PE2 - Total journey time
	OPS_PE3	Passengers time	Best possible journey time	Strategic	L3	'Multimodality and	OPS_PE3 - Passengers time efficie

On the detailed definition page, the user can find for each indicator their:

- Description
- Rationale
- Variants
- Data
- Calculation
- Example
- Further development/comments

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Total journey time

MW Owned by Michal Weiszer ···
Last updated: about 5 hours ago • 1 min read • 1 person viewed

Basic Information

Category	Value
Indicator name	Total journey time
KPA	Efficiency
Highest level	L3

Description

Time to complete the whole door to door trip based on itineraries according to published schedules.

Rationale

This PI takes into account the whole trip, including access/egress times and therefore gives more accurate picture of the passenger experience. It relies on complete itineraries which may not be available.

Variants

Name	Description	Unit	Level
avg	average per passenger	min	L3
sum	total sum for all passengers	min	L3
avg grouped by NUTS	average per passenger, grouped by origin and/or destination	min	L3
avg for connecting pax		min	L3

Data

Passenger itineraries, including access/egress time

Calculation

avg = sum(T)/pax [min]

T - total journey time (weighted by number of passengers) [min*pax]

pax - number of passengers [pax]

Examples

avg grouped by NUTS

Total journey time from ES51

Further development/comments

+ Add label

Figure A1: Screenshot of the Total journey time page in Confluence.

Figure A1 shows an example of one of these indicators as in the catalogue. Notice how the level is defined for the different variants, as it could be possible that the same indicator could be at different levels according to the approach used for its estimation.

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KPA	PI Id	PI short name	PI Definition	Type	Highest Maturity Level	Source
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
	OPS_PE2	Total journey time	Strategic based on published schedules, actual based on the recorded performance on the day of operations.	Strategic	L3	MultimodX
	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
	OPS_PE4	Buffers in itineraries	Amount of time used as buffers in connections in itineraries.	Strategic	L3	MultimodX
	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

	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 missed connections, passengers rerouted, etc.).	Tactical	L3	'Multimodality and passenger experience in the SESAR Performance Framework' workshop
	OPS_PE6	Cancellations due to ATFM	Percentage rate.	Tactical	L2.1	'Multimodality and passenger experience in the SESAR Performance Framework' workshop
	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
	OPS_PE8.1	Stranded passengers	Percent of pax not reaching their destination.	Tactical	L2.2	MultimodX
	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
	OPS_PE8.3	Stranded passengers	Percentage of passengers not reaching their destination due to replanning.	Replanning	L3	MultimodX
	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

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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
	INT_PE2	Seamless of travel (time)	Journey transition time (between modes and stops) [mins]	Strategic	L3	MultimodX
	INT_PE3	Infrastructure connectivity	Volume of passengers that are connecting at a given infrastructure node	Strategic	L2.2	MultimodX
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
	FLX_PE1.2	Passenger Resilience replanned	Difference between planned and replanned itineraries	Replanning	L3	MultimodX

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	FLX_PE2	Diversity of destinations	Number and type of destinations which can be reached from an origin	Strategic	L3	MultimodX
	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
Cost-Efficiency (CEF)	CEF_PE1	Direct operating cost per user	Operating cost per trip per user [Euros]	Strategic	L3	MultimodX
	CEF_PE2	Load factor	Number of passengers over number of seats per operator / mode / total	Strategic	L3	MultimodX
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

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	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
	CAP_PE3	Capacity available	Number of seats available between a given origin-destination pair.	Strategic	L3	MultimodX
Environment (ENV)	ENV_PE1	CO2 emissions	Total emissions of services used (could be normalised by passenger-km considering the demand served)	Strategic	L3	MultimodX
Predictability (PRED)	PRED_PE1	Variability	Share of passengers arriving late (within pre-defined time slot) [percentage]	Tactical	L3	MultimodX

Table A4: List of performance indicators

Table A4 provides a list of the performance indicators that are the result of the activities mentioned above. These are compiled from the workshop, a literature review of previous work in the field, and interaction and feedback obtained from stakeholders and other related research projects. As mentioned, these indicators should be further developed in the digital catalogue through the Passenger Experience and Multimodality Flagship and coordinated with other projects, namely, SIGN-AIR [11], MAIA [14], PEARL [9], AMPLE3 [10] and Travel Wise [12]. These indicators are the ones that form the multimodal performance framework; they are the basis for the assessment of the mobility networks by the Strategic and Tactical Multimodal Evaluators (as shown in Appendix B).

A.3.2.2.3. Conclusions on OBJ-0399-TRL2-ERP-020

The criteria EXE01-CRT-0399-ERP-020.1 can be considered to have been reached as the activities above mentioned show how the indicators have been presented to the Industry Board and relevant stakeholders to help identify their development level. Note that the framework, in some aspects, goes beyond multimodality to include elements of passenger experience and support other ER and IR projects. All these activities are compiled in the performance indicator digital catalogue.

Appendix K Unexpected behaviours/results

There were no unexpected behaviours or results.

Appendix L Confidence in results of validation exercise #01

A.3.4.1 Level of significance/limitations of validation exercise results

The stakeholders that participated in the Industry Board workshops were composed of experts from a wide range of fields, both from the aviation and the rail industry. The participants and their diversity of profiles captured a good cross-section of stakeholder experience. Thus, we believe that the level of significance of this validation exercise is high and that the results of the workshop can be extrapolated to the wider aviation and rail industry community.

As mentioned, besides the Industry Board, MultiModX has reached out to ER and IR projects involved in SESAR performance with a focus on passenger and multimodality. In particular with PEARL and AMPLE3 for the consideration of the updated SESAR Master Plan and Performance Framework and SESAR architecture. The integration of the Multimodality and Passenger Experience flagship has supported the further inclusion of relevant projects working in multimodality: MultiModX, SIGN-AIR, MAIA, Travel Wise. All these entities have (or have been given) the opportunity to collaborate on the performance indicators catalogue and on the dedicated Passenger Experience and Multimodality Workshop. Therefore, the results obtained are considered to capture a good cross-section of stakeholder experience.

A.3.4.2 Quality of validation exercises results

The quality of the results is influenced by the number of stakeholders involved. We consider that key relevant actors have been involved. Further work could be done to extend the framework with other modes.

A.3.4.3 Significance of validation exercises results

The operational significance does not apply here. The different maturity levels of the indicators account for different capabilities to measure and estimate them.

Appendix M Conclusions

Appendix N Conclusions on concept clarification

[This validation exercise matured the concept of the multimodal performance framework. The data catalogue is a starting point for future work on aspects of multimodality and passenger experience performance assessment which can, hopefully, be reused and further extended by subsequent projects.

Appendix O Conclusions on technical feasibility

[This validation exercise confirmed the functional requirements indicated in the Functional Requirements Document (FRD).

Appendix P Conclusions on performance assessments

The performance assessment does not apply here.

Appendix Q Recommendations

The Multimodality and Passenger Experience 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. 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.

Appendix R Validation exercise #02 report

Appendix S Summary of the validation exercise #02 plan

The validation exercise follows in its principles the one presented in the ERP SESAR solution SOL399/SOL1.

Appendix T Validation exercise description and scope

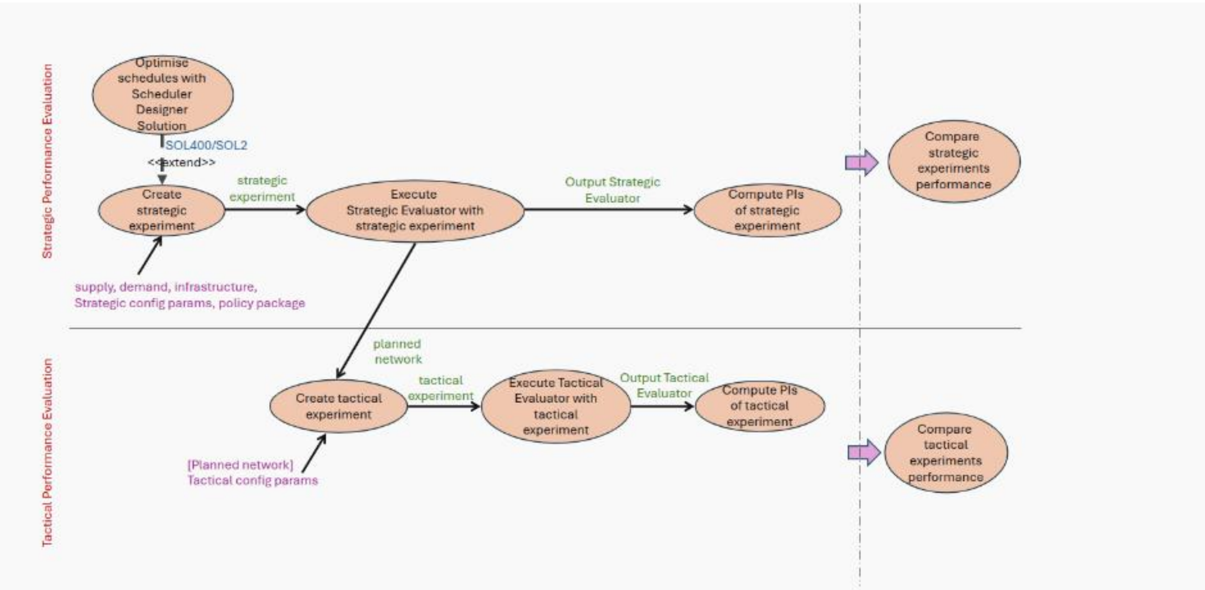

Figure B1: Use cases validated in Validation exercise TVAL.02.1-MultiModX-0399-TRL2

As reported in the ERP [18], and depicted in Figure B1, the operational scope of the validation exercise covers the use case performed by the actors 'Strategic Performance Assessment Expert' and 'Tactical Performance Assessment Expert' as described in OSED [15]. The validation exercise flow follows:

- The Strategic Multimodal Evaluation of the network by means of:
  - The Use Case 'Create strategic experiment' with either the outcome of SOL400/SOL2 or from historical data (*planned network*),
  - The 'Execute Strategic Evaluation with strategic experiment' Use Case uses, which using the information embedded in a strategic experiment to execute the Strategic Evaluator pipeline.
  - The Use Case 'Compute PIs of strategic experiments' to compute multimodality strategic performance indicators.
  - The Use Case 'Compare strategic experiments performance' can be used to compare the performance of different planned networks (e.g. with or without the schedules being optimised by SOL400/SOl2).

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- The Tactical Multimodal Evaluation of the planned network by means of:
  - The Use Case 'Create tactical experiment' translates the outcome of the Strategic Multimodal Evaluator into the input required by the Tactical Multimodal Evaluator (among the configuration of other required parameters).
  - The 'Execute Tactical Evaluator with tactical experiment' Use Case uses the information from the tactical experiment to execute the Tactical Evaluator.
  - The outputs of the Tactical Evaluator can then be used by the 'Compute PIs of tactical experiment' Use Case to generate the required multimodal performance indicators.
  - A comparison of the result of different tactical experiments can be carried out with the 'Compare tactical experiments performance' Use Case.

The multimodal performance framework is independent of a given geographical scope and should be valid for operations to-from-within the ECAC region, which combines air and rail itineraries. Following the scope defined in the OSED [15] representative case studies are analysed. As described in OSED [15] and D3.1 [16], the regional archetypes analysis identified three regional archetypes within Europe (see Figure B2):

1. <u>Advanced urban regions with strong travel activity</u>
2. <u>Conservative regions with median travel activity</u>
3. <u>Emerging rural regions with low travel activity</u>

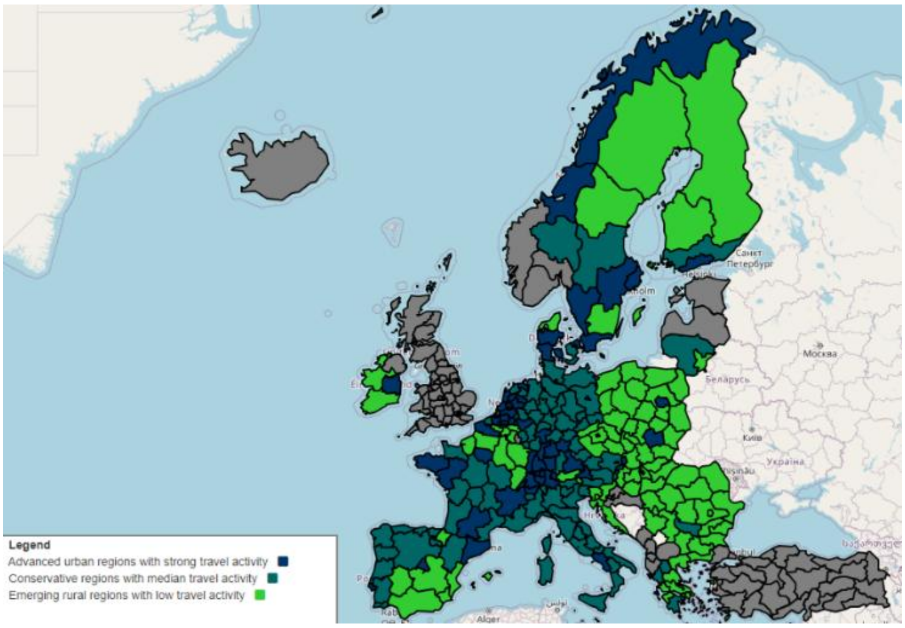

Figure B2: Mapping of clusters to NUTS2 regions in EU (note – grey regions are not clustered due to lack of data or not part of EU)

Figure B3: Mapping of clusters to NUTS2 regions in Spain

As can be seen in Figure B3, Spain contains all three regional archetypes. Therefore, the Spanish national air and rail network can provide a good representation of diverse regional archetypes within the European context, and the validation experiment's geographical scope will this network.

In terms of infrastructure characteristics, Spain has infrastructure nodes which are more likely to be part of multimodal connections (e.g. hub airports such as LEMD and LEBL with rail links to the airport (or nearby)); and collection of infrastructure nodes (airports and/or rail stations) in less connected regions (e.g. LEZL). Note that optimising schedules within a nationwide mobility network also enabled the focus on subparts of the network (e.g. a hub airport or a regional airport) by filtering the results in a post-processing manner to produce performance indicators that capture the impact of multimodality on those environments.

Additionally, during the project, passenger archetypes are inferred for Spain and Germany using sociodemographic data and travel data (see D3.1 [16]). These archetypes were then combined to construct the MultiModX archetypes, which are assumed to be representative of European travel patterns. Spain possesses all seven MultiModX passenger archetypes except for the “short-distance traveller” archetype, which is the least likely to engage in the mid-to-long-distance trips considered for optimisation. Therefore, we consider that the situation in Spain is representative of European mobility patterns.

Note that in terms of itineraries, intra-Spain mobility captures mid-distance trips as well as longer-distance itineraries with connectivity towards the Canary Islands.

Capturing examples of long-distance travel with international flights could be beneficial but considered not essential to showcase the capabilities of SOL399/SOL1 as described in B.1.3.

Besides the demand characteristics, the development of multimodal networks is strongly influenced by policies, as explained in OSED [15]. These policies are grouped into policy packages which represent different representative operational environments. This will be considered when defining the reference and solution scenarios.

The validation exercise will consist of the following experiments:

Experiment 1: Validation of modelling assumptions of the Strategic and Tactical Evaluator

Step 1: The modelling assumptions of the Strategic and Tactical Evaluator are reviewed and validated by a panel of at least five transport experts.

The validation exercise targeted at least five transport modelling experts to validate the assumptions of the strategic performance evaluator with the goal of:

- ensuring that the approach is sound for translating the underlying aggregated demand into disaggregated at flow level demand.
- assumptions on the overall strategic framework and operational concept.
- approach to generate the air schedules, rail timetables, fleet assignments and passenger itineraries by the assessment framework.
- documenting any issues and aspects that should be refined in future research.

Finally, at least five transport modelling experts are consulted to ensure that the same sound modelling principles apply to the tactical evaluator:

- providing realistic modelling of tactical operations, including the multimodality exchanges between the air and the rail layer.
- assumptions on the overall tactical evaluator and applying the Disruption Management Solutions and Mechanisms for multimodality.
- documenting any issues and aspects that should be refined in future research.

This Experiment relies on the feedback obtained from the Industry Board (which includes modelling experts), review meetings with the SESAR Joint Undertaking and presentation of the models to relevant research communities and events, such as the SESAR Innovation Day.

Experiment 2: Calibration of the Strategic and Tactical Evaluators

Step 1: Run the Strategic Evaluator on a reference scenario and compare the results with the historical data. Adjust the parameters of the evaluator to calibrate all models/sub-models.

Step 2: Run the Tactical Evaluator on a reference scenario and compare the results with the historical data. Adjust the parameters of the evaluator to calibrate all models/sub-models.

Experiment 3: Strategic and Tactical evaluation of a mobility network

Step 1: Define a Strategic Experiment for the considered scenario, which is then executed with the Strategic Evaluator pipeline as a planned network to compute multimodality strategic performance indicators.

Step 2: Define a Tactical Experiment for the considered scenario, which is then executed with the Tactical Evaluator pipeline to compute multimodality tactical performance indicators.

As explained in B.2, more than one experiment is presented so that results can be compared among different networks to showcase the capabilities of the model to assess the mobility performance indicators and the comparison of networks.

Experiment 4: Evaluation of SOL400/SOL2 Schedule Optimiser

Step 1: Get the computed KPIs from Experiment 3 for the considered scenario.

Step 2: Repeat Step 1 and Step 2 from Experiment 3 where the supply characteristics (flight schedules and rail timetables) are replaced with the outcome of executing Scheduler Designer Solution SOL400/SOL2.

Step 3: Compare the performance of strategic and tactical experiments based on indicators computed in Steps 1 and 2.

It is worth noticing that the objective of these validation experiments and exercises is not to assess if a given planned network (either historical or as an outcome of SOL400/SOL2) subject to a given policy package performs in a better way than another alternative, not to necessarily assess the benefits and drawbacks of such networks and policies. On the contrary, SOL399/SOL1 and its validation focus on showing that the indicators, tools and methodologies developed in this solution are able to do these types of assessments. Therefore, some analysis of the impact of the policies and SOL400/SOL2 on the network will be provided, but to understand the benefits of this scheduler solution (SOL400/SOL2), the reader is referred to the ERP of SOL400/SOL2 [17].

Section B.1.3 describes in more detail the validation scenarios used. In summary, they rely on the modelling of intra-Spain mobility with different policy packages, which provide different support to multimodality. Some of these, in addition to being modelled strategically (considering the planned network), will also be modelled tactically (simulating the realisation of the network).

The validation exercise technique is simulations run/modelling using Python and the pipeline of SOL399/SOL1 for experiments 2 to 4 and interaction with the relevant experts as part of workshops for experiment 1. The validation platform is the computer(s) used to perform the models.

Appendix U Summary of validation exercise #02 validation objectives and success criteria

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise	Exercise validation objective	Exercise success criteria
EXE02-OBJ-0399-TRL2-ERP-030	EXE02-CRT-0399-ERP-030.1	Fully covered	Given the input supply, demand, infrastructure, strategic/tactical configuration parameters, and policy packages, compute multimodality strategic and tactical performance indicators.	• Modelling assumptions are peer-reviewed and validated by a panel of at least five transport modelling experts. • Key modelling assumptions shall be clearly identified and documented.
	EXE02-CRT-0399-ERP-030.2	Fully covered		• Strategic and Tactical Evaluators calibrated.
	EXE02-CRT-0399-ERP-030.3	Fully covered		• A strategic experiment (without the Schedule Design Solution (SOL400/SOL2) is set up and executed with the Strategic Multimodality Evaluator, and strategic multimodality-related PIs are measured.
	EXE02-CRT-0399-ERP-030.4	Fully covered		• A tactical experiment is set up and executed with the Tactical Multimodality Evaluator, and tactical multimodality-related PIs are measured.

EXE02-OBJ-0399-TRL2-ERP-040	EXE02-CRT-0399-ERP-040.1	Fully covered	Evaluate the performance of the Schedule Design Solution (SOL400/SOL2).	• Set an experiment without Schedule Design Solution (SOL400/SOL2), and execute it to generate the inputs that SOL400/SOL2 requires and to compute multimodality-rated PIs with a focus on strategic multimodality-related PIs, as these are the ones required to validate SOL400/SOL2, see [24]; the experiment could be evaluated by the Tactical Multimodality Evaluator to assess tactical PIs to assess how the network would materialise, but this is not required for the validation of SOL400/SOL2 and therefore not a strict requirement to meet this criteria. • Generate updated flight schedules and rail timetables computed with Schedule Design Solution (SOL400/SOL2) (see [21]). • Update the experiment with the updated flight schedules and rail timetables, execute it and compute multimodality-rated PIs as for the experiment without the Schedule Design Solution (SOL400/SOL2). • The performance of the Schedule Design Solution (SOL400/SOL2) is evaluated by comparing PIs for the two experiments.

Table B1: Validation objectives for the exercise #02

Appendix V Summary of validation exercise #02 validation scenarios

The scenarios which consider a planned network in MultiModX are a combination of geographical scope (cs), policy packages (pp), network definition (nd) and the application (or not) of SOL400/SOL2 (so). Table B2 presents a description of these different parameters that define the scenarios.

Category	Sub-Category	Definition
cs (Case Study)	cs10: Intra-Spain Mobility	• Intra-Spain mobility with demand defined between NUTS3 regions and flight schedules and rail timetables from busy historical periods.
	cs11: Intra-Spain+International flights	• Intra-Spain with international mobility; extension of cs10 to consider international flights to/from Spain to significant international destinations.
pp (Policy Package)	pp00: No policies	• No specific multimodal policies are put into place. This means that multimodal connections are increased with respect to the minimum possible by 30 and 15 additional minutes for rail-to-air and air-to-rail connections, respectively. This asymmetry reflects the potential sensitivity of passengers to missing connections and the inherent uncertainty of the airport and rail station processes when no integrated ticket is present.
	pp10: Multimodality incentivised	• Integrated tickets in place, i.e., rail-to-air and air-to-rail connections, are considered doable as quickly as possible. • A CO_2 tax for air itineraries is implemented (0.15 EUR / Kg CO_2).
	pp20: Multimodality enforced	• Integrated tickets in place (as in pp10). • A CO_2 tax for air itineraries (as in pp10). • A flight ban (where a rail alternative under 3h exists).

nd (Network definition)	nd00: Baseline	• A maximum of 2 connections are allowed for the itineraries.
		• Multimodal connections are allowed among all operators.
		• Air-air connections respect airline alliances.
		• Assignment of passengers to itineraries lexicographic optimisation:
		  ○ 1st maximum number of connecting passengers satisfied
		  ○ 2nd maximum number of passengers overall,
		  ○ 3rd distribution of passengers across services (reduce underutilisation)

	nd01: Focus on connecting passengers	• A maximum of 2 connections are allowed for the itineraries.
		• Multimodal connections are allowed among all operators.
		• Air-air connections among all operators (mixed operators allowed).
		• Assignment of passengers to itineraries lexicographic optimisation:
		    ○ 1st maximum number of connecting passengers satisfied
		    ○ 2nd maximum number of passengers overall,
		    ○ 3rd distribution of passengers across services (reduce underutilization)

	nd02: Focus on total passengers	• A maximum of 2 connections are allowed for the itineraries.
		• Multimodal connections are allowed among all operators.
		• Air-air connections among all operators (mixed operators allowed).
		• Assignment of passengers to itineraries lexicographic optimisation:
		    ○ 1st maximum number of passengers overall,
		    ○ 2st maximum number of connecting passengers satisfied
		    ○ 3rd distribution of passengers across services (reduce underutilization)

so (Schedule Optimisation)	so00.00: Baseline	• No schedule optimisation (no SOL400/SOL2)
	so01.01: SOL400/SOL2 applied	• Time shift strategies in SOL400/SOL2 • Maximum timetable deviation of 20 minutes per service.
	so01.X, where X is greater or equal to 02	• This corresponds to X successive applications of SOL2 jointly with SOL1 (see the use case diagram B1)

Table B2: MultiModX scenarios for planned networks and nomenclature.

To construct the scenarios from a supply and demand perspective (cs10/cs11), we will use the data gathered from a busy day in 2019 for air and from a busy day in 2023 for rail operations, which will be representative of a nominal day in 2030. For the demand, origin-destination demand per passenger archetype is computed based on mobile phone data (Mobile Network Data (MND)) from a busy day in September 2022 (Friday 23/09/2022). See [18] for more details on the justification of these parameters and their representativeness of 2030 operations. As explained in [18], it is considered that cs10 is sufficient for the validation of SOL399/SOL1, i.e., to demonstrate the capabilities of SOL399/SOL1 to assess the planned network (with or without SOL400/SOL2). Therefore cs11 (intra-Spain mobility with international flights) will not be discussed in this document and will be analysed as future work.

For the policy packages, pp00 represents the situation if the network continues with 'business as usual'. As the multimodality-enforced policy package (pp20) should result in the most multimodal itineraries (with respect to other policy packages), this one is expected to be the one providing the largest benefits from multimodal solutions (i.e., an operational environment where the multimodal Solutions perform the best). The multimodality incentivised policy package (pp10) is expected to provide some in-between results and travelling pattern shifts due to the reduced multimodal connecting times provided by the integrated tickets.

The different network definition alternatives are considered as the current implementation of SOL400/SOL2 considers that connections are possible among all operators (nd01 and nd02), and the results provided by the ERR of SOL400/SOL2 focus on the case when the total number of passengers assigned are first considered in the final passenger assignment (nd02) [19]. However, from a SOL399/SOL1 perspective, it is desirable to compare the nd00 case (where intra-airline connectivity respects airline alliances), as this is more representative of the current (and expected future) type of operations. For these reasons, depending on the validation experiment, different reference scenarios might be considered (as shown in Table B3).

Table B3 presents the list of scenarios used in this validation exercise with a short description and information if they are used as reference or as solution scenarios and the rationale for their usage, i.e., for what are they used in the validation.

Scenario	**Description**	**Rationale**

cs10.pp00.nd00.so00.00	Baseline intra-Spain mobility without multimodal policies, respecting air alliances.	• Solution for Experiment 2
		  ○ Strategic evaluation → EXE02-CRT-0399-ERP-030.2
		  ○ Tactical evaluation → EXE02-CRT-0399-ERP-030.2
		• Reference for Experiment 3
		  ○ Strategic evaluation → EXE02-CRT-0399-ERP-030.3
		• Solution for Experiment 3
		  ○ Tactical evaluation → EXE02-CRT-0399-ERP-030.4

cs10.pp10.nd00.so00.00	Intra-Spain mobility with incentivised multimodal policies (integrated ticketing and extra CO_2 cost for aviation), respecting air alliances.	• Solution for Experiment 3 ○ Strategic evaluation → EXE02-CRT-0399-ERP-030.3
cs10.pp20.nd00.so00.00	Intra-Spain mobility with flight ban (180 min rail alternative) and incentivised policies, respecting air alliances.	• Solution for Experiment 3 ○ Strategic evaluation → EXE02-CRT-0399-ERP-030.3

cs10.pp00.nd02.so00.00	Baseline intra-Spain mobility without multimodal policies, allowing all connections and prioritising total passenger assignment.	• Reference for Experiment 4
		  ○ Strategic evaluation → EXE02-CRT-0399-ERP-040.1
		  ○ Tactical evaluation → EXE02-CRT-0399-ERP-040.1

cs10.pp20.nd02.so00.00	Baseline intra-Spain mobility with flight ban (180 min rail alternative) and incentivised policies, allowing all connections and prioritising total passenger assignment.	• Reference for Experiment 4
		  ○ Strategic evaluation → EXE02-CRT-0399-ERP-040.1
		  ○ Tactical evaluation → EXE02-CRT-0399-ERP-040.1
		(several ground mobility delays)

cs10.pp00.nd02.so10.02	Baseline intra-Spain mobility without multimodal policies, allowing all connections and prioritising total passenger assignment.	• Solution for Experiment 4
		  ○ Strategic evaluation → EXE02-CRT-0399-ERP-040.1
		  ○ Tactical evaluation → EXE02-CRT-0399-ERP-040.1

cs10.pp20.nd02.so10.01	Baseline intra-Spain mobility with flight ban (180 min rail alternative) and incentivised policies, allowing all connections and prioritising total passenger assignment.	• Solution for Experiment 4 ○ Strategic evaluation → EXE02-CRT-0399-ERP-040.1 ○ Tactical evaluation → EXE02-CRT-0399-ERP-040.1 (several ground mobility delays)

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Table B3 Scenarios considered in Validation exercise #02

As shown in Table B3, cs10.pp00.nd00.so00.00 will be used for the calibration of the models, as it represents operations where no particular multimodal policy is in place and with airlines providing connectivity within their alliances. This scenario will also be used to show how a tactical evaluation can be performed (hence being the 'solution' scenario for Experiment 3), and it will be compared strategically with the options of having policy packages which incentivise multimodality (cs10.pp10.nd00.so00.00) or which enforce the reduction of flights (cs10.pp20.nd00.so00.00). Therefore, the cs10.pp00.nd00.so00.00 will become the 'reference' scenario for the strategic comparison with the other two cases.

In order to show how SOL399/SOL1 is able to assess the application of SOL400/SOL2 four further scenarios are considered. In this case, nd02 is used, as alliances within air operators are currently not respected in SOL400/SOL2, and this is the network configuration used in the ERR of SOL400/SOL2 [19]. Two different policies will be considered: baseline (pp00), and multimodality enforced (pp20). These are selected as they show how SOL400/SOL2 improves the connectivity when no particular multimodal policies are put in place, and in the case where the biggest impact of multimodality is expected. The case without SOL400/SOL2 will be the reference scenarios (cs10.pp00.nd02.so00.00 and cs10.pp20.nd02.so00.00), and the solution scenarios (with SOL400/SOL2 in place will be based on the work conducted for the ERR of SOL400/SOL2 (cs10.pp00.nd02.so10.02, cs10.pp20.nd02.so10.01). All these scenarios will be analysed strategically and tactically, showcasing all the use cases presented in Figure B1. In addition, the scenarios with flight ban (pp20) will be assessed tactically considering different levels of ground mobility disruption. Finally, to show how SOL399/SOL1 is able to analyse the impact of SOL400/SOL2 a comparison between key PIs between the strategic planned network and the tactical realisation of the network will be provided.

Once again, it is worth reiterating that the objective of the ERR of SOL399/SOL1 is to showcase how this Solution is able to assess the performance provided by SOL400/SOL2, and not to discuss or analyse the benefits (or drawbacks) of such a Solution per se. The reader is referred to the ERR of SOL400/SOL2 for such analysis.

Note how Experiment 3 (strategic and tactical evaluation of a mobility network) can be achieved only using the reference and solution scenarios devised to evaluate SOL400/SOL2. However, we consider that showing the results for nd00 (where the network is modelled similarly to current commercial agreements, i.e., respecting alliances between airlines) and including the incentivised policies (pp10) provide a better overview of the impact of multimodality in the transport network.

Finally, all four scenarios which were defined as 'fundamental' in the ERP of SOL399/SOL1 have been implemented and analysed in this ERR. In addition to those, further scenarios with incentivise policies (pp10) and with different network configurations are implemented to provide a comprehensive view of SOL399/SOL1 capabilities as previously mentioned.

Appendix W Summary of validation exercise #02 validation assumptions

No extra assumptions are needed for this exercise.

Appendix X Deviation from the planned activities

No major deviations have been encountered with respect to the planned activities in the ERP of SOL399/SOL1. Some experiments have been adjusted to provide a broader representation of the capabilities of SOL399/SOL1 to assess planned networks. These deviations are as follows:

- Experiment 1 - Validation of modelling assumptions of the Strategic and Tactical Evaluator - relies on the feedback obtained from the Industry Board (which includes modelling experts), review meetings with the SESAR Joint Undertaking and presentation of the models to relevant research communities and events, such as the SESAR Innovation Days rather than a formal review. All modelling assumptions and improvements are documented.
- Experiment 3 - Strategic and Tactical evaluation of a mobility network - according to the ERP focused on a) defining a Strategic Experiment for a scenario, which is then executed with the Strategic Evaluator pipeline as a *planned network* to compute multimodality strategic performance indicators; and b) defining a Tactical Experiment for the considered scenario, which is then executed with the Tactical Evaluator pipeline to compute multimodality tactical performance indicators. To fully present the capabilities to analyse strategic planned networks, instead of one, three networks are evaluated (with different policy packages) and compared among them.
- Experiment 4 - Evaluation of SOL400/SOL2 Schedule Optimiser - will focus on presenting how SOL399/SOL1 is able to compute the performance indicators on the planned network updated with the outcome of the optimisation of schedules performed by SOL400/SOL2. However, the analysis of the potential benefits of SOL400/SOL2 itself is presented in its associated ERR of SOL400/SOL2.

In terms of technical capabilities, the simulation environment of the Tactical Multimodal Evaluator covers multimodal connections (rail-air) and (air-rail), and on aviation-related connections (air-air). Rail-rail connections are not included in the simulation due to computational and time constraints. These connections have been considered in a post-processing manner.

Appendix Y Validation exercise #02 results

Appendix Z Summary of validation exercise #02 results

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Exercise #02 validation objective ID	Exercise #02 validation objective title	Exercise #02 success criterion ID	Exercise #02 success criterion	Sub-operating environment	Exercise #02 validation results	Exercise #02 validation objective status
EXE02-OBJ-0399-TRL2-ERP-030	Given the input supply, demand, infrastructure, strategic/tactical configuration parameters, and policy packages, compute multimodality strategic and tactical performance indicators.	EXE02-CRT-0399-ERP-030.1	• Modelling assumptions are peer-reviewed and validated by a panel of at least five transport modelling experts. • Key modelling assumptions shall be clearly identified and documented.	N/A	• Modelling assumptions for Strategic and Tactical Evaluator presented to relevant experts (Industry Board, scientific community). • Modelling assumptions identified and documented.	OK
		EXE02-CRT-0399-ERP-030.2	Strategic and Tactical Evaluators calibrated.	N/A	• Components of the Strategic Evaluator subject to calibration have been analysed and reviewed. • Tactical Evaluator ground mobility calibrated, and gate-to-gate mobility previously calibrated.	OK
		EXE02-CRT-0399-ERP-030.3	A strategic experiment (without the Schedule Design Solution (SOL400/SOL2) is set up and executed with the Strategic Multimodality Evaluator, and strategic multimodality-related PIs are measured.	N/A	• Baseline (cs10.pp00.nd00.so00.00), incentivised policies (cs10.pp10.nd00.so00.00), and enforced policies (cs10.pp20.nd00.so00.00) executed, PIs computed with focus on different aspects (regions, infrastructure,	OK

					passenger mobility, etc).	
		EXE02-CRT-0399-ERP-030.4	A tactical experiment is set up and executed with the Tactical Multimodality Evaluator, and tactical multimodality-related PIs are measured.	N/A	• The baseline scenario has been executed tactically (cs10.pp00.nd00.so00.00) with a focus on multimodal connectivity indicators.	OK
EXE02-OBJ-0399-TRL2-ERP-040	Evaluate the performance of the Schedule Design Solution (SOL400/SOL2).	EXE02-CRT-0399-ERP-040.1	• Set an experiment without Schedule Design Solution (SOL400/SOL2), and execute it to generate the inputs that SOL400/SOL2 requires and to compute multimodality-rated PIs with a focus on strategic multimodality-related PIs, as these are the ones required to validate SOL400/SOL2, see [24]; the experiment could be evaluated by the Tactical Multimodality Evaluator to assess tactical PIs to assess how the network would	N/A	• Scenario for baseline policies (pp00) and enforced policies (pp20) have been executed without and with SOL400/SOL2 (cs10.pp00.nd02.so00.00, cs10.,pp20.nd02.so00.00, and cs10.pp00.nd02.so10.02, cs10.,pp20.nd02.so10.01). • Strategic PIs have been computed and compared across the experiments. • In addition, these four scenarios have been executed tactically with a sensitivity analysis on passenger missing connections as a function of ground mobility delay for the case with enforced policies (pp20).	OK

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			materialise, but this is not required for the validation of SOL400/SOL2 and therefore not a strict requirement to meet this criteria. • Generate updated flight schedules and rail timetables computed with Schedule Design Solution (SOL400/SOL2) (see [21]). • Update the experiment with the updated flight schedules and rail timetables, execute it and compute multimodality-rated PIs as for the experiment without the Schedule Design Solution (SOL400/SOL2). • The performance of the Schedule Design Solution (SOL400/SOL2) is evaluated by comparing PIs for the two experiments.		• A comparison of the results between strategic and tactical indicators is also provided.	

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Table B4: Validation exercise #02 results

Table B4 presents the summary of the objective status of the validation exercise #02.

Appendix AA Analysis of validation exercise #02 results per validation objective

B.3.2.1 OBJ-0399-TRL2-ERP-030 Results

Objective: Given the input supply, demand, infrastructure, strategic/tactical configuration parameters, and policy packages, compute multimodality strategic and tactical performance indicators.

Validation: The validation of this Objective is achieved through the implementation of Experiments 1, 2 and 3 described in Section B.1.1. Those experiments address the SESAR solution success criteria in the following manner:

- Experiment 1: EXE02-CRT-0399-ERP-030.1 (modelling assumptions),
- Experiment 2: EXE02-CRT-0399-ERP-030.2 (models calibrated),
- Experiment 3: EXE02-CRT-0399-ERP-030.3 (strategic evaluation of network without SOL400/SOL2) and EXE02-CRT-0399-ERP-030.4 (tactical evaluation of network without SOL400/SOL2)

The results in this section are organised following these Experiments for clarity.

B.3.2.1.1 Experiment 1 - Validation of modelling assumptions

Validation of modelling assumptions of the Strategic and Tactical Multimodal Evaluators

First, all modelling assumptions are documented in Confluence (working space set up by the MultiModX's consortium) and reported in FDR [20], ERP of SOL399/SOL1 and ERR (see Section 3.2.3).

Then, both the modelling assumptions and approach were presented to the SESAR Joint Undertaking (as part of the Technical Review meeting) and to MultiModX's Industry Board. The Industry Board is composed of a range of stakeholders from airlines, airports, ANSPS, rail operators, and transport modelling experts. In particular feedback was obtained on which elements to focus the modelling of SOL399/SOL1 as part of the MultiModX's Industry Board meeting held in Rome on the 12th of November.

The information obtained helped to refine the performance framework, e.g. the importance of consideration of delay with respect to indented initial trip for passengers and the consideration of reliability. Some suggestions were received for future work to include the shift to busses, as this is becoming more relevant with competition with rail (particularly in some European countries). No negative feedback was received regarding the overall modelling approach for the Strategic and Tactical Evaluator.

Besides these activities, the models have been presented at scientific conferences, in particular, the Tactical Multimodal Evaluator (with the application of a fast-track mechanism to process multimodal passengers) was presented at the Air Transport Research Society (ATRS) conference in Lisbon in July 2024, and at the SESAR Innovation Days (SIDs) in Rome in November 2024. The Strategic Multimodal Evaluator has been accepted for presentation at the Euro Working Group on Transportation (EWGT) 2025 conference (to be held in Edinburgh in September 2025). The participation in these conferences enabled the presentation of the methodologies, approach and results to scientific communities to ensure that the key modelling aspects are validated by experts on aviation and overall transport modelling. Moreover, the presentation on these conferences is subject to a prior blind peer-review process of a full article (as it is the case for the SESAR Innovation Days and the Euro Working Group on Transportation). These reviews provide anonymised feedback and requests on the modelling, methodology and results.

Conclusions on Experiment 1

The activities performed in Exercise 1 aimed at satisfying the success criteria EXE02-CRT-0399-ERP-030.1. This required that modelling assumptions were peer-reviewed and validated by a panel of at least five transport modelling experts and for key modelling assumptions to be clearly identified and documented. We consider that this has been achieved as more than five transport modelling have been presented with the modelling approach and methodology and feedback obtained. As indicated, this has been performed by a set of continuous verification and validation activities. Moreover, one could consider this to be an ongoing process with further presentation of the modelling to relevant experts (e.g. at the EWGT conference), and with the identification of mobility aspects to be improved in the future.

B.3.2.1.2 Experiment 2 - Calibration of Evaluators

Calibration of the Strategic Multimodal Evaluator

The Strategic Multimodal Evaluator relies on the computation of potential paths, possible itineraries and the assignment of passengers to services (based on passengers preference with respect to possible clustered alternatives) (see Functional Requirement Document of SOL399/SOL1 for more details [20]).

The first elements of the Strategic Evaluator pipeline, therefore, are the computation of these potential and possible paths and itineraries. The functionalities associated with performing these tasks have been verified by reviewing their outcome and exploring selected origin-destination pairs. The model requires estimations of the minimum connecting time inter and intra-modes and the estimation of the processing time of passengers at infrastructure nodes (kerb-to-gate and gate-to-kerb at airports and kerb-to-platform and platform-to-kerb at train stations). These values have been obtained from historical datasets (e.g. minimum connecting times at airports (based on OAG data) and train stations (provided by UIC)), manual exploration of travelling alternatives between nodes with public transport (using Google maps), and expert judgement for processing time at infrastructures. Of course, these values can be adjusted by creating new inputs for the model, but we have ensured that the values used produce options which correlate with historically observed paths (from anonymised paths obtained from mobile network data (MND)) and expert judgment and review of selected origin-destination pairs. In addition to this, the computation of potential and possible paths and itineraries requires the selection of maximum number of connections allowed, number of paths and computed and thresholds for cost, total travelling time and emissions to consider that two alternative itineraries should be clustered into the same alternative. These parameters have been adjusted following a calibration process by reviewing selected origin-destination pairs.

Besides these calibrations of modelling parameters, the Strategic Multimodal Evaluator relies on the preference of passengers to select among the alternatives presented to them to fulfil their travel. Therefore, the performance of the logit model is critical to ensure that adequate results are obtained. For these reasons, effort has been devoted to ensuring that these models are properly calibrated.

This calibration is based on a comparison of the observed probabilities for the itineraries from mobile network data and predicted probabilities by the logit model. This is carried out in two steps: First with a statistical analysis considering all itineraries to calibrate six independent logit models (one per archetype); Second, by assessing the probabilities to choose a given itinerary for a subset of 10 representative origin-destination pairs for the baseline scenario.

Quantity	**Archetype 0**	**Archetype 1**	**Archetype 2**	**Archetype 3**	**Archetype 4**	**Archetype 5**
Mean Squared Error	0.0638	0.0621	0.0623	0.0615	0.0615	0.0617
Mean Absolute Error	0.1952	0.1958	0.1961	0.1939	0.1940	0.1948
Pearson Correlation	0.6401	0.6418	0.6400	0.6455	0.6431	0.6424
Spearman Correlation	0.6272	0.6264	0.6259	0.6302	0.6287	0.6278
Standard deviation	0.2523	0.2488	0.2493	0.2477	0.2476	0.2480

Table B5: Performance Comparison of Predictive Models Across Archetypes

The results are similar for all archetypes. The mean absolute error is an acceptable value. The Pearson correlation means the logit model is, on average, around 19% inaccurate when predicting probabilities. The Spearman correlation value suggests the model is able to capture the real trends. For the standard deviation, the errors are quite spread out, so for some OD pairs, the error can be high.

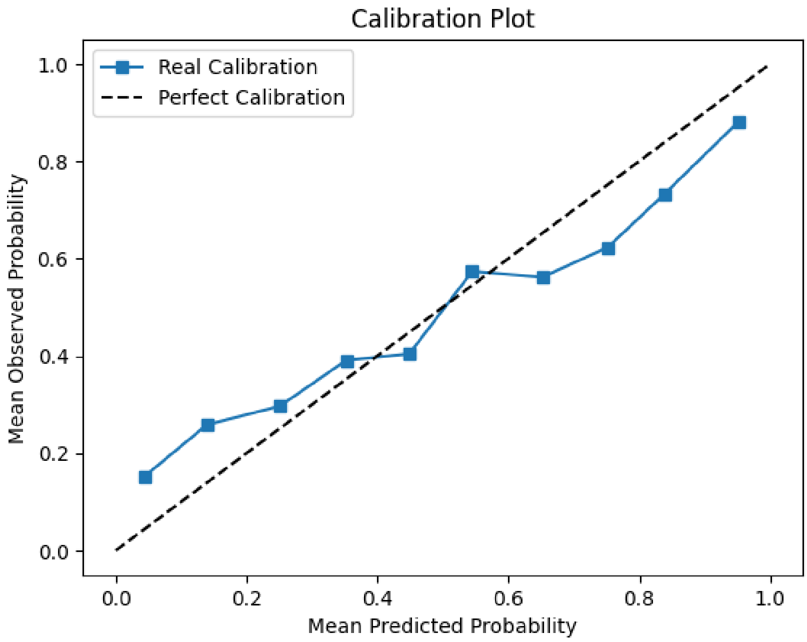

Figure B4: Calibration plot for archetype 0

Figure B4 shows the calibration plot for archetype 0. The probabilities have been divided into 10 groups from 0 to 1, and the mean probability has been calculated for each group. The blue line represents the mean predicted probability vs the mean observed probability. The diagonal line is there for reference. The points above the diagonal mean that the model over-predicts, whereas the points below the diagonal mean that the model under-predicts.

It can be seen that this logit model over-predicts for very non-probable events and under-predicts for very probable events (the two go hand in hand). However, the results are deemed reasonable. Similar results are observed (not reported in this Appendix) for the other archetypes.

The results of the calibration show that most archetypes prefer flights to multimodal alternatives and flight over train journeys. All archetypes present a statistically significant negative correlation with respect to CO_2 and time, i.e., a preference for faster and low emissions alternatives is observed. Most archetypes also show a negative correlation with respect to cost, albeit not statistically significant.

Once the logit models were calibrated, they were applied to the demand and clustered alternatives provided by the Strategic Multimodal Evaluator pipeline. Selected origin-destination pairs representative of Spanish mobility were reviewed by aggregating all the demand from MND that follow those paths (observed data) and comparing the probability of the different clusters with respect to the outcome of the application of the logit models by the Strategic Multimodal Evaluator pipeline. For brevity, only two representative examples are presented: Madrid (ES300) - Barcelona (ES511) and Badajoz (ES431 - Barcelona (ES511).

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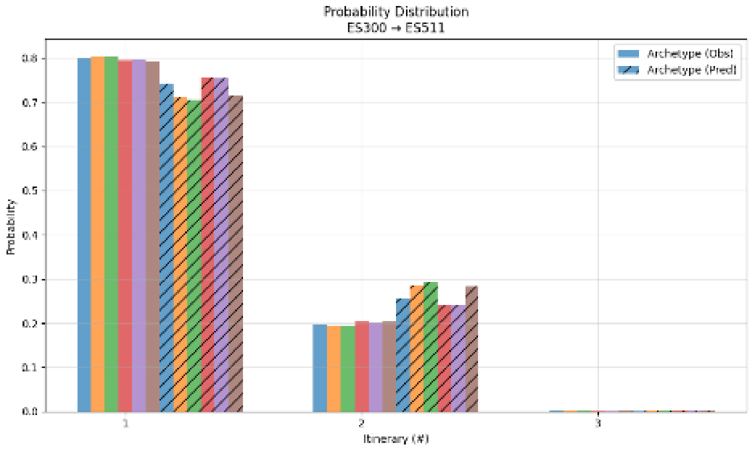
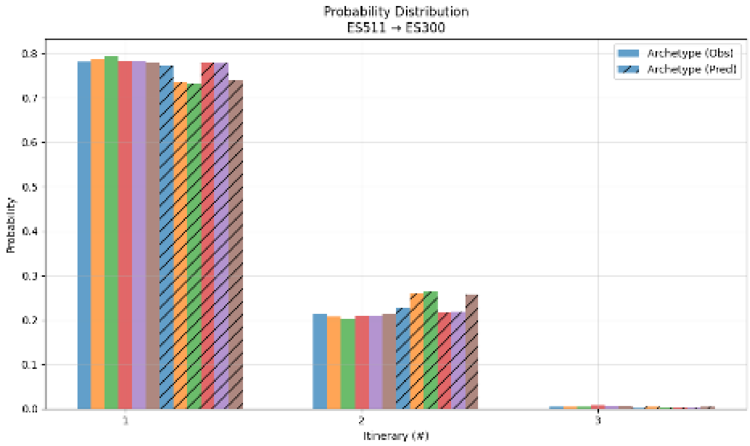


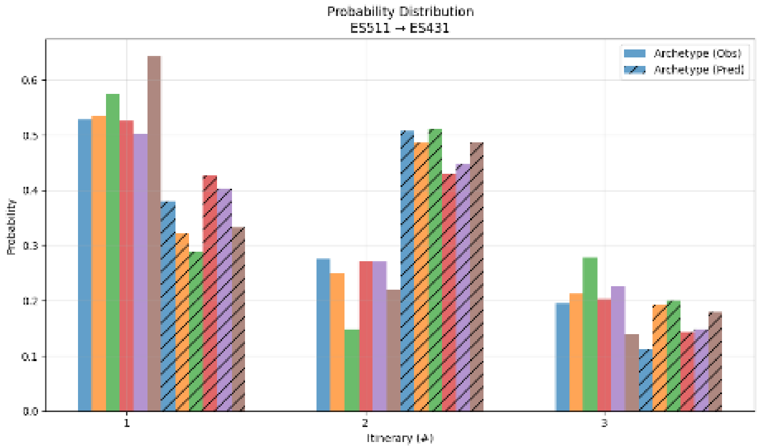
a) Madrid – Barcelona



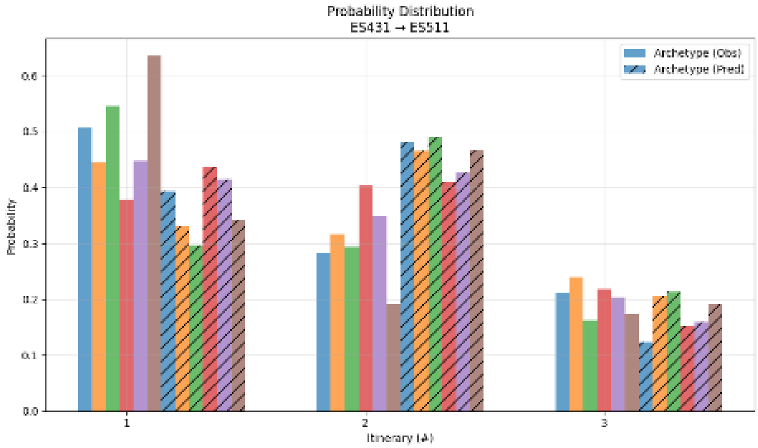
b) Barcelona - Madrid

Figure B5 Probability for alternatives per passenger archetype for MND and logit model between Madrid and Barcelona.

Figure B5 shows the results for the cases from Barcelona (ES511) to Madrid (ES300) and Madrid to Barcelona cases. These origin-destination pairs have three alternatives each way: HSR (option 1), flight (option 2) or regional train (option 3). As shown, the logit model produces an assignment of 76.6% of the demand to HSR, 23.2% to flights, and only 0.2% to the regional train service. There is a slight overestimation of air demand, but overall, the logit model can predict the probabilities of selecting the different options reasonably well, as the values predicted are close to the observed values in the MND data and historically reported data.



a) Barcelona – Badajoz



b) Badajoz - Barcelona

Figure B6: Probability for alternatives per passenger archetype for MND and logit model between Badajoz and Barcelona.

Figure B6 shows the results for the case from Barcelona (ES511) to Badajoz (ES300) (and vice-versa), with the alternatives of flight Barcelona to Badajoz (option 1), flight Barcelona to Sevilla (option 2) or flight Barcelona to Madrid (option 3). This example is useful to show some of the limitations of the current approach.

The option using Seville (LEZL) airport to travel from Badajoz to Barcelona is longer in door-to-door time, as it has a longer access time (around an additional 80 minutes), but from Badajoz (LEBZ) airport, the flight uses a regional Bombardier CRJ900, which emissions per passenger are higher (94.5 kg CO_2) than from Seville (58.0 kg CO_2), where a mix of A320 and B737 are used. This is why the model overestimates this second alternative. It should be noted that, besides the extra access time, the model does not consider emissions or costs associated with access and egress, which might also impact this *encouragement* of using infrastructure located outside the origin (destination) NUTS.

Similar discrepancies between MND and logit data are observed when several arrival (departure) stations are available within the same NUTS for the model, all stations are equivalent, with respect to departing or arriving, even if different access/egress times might be present (as these are computed considering the population centroid within the NUTS as previously explained). The model considers inter-NUTS and not intra-NUTS mobility. This is the case, for example, of Malaga NUTS (ES617) where two rail stations are considered: Malaga central and Antequera (located around 60 Km north of Malaga). The model tends to slightly overestimate the trips to Antequera as the stop is before the one in Malaga city centre for rail trips from Madrid, leading to faster trips.

Calibration of the Tactical Multimodal Evaluator

The Tactical Multimodal Evaluator extends Mercury simulator. Sample data required to calibrate and run the baseline (gate-to-gate) model in Mercury is provided in [22]. Other calibrated inputs, such as passenger processes at the airport and rail station and their sources, are listed in Appendix B in OSED for SOL399/SOL1.

For the simulation of the ground mobility (i.e. connecting times between airports and rail stations), the values are based on an analysis of Google Maps with an additional standard deviation of 5 minutes. However, in contrast to the values used in the Strategic Multimodal Evaluator, the mean is decreased by two times of standard deviation (10 minutes). In the Strategic Multimodal Evaluator, these times are viewed as the minimum connecting times, i.e. values to ensure that the connections are possible. By decreasing the mean by two times of standard deviation in the Tactical Multimodal Evaluator, 95% of passengers will be able to make the connection.

The train times are modelled according to their timetable with some added noise in the simulation. An initial delay of mean 0 and standard deviation of 5 minutes is applied to all trains. The modelling approach is that the trains are delayed at the source, and this delay is propagated through their service.

The flight delays are modelled according to the probability of being regulated by ATFM delay. The probability distribution for a 'medium' level of delays has been calibrated in [23] and calculated from representatives of historical days.

Conclusions on Experiment 2

The activities conducted in Experiment 2 satisfy the criteria EXE02-CRT-0399-ERP-030.2 as both the Strategic and Tactical Evaluators have been calibrated for nominal conditions.

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B.3.2.1.3 Experiment 3 - Evaluation of planned network

Strategic evaluation of planned networks

The main activity of the strategic evaluation of a planned network in Experiment 3 is to define a scenario with a planned network to compute multimodality strategic performance indicators.

In this case, as explained in B.2, instead of a single experiment three different ones are created to compare the networks across them and showcase the capability of the model to assess the mobility performance indicators and the comparison of networks.

Therefore, this part of the experiment will define three mobility networks (experiments) as explained in Table B3:

- cs10.pp00.nd00.so00.00: Baseline intra-Spain mobility without multimodal policies, respecting air alliances.
- cs10.pp10.nd00.so00.00: Intra-Spain mobility with incentivised multimodal policies (integrated ticketing and extra CO_2 cost for aviation), respecting air alliances.
- cs10.pp20.nd00.so00.00: Intra-Spain mobility with flight ban (if 180 minutes rail alternative) and incentivised policies, respecting air alliances.

These three scenarios will allow us to show how policies can impact mobility and multimodality.

Table B6 presents the mobility performance indicators defined in the performance framework computed for the different scenarios. For some indicators, different variants are presented. In some cases, the indicators are disaggregated to the level of infrastructure (e.g. catchment areas of airports) or origin-destination pairs (e.g. total travel time between two given NUTS3 regions). These types of results are not suitable to be presented in the table. For this reason, some indicators are represented in a graphical manner below.

PI	Short definition	KPA	Variant	pp00 - Baseline	pp10 - Incentivised	pp20 - Enforced
Passengers processing time	Time for processing passengers at airports (Kerb-to-Gate and Gate-to-Kerb) [min]	Efficiency	avg	53.08	53.26	51.34
Total journey time	Door-to-door total travel time [min]	Efficiency	sum	88,349,958	88,413,449	86,046,151
			avg between NUTS (at NUTS3 level)	See the graphical representation below		
			avg between NUTS (aggregated at NUTS2 level)	See the graphical representation below		
			sum per region archetype (as origin)	• advanced: 29,652,406 • emerging: 31,980,734 • median: 20,566,862 • Canary Islands: 6,149,956	• advanced: 29,684,175 • emerging: 32,004,929 • median: 20,534,091 • Canary Islands: 6,190,254	• advanced: 27,807,965 • emerging:31,677,144 • median: 20,399,900 • Canary Islands: 6,161,142
			avg per region archetype (as origin)	• advanced: 206.42 • emerging: 234.95 • median: 225.60 • Canary Islands: 336.84	• advanced: 206.64 • emerging: 235.26 • median: 225.33 • Canary Islands: 338.39	• advanced: 203.01 • emerging: 234.34 • median: 224.98 • Canary Islands: 338.08
			avg for connecting passengers	432.75	429.22	428.57

Passengers time efficiency	Best possible journey time (from schedules)/planned time travel (from planned operations) [percentage]	Efficiency	total	0.88	0.87	0.88
Buffers in itineraries (min)	Total waiting time between all connections in itinearies [min]	Efficiency	sum	561,044	560,769	592,084
			avg for connecting passengers	23.39	22.29	22.24
Modal share	Share of transport modes in passenger itineraries [number passengers per mode and percentage]	Interoperability	total	• air: 102,290 (0.26) • rail: 280,524 (0.72) • multimodal: 6,377 (0.02)	• air: 101,052 (0.26) • rail: 279,959 (0.72) • multimodal: 8,103 (0.02)	• air: 90,694 (0.24) • rail: 282,265 (0.74) • multimodal: 8,095 (0.02)
			total by NUTS	See the graphical representation below		
			total by region archetype	• advanced ○ air: 33,700 (0.23) ○ rail: 108,924 (0.76) ○ multimodal: 1,027 (0.01)	• advanced ○ air: 33,393 (0.23) ○ rail: 108,871 (0.76) ○ multimodal:	• advanced ○ air: 26,141 (0.19) ○ rail: 109,352 (0.80) ○ multimodal: 1,487 (0.01) • emerging ○ air: 33,117

				• emerging ○ air: 36,334 (0.27) ○ rail: 97,383 (0.72) ○ multimodal: 2,400 (0.02) • median ○ air: 14,984 (0.16) ○ rail: 74,217 (0.81) ○ multimodal: 1,964 (0.02) • Canary Islands ○ air: 17,272 (0.95) ○ rail: 0 (0) ○ multimodal: 986 (0.05)	1,390 (0.01) • emerging ○ air: 35,912 (0.26) ○ rail: 97,079 (0.71) ○ multimodal: 3,049 (0.02) • median ○ air: 14,575 (0.16) ○ rail: 74,009 (0.81) ○ multimodal: 2,543 (0.03) • Canary Islands ○ air: 17,172 (0.94) ○ rail: 0 (0) ○ multimodal:	(0.24) ○ rail: 99,073 (0.73) ○ multimodal: 2,987 (0.02) • median ○ air: 14,375 (0.16) ○ rail: 73,840 (0.81) ○ multimodal: 2,458 (0.03) • Canary Islands ○ air: 17,061 (0.94) ○ rail: 0 (0) ○ multimodal: 1,163 (0.06)

					1,121 (0.06)	
Seamless of travel	transition time (between services) [mins]	Interoperability	avg	90.01	88.84	86.58
Infrastructure connectivity	Volume of passengers that are connecting at a given infrastructure node	Interoperability	By type of connection	See the graphical representation below		
Resilience alternatives	Numer of strategic (planned) and tactical (actual) alternatives available for a given origin-destination pair. [Number alternatives]	Flexibility	by NUTS	See the graphical representation below		
			by NUTS and mode type	See the graphical representation below		
			by region archetype	See the graphical representation below		
			by region archetype and mode type	See the graphical representation below		
Diversity of destinations	Number of destinations reachable from an origin [Number destinations]	Flexibility	by NUTS3 [total]	2,173	2,173	2,172
			by NUTS3 [avg]	38.1	38.1	38.1
			for each NUTS3	See the graphical representation below		
			by airport	400 (254 air, 146 rail)	421 (254 air, 167 rail)	404 (240 air, 164 rail)

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			[total]			
			by airport [avg]	11.4 (for 35 airports)	12.0 (for 35 airports)	11.8 (for 34 airports)
			by Hubs	See the graphical representation below		
Direct operating cost per user	Cost of trip for user [EUR]	Cost effectiveness	avg	55.05	57.78	55.60
Load factor	Number of passengers over capacity (seats) [percentage]	Cost effectiveness	total	0.70	0.70	0.70
			by modes	• flights: 0.70 • rail: 0.70	• flights: 0.69 • rail: 0.70	• flights: 0.70 • rail: 0.71
Capacity available	Capacity (seats) available between origin-destinations [Number seats and percentage over seats (1-load factor)]	Capacity	total	958,223	953,561	716,653
			between NUTS (at NUTS3 level) [total]	See the graphical representation below		
			between NUTS (at NUTS3 level) [total per mode]	See the graphical representation below		
			between NUTS (at NUTS2 level) [total]	See the graphical representation below		
			between	See the graphical representation below		

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			NUTS (at NUTS2 level) [total per mode]			
Demand served	Number of passengers assigned to itineraries over demand between origin-destination	Capacity	total [percentage]	0.81	0.81	0.79
			total [number pax]	389,191 (over 481,141)	389,114 (over 481,141)	381,054 (over 481,141)
			total connecting passengers [percentage]	0.05	0.05	0.06
			by NUTS (at NUTS3 level)	See the graphical representation below		
			by NUTS (at NUTS2 level)	See the graphical representation below		
			by region archetype	See the graphical representation below		

Catchment area of airports	Distance from which passengers access the airport (different definitions as a function of variant)	Capacity	by airport as time of rail distance in multimodal journey (min)	See the graphical representation below
			by airport as volume passengers accessing (egressing) airport per NUTS3	See the graphical representation below
			by airport as volume passengers per region accessing (egressing) in multimodal journey per NUTS3	See the graphical representation below
			by airport as total volume passengers accessing (egressing)	See the graphical representation below

			airport per NUTS3			
CO2 emissions	Emissions per passenger on services used by passengers based on emissions per seat [Kg CO_2]	Environment	avg	20.84	20.89	20.11

Table B6: Main performance indicators defined in the multimodal performance framework for cs10.ppxx.nd00.so00.00 (intra-Spain mobility, with network respecting airline alliances, without SOL400/SOL2)

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Discussion per PI (and graphical performance indicators)

Passengers processing time

As shown in Table XYZ, the average processing time of passengers (kerb-to-gate, gate-to-kerb, kerb-to-platform and platform-to-kerb) does not change significantly across the scenarios. The reduction observed in pp20 could be attributed to a reduction of passengers in some airports, which means that in proportion, more passengers are using rail where processes are shorter.

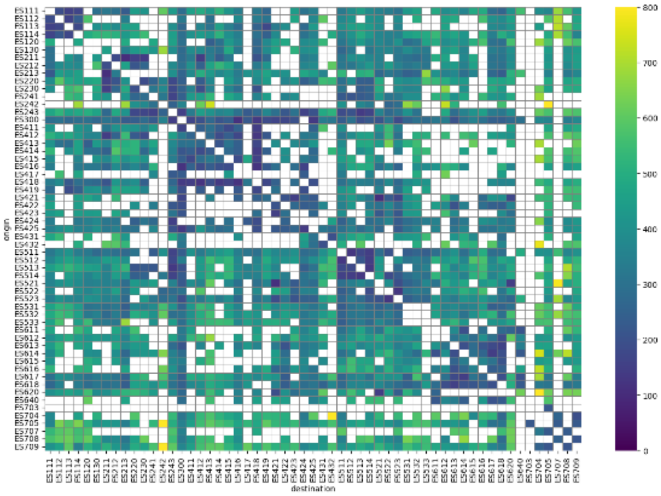
Total journey time

The total journey time is very similar between pp00 and pp10, with a small increase in pp10 which could be attributed to the slightly higher use of multimodal journeys. In pp20, with the flight ban, the total travel time decreases slightly, even if flights are removed. This is due to the fact that only flights with trains with similar door-to-door time are banned (up to 180 minutes), the rail demand increases and the overall demand satisfied is reduced (from 0.81% of the demand satisfied in pp00 and pp10 to 0.79%).

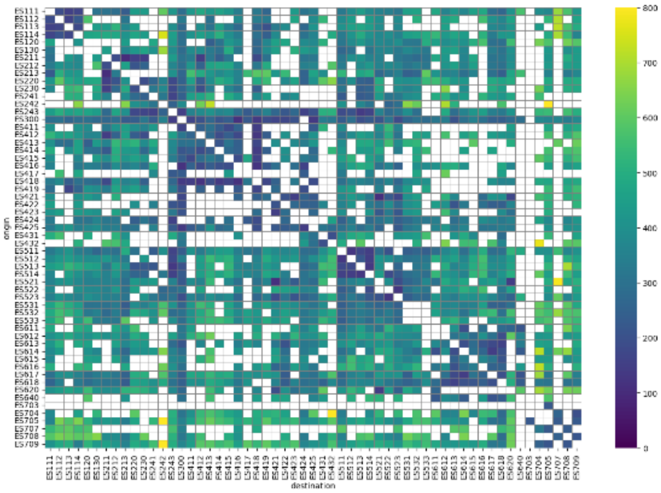
At aggregated level, it is difficult to observe the impact of the regulations on the total travelling time (even when disaggregated per region archetype). In the disaggregation per region archetype, it is possible to observe how the largest reduction in total travel time for pp20 with respect to the other scenarios is for the 'advanced' regions. This could be again linked to these regions being the ones impacted the most by the ban and, therefore, with lower demand satisfied.

To assess better the total journey time, further disaggregation at the NUTS level can be performed. Here the average total journey time is shown between NUTS in a graphical representation: Figure B7 presents the average total travelling time between all NUTS3; Figure B8 aggregates the results at NUTS2 level (to simplify the visualisation); and Figure 9 shows how with the data computed by SOL399/SOL1 it is possible to obtain a graphical representation of the total journey time from a given region (at NUTS2) to all other regions.

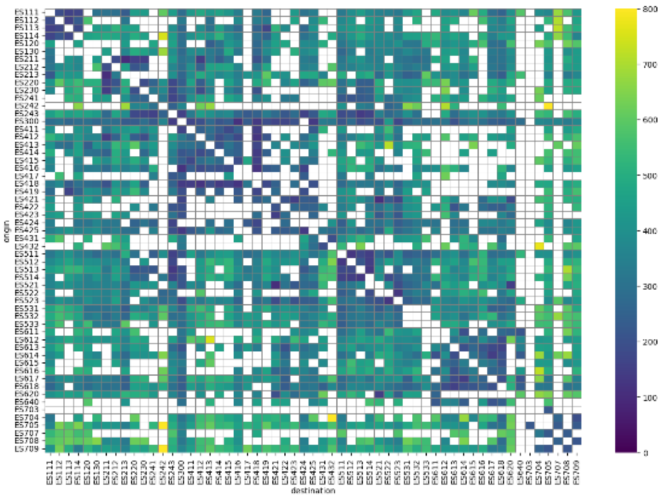
Average total journey time between NUTS at NUTS3 level



pp00



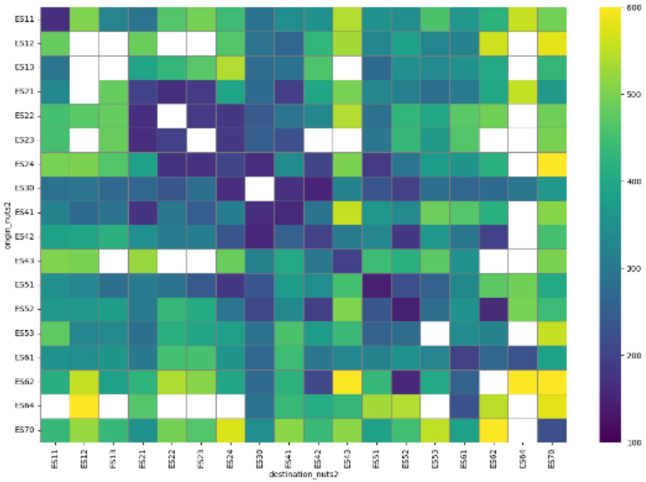
pp10



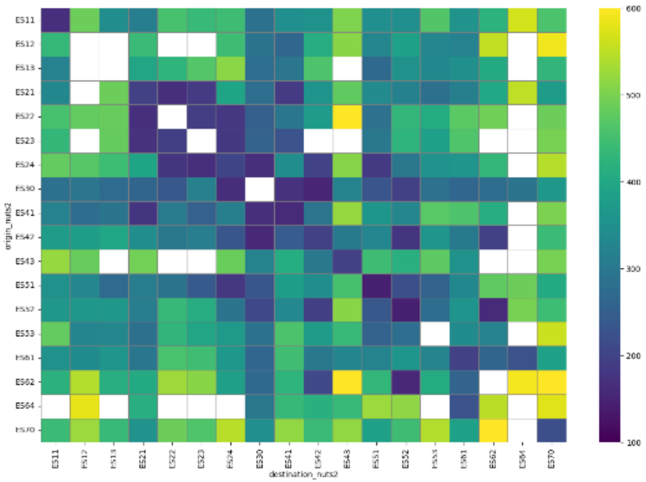
pp20

Figure B7: Total travel time between NUTS3 regions for different scenarios.

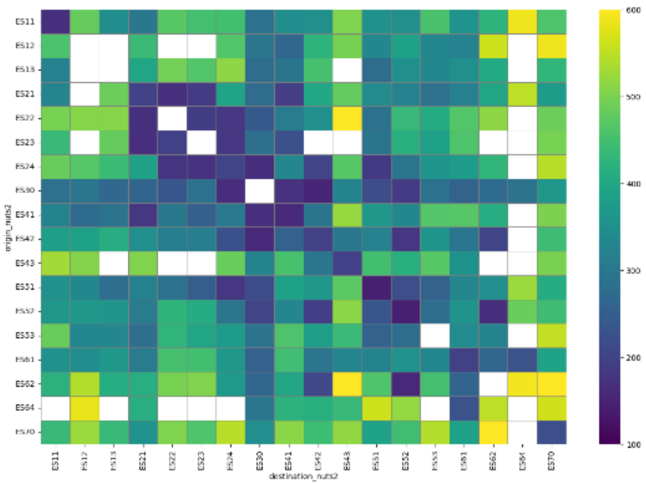
Average total journey time between NUTS at NUTS2 level



pp00



pp10



pp20

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Figure B8: Total travel time between NUTS2 regions for different scenarios.

Average total journey time between NUTS from NUTS2 to NUTS3 level

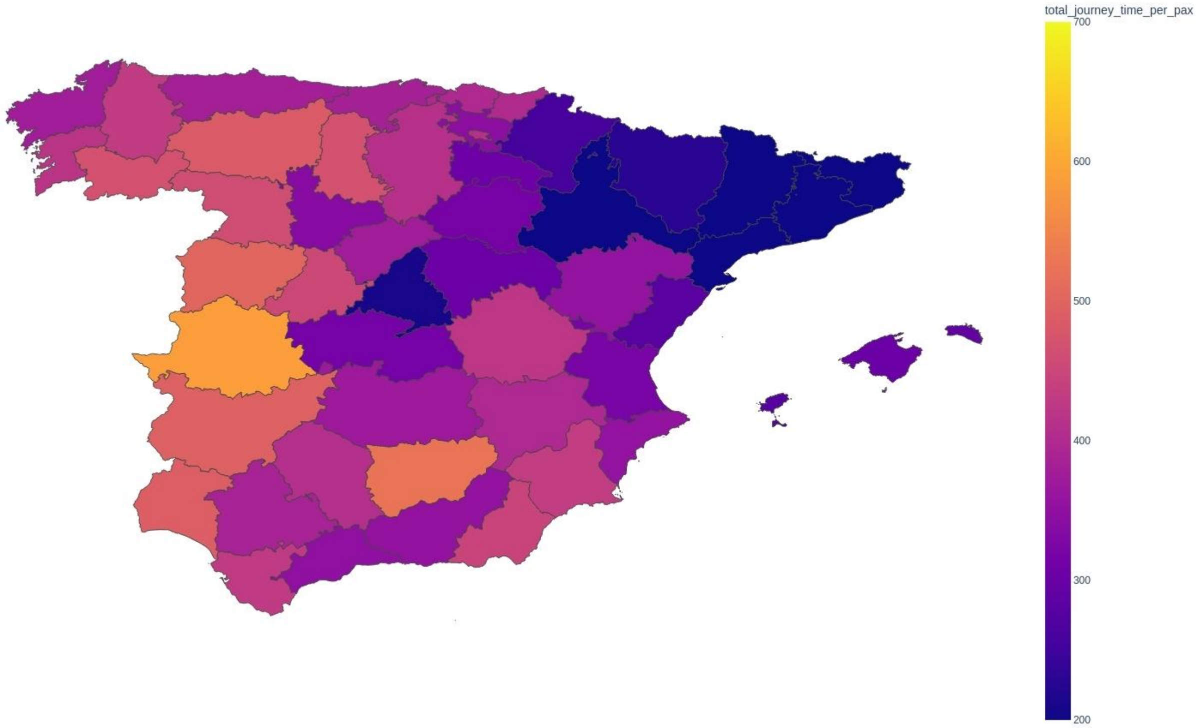

Figure B9: Total mobility time from ES51 to NUTS3 regions for pp00 scenario

Passenger time efficiency

This indicator is computed by considering the best possible journey time over the planned time of travel. As shown the results are very similar across the three scenarios (0.88). This could be expected as the indicator is computed with respect to the best possible journey within each scenario. Future evolution could be the comparison of the journey times with respect to the best in the baseline scenario. That could provide a better view of the improvement/degradation of the time efficiency across scenarios.

Buffer in itineraries

As shown in Table B6, with the flight ban (pp20), the total waiting time increases but not in a significant way. The average waiting time is similar across all three scenarios. This is expected as schedules are not optimised (only connecting time is reduced with the introduction of integrated ticketing (in pp10 and pp20)). Therefore, the average waiting time is not optimised and similar. We could expect that when SOL400/SOL2 is implemented, these values would be reduced.

Modal share

As shown in Tabler B6, the modal share between the three modes (air, rail, multimodal) in the three scenarios is similar (26% air, 72% rail and 2% multimodal). The introduction of incentivised policies

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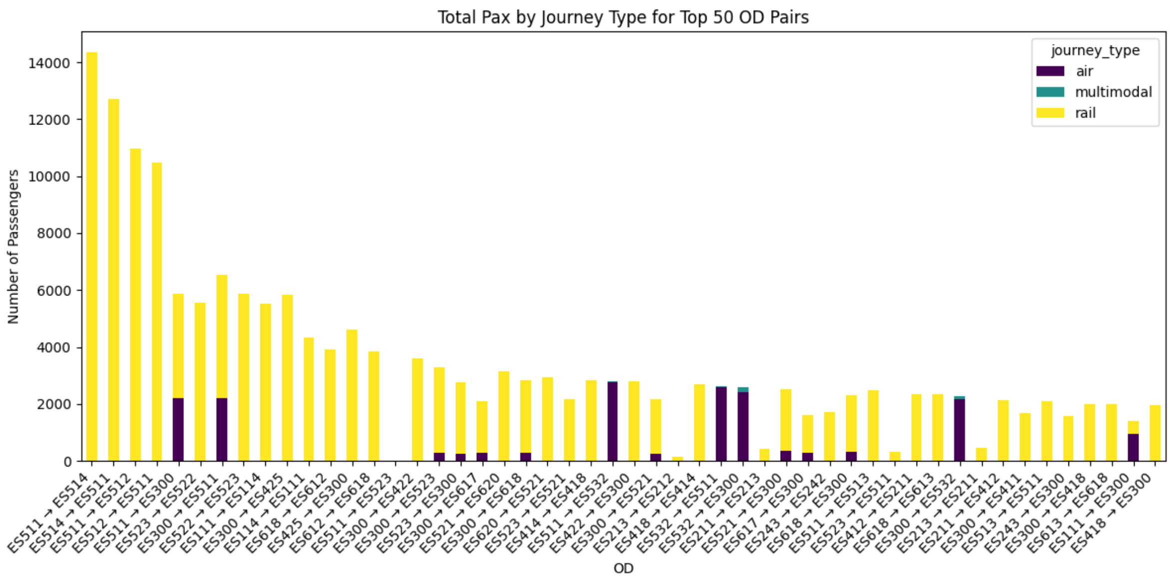
(pp10) and enforced policies (pp20) reduce the absolute number of air passengers while increasing multimodal passengers, but still in a very limited way. With the enforced policies (pp20), there is a slight increase in multimodal journeys (to 2.1%) but mainly a reduction of air share (23.8%) and an increase in rail demand (74.1%).

Besides looking at the values for the whole network, as the observed shift is due to the introduction of flight ban, the model allows us to evaluate the modal share between origin-destination pairs that were originally linked using one of the 104 flights banned in pp20. For those regions, the mode share is 18.1%, 80.7%, and 1.2% for air, rail and multimodal, respectively in the baseline case (pp00), while in pp20, we observe 7.8%, 90.6% and 1.5%. So, the increase in multimodal is still limited and more passengers are instead shifted to rail. This is because, in most cases, the multimodal alternative is significantly longer in time on average (533 minutes in the multimodal alternative instead of 220 and 320 minutes for rail and air, respectively). So, the average travel time between those regions does not change significantly due to the flight ban. This could also be expected, as flights are only removed if a suitable fast rail alternative is available. However, the total demand served between those regions is reduced. From 94.5K passengers in pp00 to 86.6K passengers in pp20. This analysis shows, once again, the importance of not focusing on a single indicator but delving into different ones to get a more complete picture of the impact of the policies.

Besides this analysis, we could focus on the different region archetypes, where once again, we observed how the shift to rail is more pronounced in advanced regions, as these are the ones more directly impacted by the elimination of the flights.



Number of passengers served per mode between top 50 higher demand NUTS3 pairs in pp00

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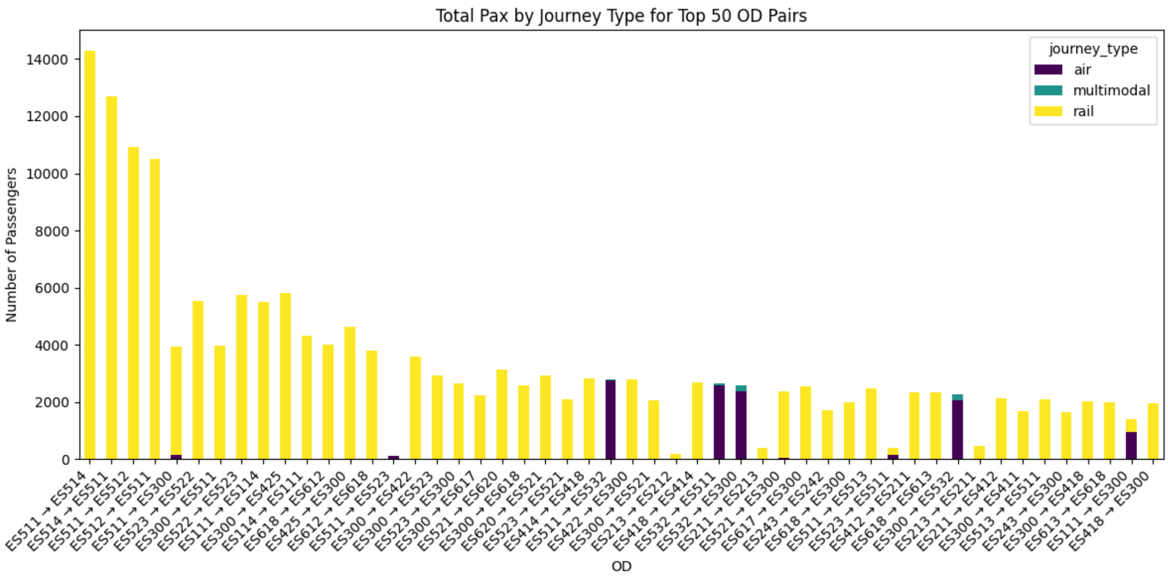
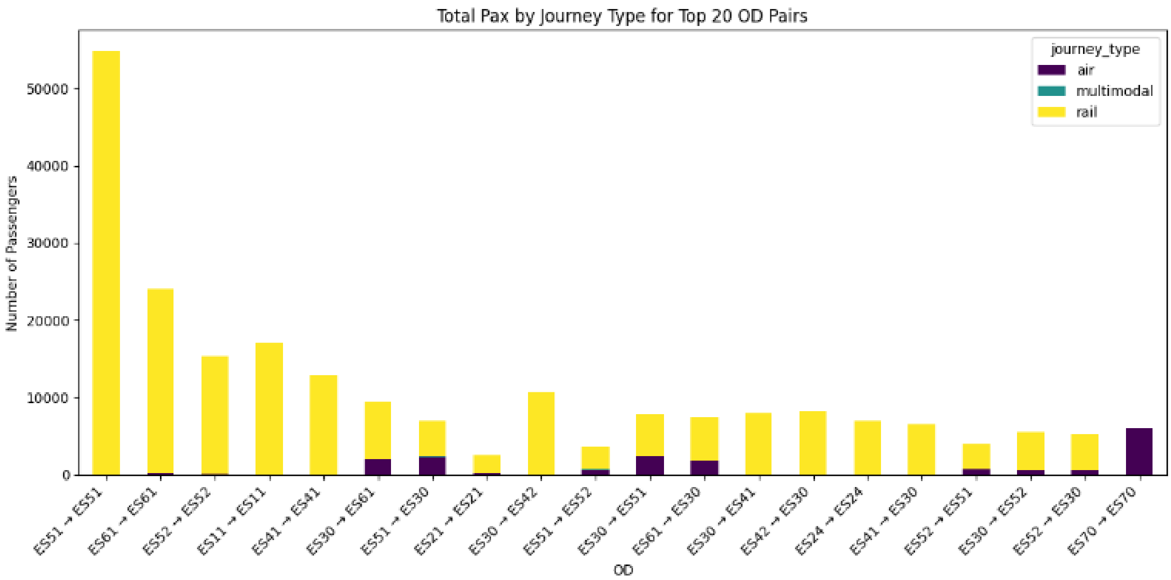
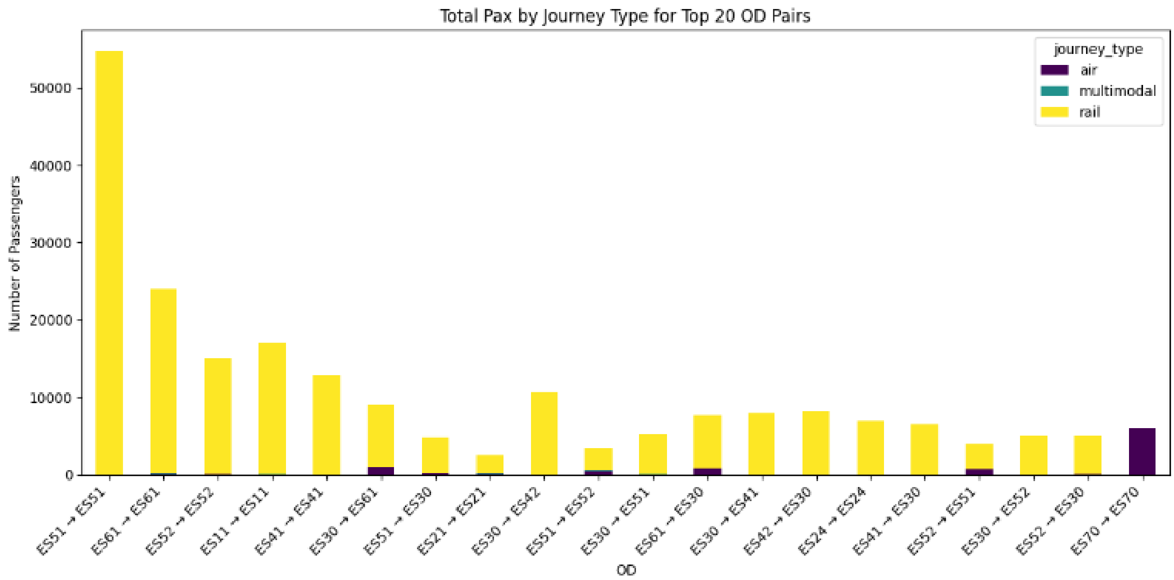


Number of passengers served per mode between top 50 higher demand NUTS3 pairs in pp20



Number of passengers served per mode between top 20 higher demand NUTS2 pairs in pp00



Number of passengers served per mode between top 20 higher demand NUTS2 pairs in pp20

Figure B10 Number of passengers served per mode between NUTS

Finally, it is possible to study the modal share with more granularity by assessing the split of passengers between modes for specific origin-destination pairs. Figure B10 presents the total number of passengers served between the origin-destinations pair with higher demand split by mode. Of course, a similar representation could be done by the percentage of mode share rather than an absolute number of passengers.

First, it is interesting to observe how, in some cases, the demand satisfied is higher for origin-destination pairs, which have lower overall demand. For example, there are more passengers served between ES300 to ES511 (Madrid to Barcelona) than between ES523 to ES522 (Valencia to Castellon) in pp00 even though there are more passengers demanding ES523 to ES522 than ES300 to ES511 as per their order in the plot. Note how in pp20, ES523 to ES522 serves more passengers (as not effected by the flight ban), while Madrid to Barcelona (and Barcelona to Madrid) suffer a significant reduction of demand satisfied (see *Capacity available* indicator for more details on this case).

Second, it is worth noticing the importance of rail to connect the regions with higher demand for intra-Spain mobility. This is expected as, in some cases, the demand is between adjacent (or close) regions (e.g. ES511 (Barcelona) to ES514 (Tarragona)), where the only reasonable mode of transport is rail.

Third, the lack of capacity in the system for some origin-destination pairs might shift the mode share. For example, in the Madrid to Barcelona case, the logit model for the baseline case produce a split of 76.6% of demand to rail and 23.4% to air (as shown in Section B3.2.1.2 – Experiment 2 - Calibration of Evaluators). However, the split observed here for pp00 is 66.3% and 33.7% for rail and air respectively. This higher proportion of flight passengers is due to a lack of capacity in the rail system as shown in *Capacity available* indicator below.

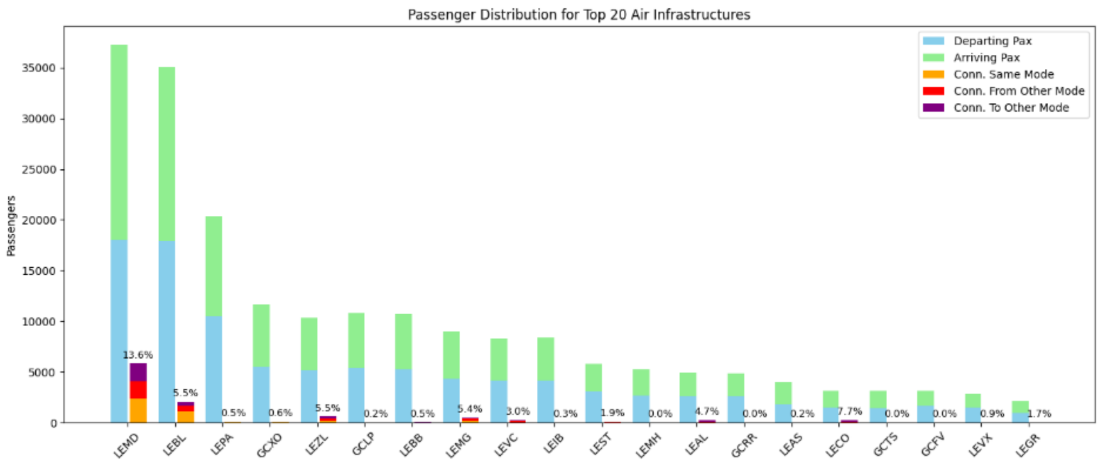
Finally, one can see how multimodality is very limited appearing mainly when reaching destinations outside mainland Spain (e.g. ES532-ES300 (Mallorca to Madrid)).

Seamless of travel

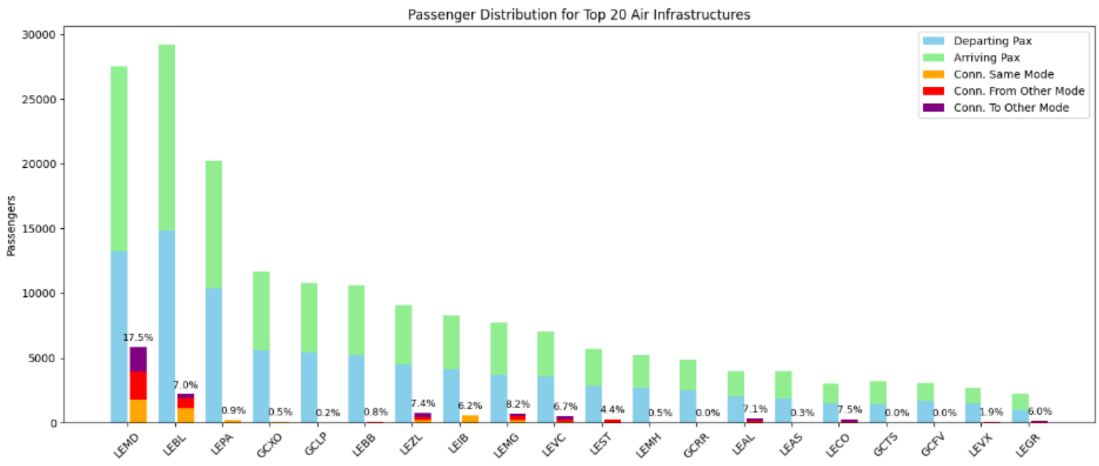
In this case, the definition of this indicator relies on the connecting time between services. We can observe a small reduction between pp00 and, pp10 and pp20, which could be attributed to the use of integrated ticketing, which reduces the inter-mode connecting times. However, as the number of multimodal passengers is low in comparison with rail-rail connections (for example), the total reduction is limited (from 90 in pp00 to 88 and 87 minutes for pp10 and pp20). Once again, the usage of SOL400/SOL2 might reduce these times by producing optimised connections for passengers.

Infrastructure connectivity

Besides analysing the mobility between regions, it is possible to analyse the passenger types within the infrastructure nodes to better understand how they are connected and the impact of the policies.



Baseline (pp00)



Multimodality enforced (pp20)

Figure B11: Top 20 airports (per volume of passengers) with type of passengers for baseline and multimodality enforced cases.

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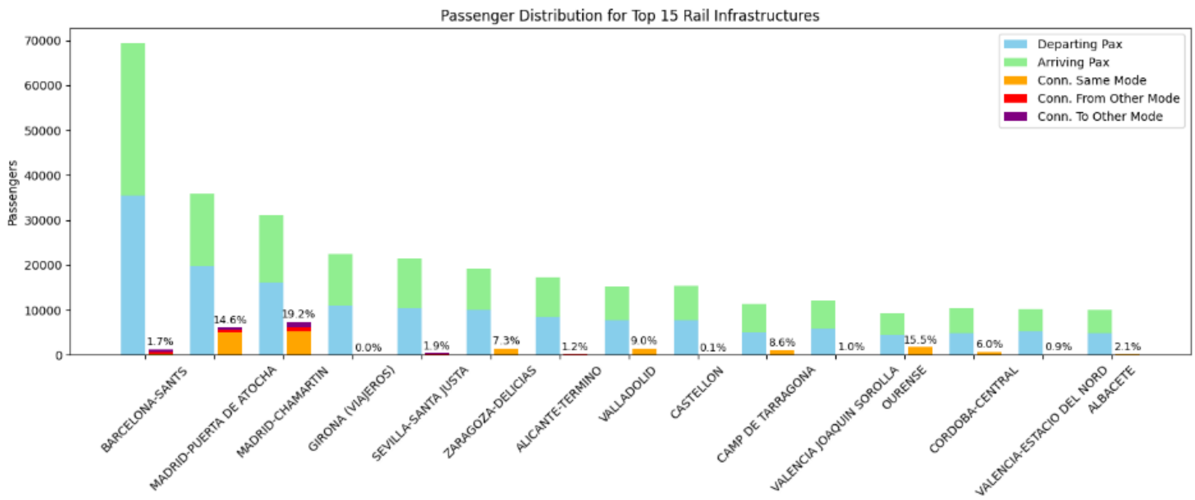
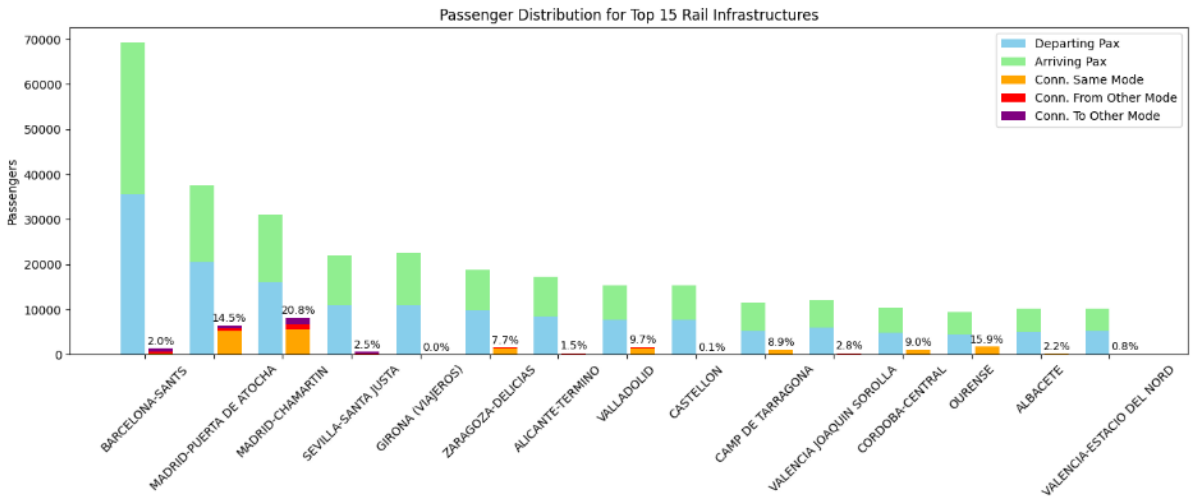
Figure B11 shows how Madrid (LEMD), Barcelona (LEBL) and Palma de Mallorca (LEPA) are the airports with the higher volume of passengers. For all airports, there is a natural split between arrival (starting their journey at the infrastructure) and departing (finalising their trip at the infrastructure) passengers. It is observed how, in the multimodality-enforced case, the number of connecting passengers tends to increase (e.g. from 13.6% in LEMD to 17.5%). Note how more than half of the connecting passengers in LEMD are multimodal. This is due to the fact that we are focusing only on intra-Spain mobility. As previously discussed (not shown due to the low volume of passengers), Valladolid (LEVD) has the highest percentage of connecting passengers, 45.1% and all of them are multimodal.



Baseline (pp00)



Multimodality enforced (pp20)

Figure B12: Top 20 rail stations (per volume of passengers) with type of passengers for baseline and multimodality enforced cases.

Figure B12 shows the same results but for rail stations. As observed, Madrid rail stations are the ones with higher connectivity, and most of it is wishing the same mode.

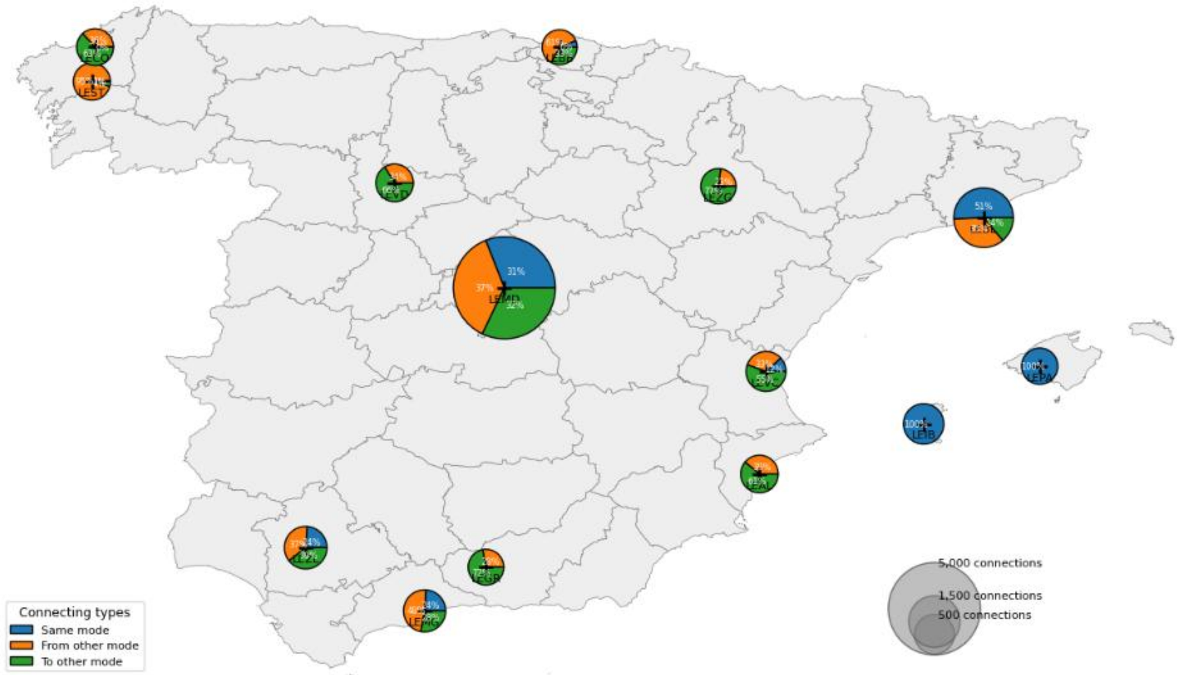


Figure B13: Connectivity at airports for multimodality enforced (pp20)

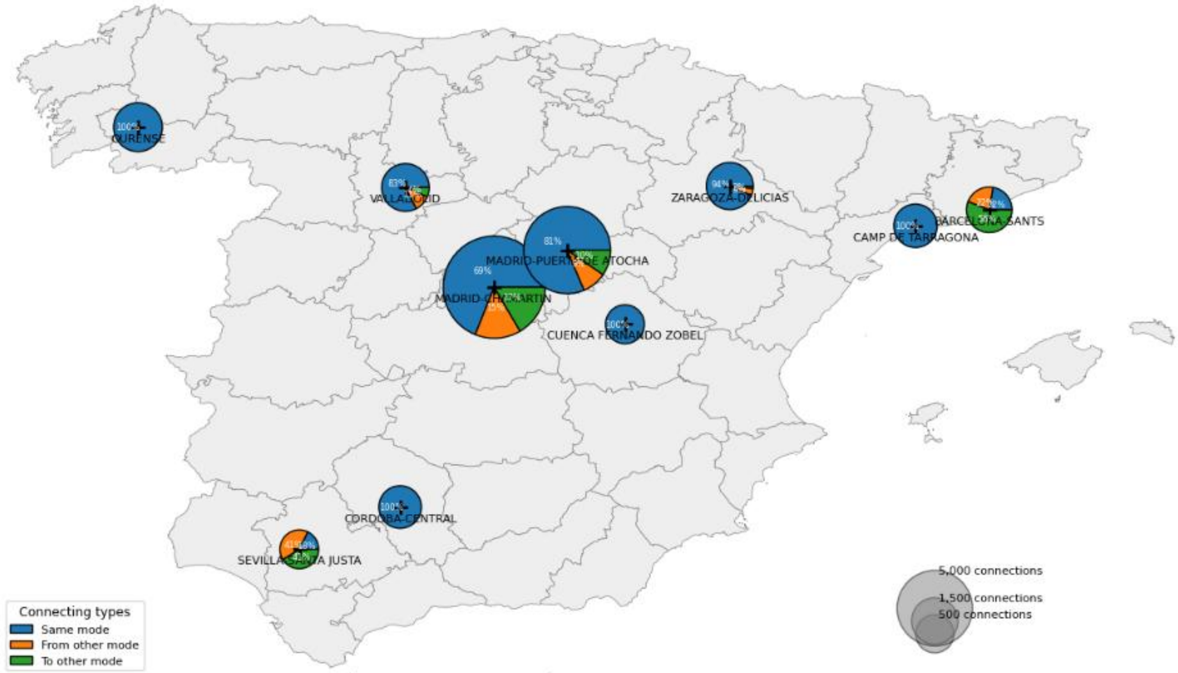


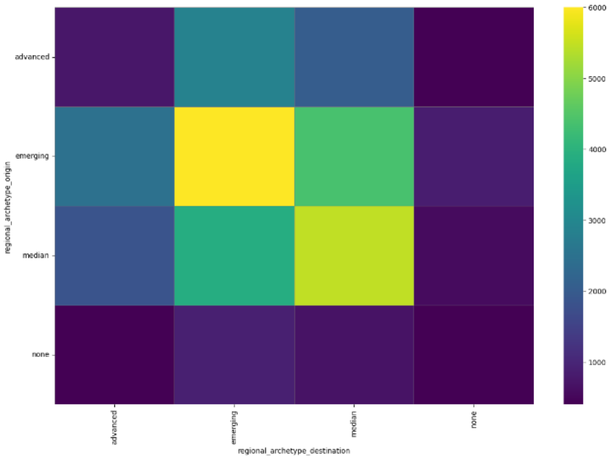
Figure B14: Connectivity at rail stations for multimodality enforced (pp20)

Finally, Figures B13 and B14 present maps of Spain with the infrastructure nodes representing the volume and type of connections.

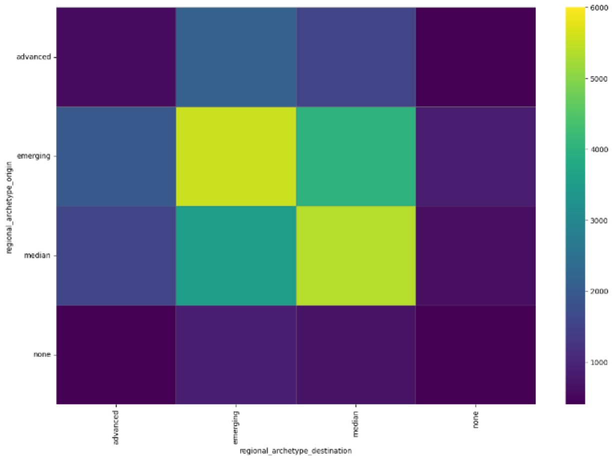
<u>Resilience alternatives</u>

The resilience is estimated by the number of alternatives available between a given origin and destination. In this case, the representation is shown in Figure 15 for mobility between region archetypes, NUTS3 regions and NUTS3 regions disaggregated by mode (air, rail and multimodal) for pp00 and pp20.

It is possible to observe how, overall, the flight ban that pp20 implements represents a significant reduction of air alternatives between the regions impacted by the ban (as those flights are removed) and also between regions which rely on air-air connections (which now might have a lower number of alternatives). This is shown overall in the number of alternatives, which for p00 is 34,008 between all the origin-destination pairs; increases to 34,712 in pp10 with the integrated ticketing, which reduces the multimodal connecting times; and gets reduced to 29,765 in pp20 when the flight ban is applied and alternatives using air (and air connections) are eliminated.



Between region archetypes for pp00



Between region archetypes for pp20

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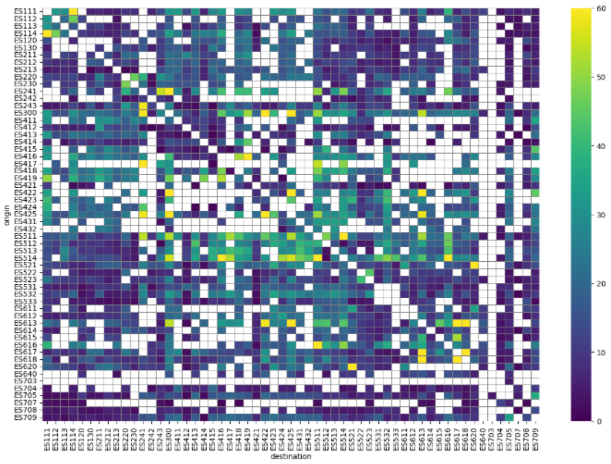
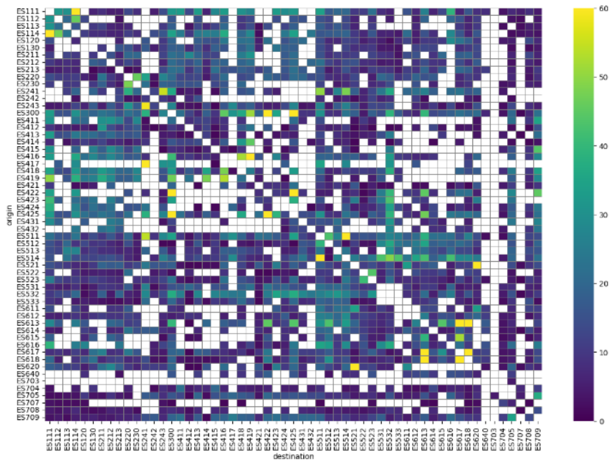
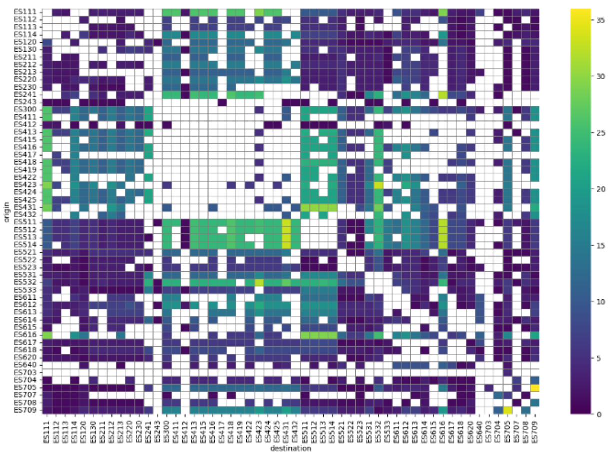


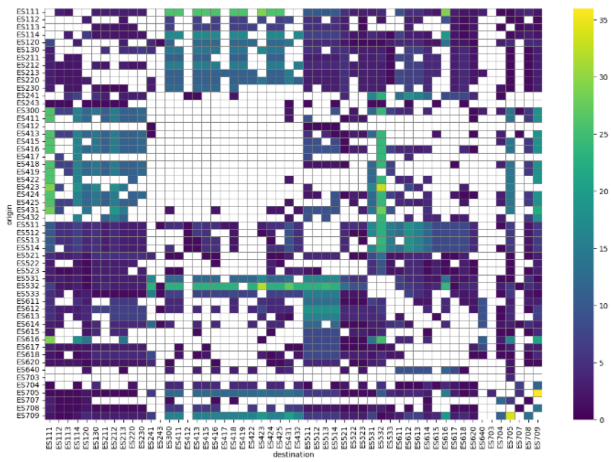
Between NUTS3 for pp00



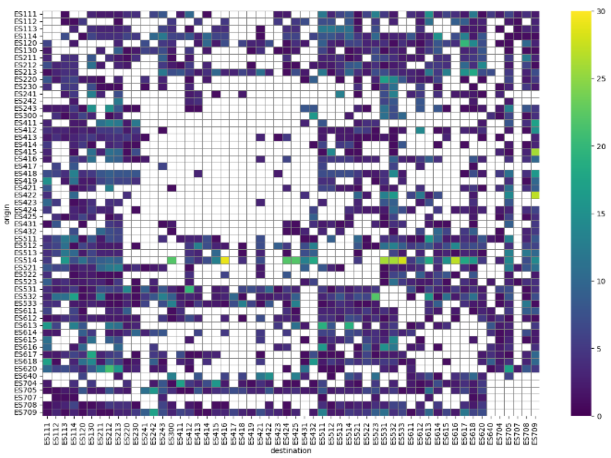
Between NUTS3 for pp20



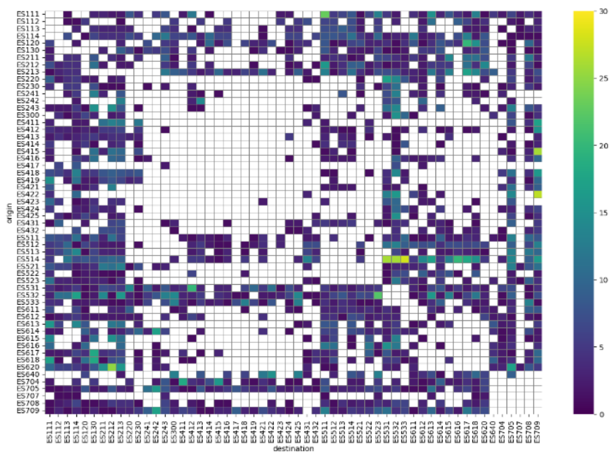
Between NUTS3 for pp00 - air mode



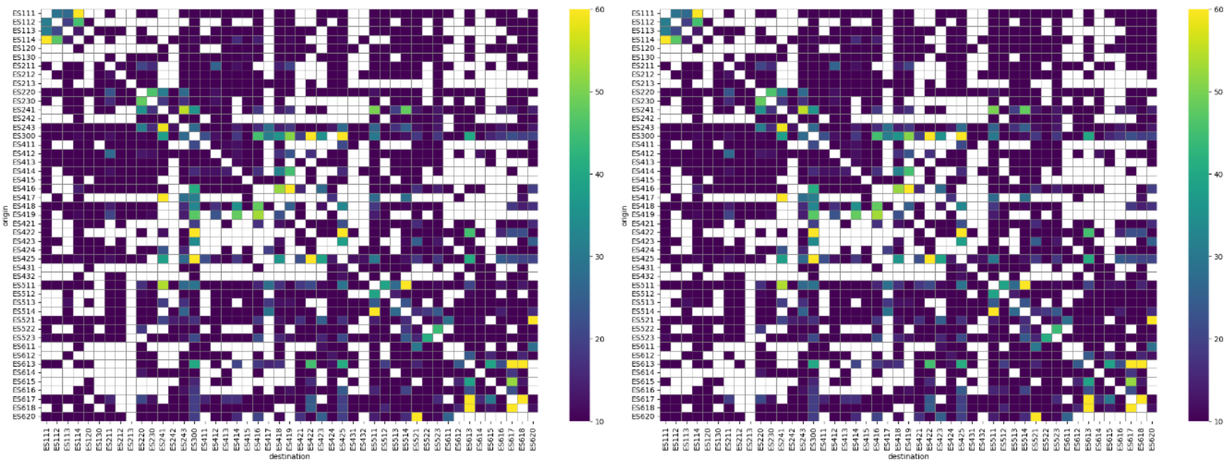
Between NUTS3 for pp20 - air mode



Between NUTS3 for pp00 - multimodal



Between NUTS3 for pp20 - multimodal



Between NUTS3 for pp00 - rail

Between NUTS3 for pp20 – rail

Figure B15: Resilience alternatives (number of alternatives between origin and destination)

<u>Diversity of destinations</u>

The diversity of destinations is simply defined as the number of destinations reachable from a given NUTS or infrastructure node (airport).

Diversity of destination NUTS

Even if the number of alternatives might be different for the different scenarios (with the reduction indicated for pp20 due to the flight ban), this does not translate into a significant reduction in the destinations that can be reached from each NUTS. In fact, between pp00 (baseline) and pp10 (incentivised policies), the total (addition) number of destinations reachable considering each NUTS3 in Spain is 2,173 (an average of 38.1 destinations per starting NUTS), i.e., the introduction of the policies does not change the reachability from each region. In the case of the flight ban (pp20), the total number of destinations is 2,172, and only ES511 (Barcelona region) gets a reduction of one possible NUTS3 (from 55 to 54). Therefore, the introduction of the policies does not prevent (or block) the mobility between regions in any meaningful way.

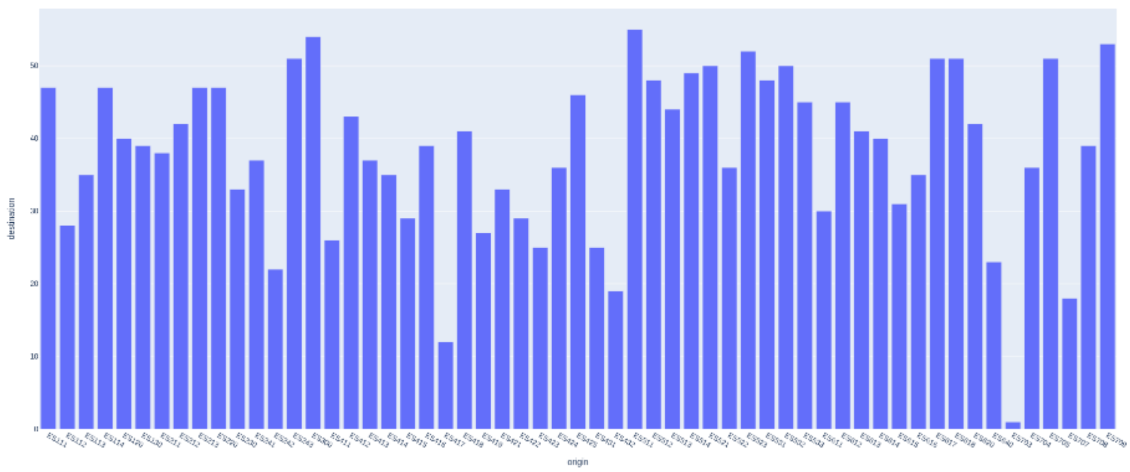


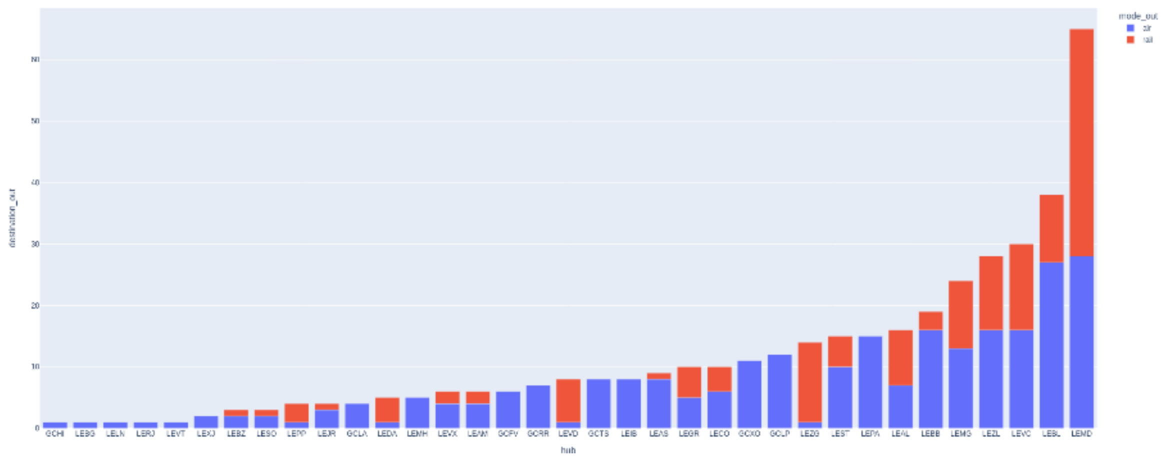
Figure B16: Diversity of destinations from each NUTS3 in pp00.

Figure B16 shows the number of destinations reachable from each NUTS3 for pp00.

Diversity of destination Airports

When focusing on airports we can estimate the diversity of destinations reachable from the airports. In the baseline case (pp00) there are a total of 400 destinations reachable starting at the airports with 254 by air and 146 with a follow up rail multimodal connection (average of 11.4 destinations per airport). With the incentivisation policies (pp10), the diversity of destinations increases to 421 thanks to the increment to 167 of follow-up rail multimodal connections (as connecting times are reduced due to integrated tickets). Therefore, the average diversity of destination per airport increases to 12.0. Finally, the flight ban (pp20) reduces the number of air destinations to 240, leading to a total diversity of destinations of 404 (an average of 11.8 per airport).

The comparison between the baseline (pp00) and enforced policies (pp20) shows that LEMD reduced the air connections by six (from 28 to 22) due to the air ban while increasing the rail connections from 37 to 38. Barcelona airport (LEBL), also impacted by the flight ban in its flights to Madrid, reduces the air destinations from 27 to 25 while increasing the rail ones from 11 to 12. Some regional airports increase their multimodal connectivity as they provide service to a wider region; for example, Granada increases from 5 to 6 rail destinations while Valladolid (LEVD) increases significantly the destinations reachable by rail from 7 to 12 (increment of 5), both airport maintain their air destinations. This shows how the flight ban can have an indirect impact on airports, which are not directly affected by the banning of flights, but that they gain relevance as regional connectors. This will be further explored in the analysis of the catchment are of airports. Finally, airports like Palma de Mallorca (LEPA) do not change the diversity of destinations due to the implementation of the policies in pp20.



pp00

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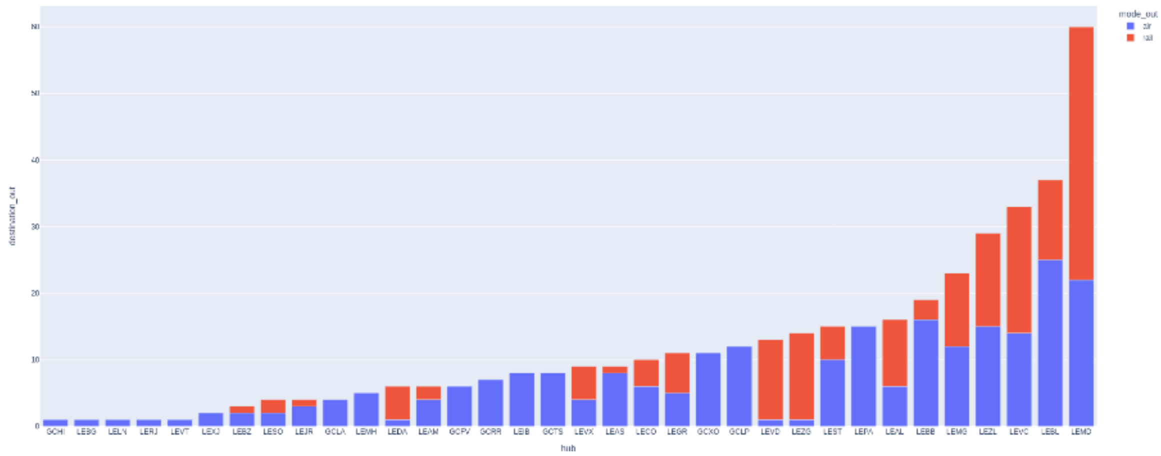

pp20

Figure B17: Diversity of destinations from airports

Figure B17 shows airports ranked by the destinations that can be directly reached from them by mode for the baseline and enforced policies scenarios. It is interesting to observe how the number of destinations reachable changes, including the relevance of airports.

<u>Direct operating cost per user</u>

The direct operating cost per user is estimated by adding the cost of the services (rail and flights) used by the passengers. As observed in Table xyz, there is no significant change in average on the cost for passengers to travel within Spain (around 55-57 EUR per trip for all cases on average). It could be interesting to consider (as future work) the assessment of cost per origin-destination pair to better assess the impact of the different policies on more specific cases.

<u>Load factor</u>

When considering the load factors, it is observed that, on average, 70% of the capacity is used. This is maintained across modes and across scenarios. However, it is worth noticing that this is, on average, for the whole system capacity. This means that some regions might have a large oversupply while other areas might be constrained. This will be further analysed in the Capacity available indicator.

<u>Capacity available</u>

The total capacity available in the system (seats available) is similar between the baseline (pp00) and the incentivised cases (pp10). This can be expected as the demand served is similar (389K passengers). In pp20, the extra capacity of the system is reduced by over 200K seats. In this case, the reasons are two-fold: first, 104 flights are banned; however, they account directly for only 14.7K seats; the second reason is the increase in rail demand and the indirect effect of services. As shown by the *modal share* indicator, pp20 has close to 2.5K extra passengers in rail than pp00 and pp10. These passengers not only use those 2.5K seats but can effectively block many possible itineraries (e.g. passengers using a train service between stops 3 and 5 will impede other passengers from using the same train service between stops 1 to 4, 1 to 5, 2 to 4, 2 to 5, etc.). This means that the train system gets saturated on links with high demand. On the air side, the 14.7K seats directly removed

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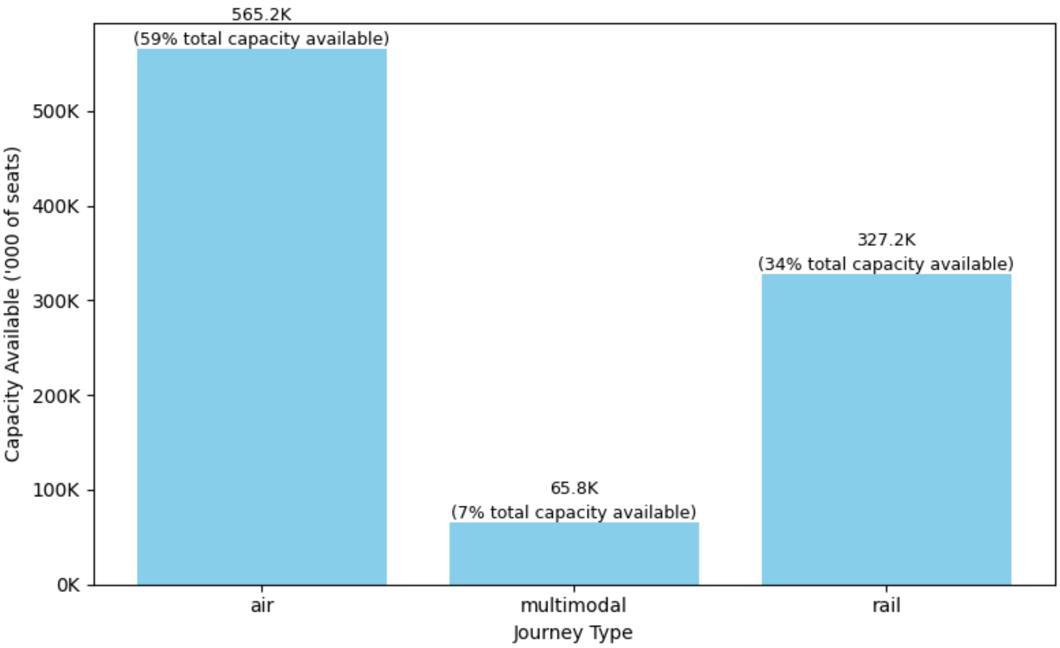
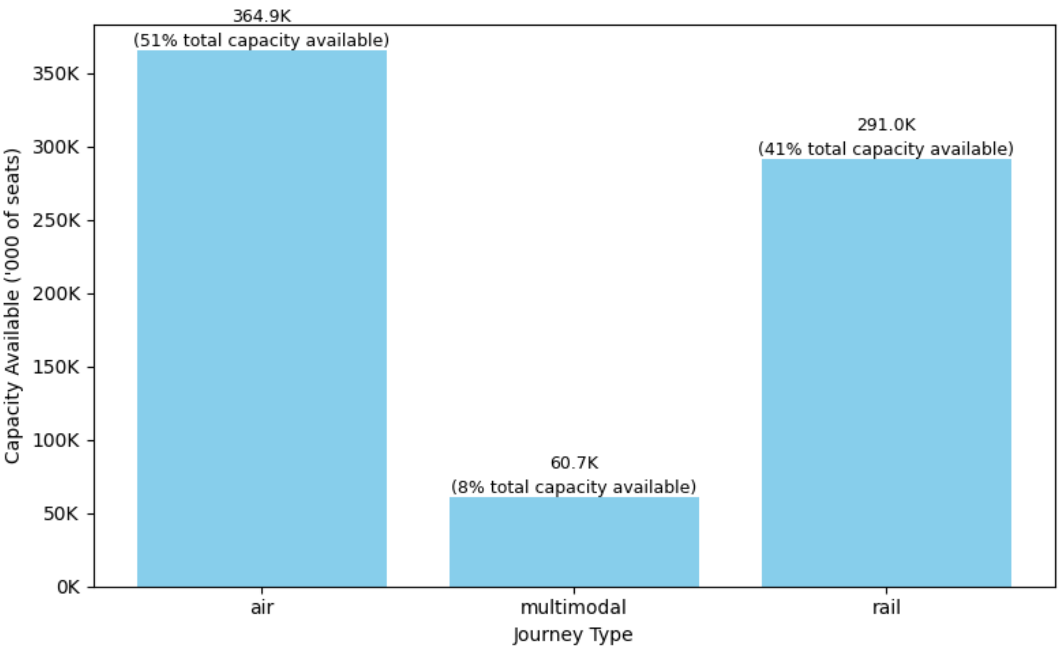
limit the possible seats available when considering the possible connections that could have been made with those services. Due to these interactions between services, when reporting the capacity available some *double counting* is produced on the aggregated numbers.



Baseline - pp00



Enforced policies - pp20

Figure B18: Capacity available per mode for the three scenarios.

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Figure B18 shows the capacity available in the system considering the type of journeys for the baseline and enforced policies scenarios. The incentivised policy case has similar results as the baseline but is not presented for simplicity.

Note that, as mentioned, this capacity is not independent, i.e., in the air capacity some of it might be provided by connecting flights which *overlap* with other itineraries (either air or multimodal).

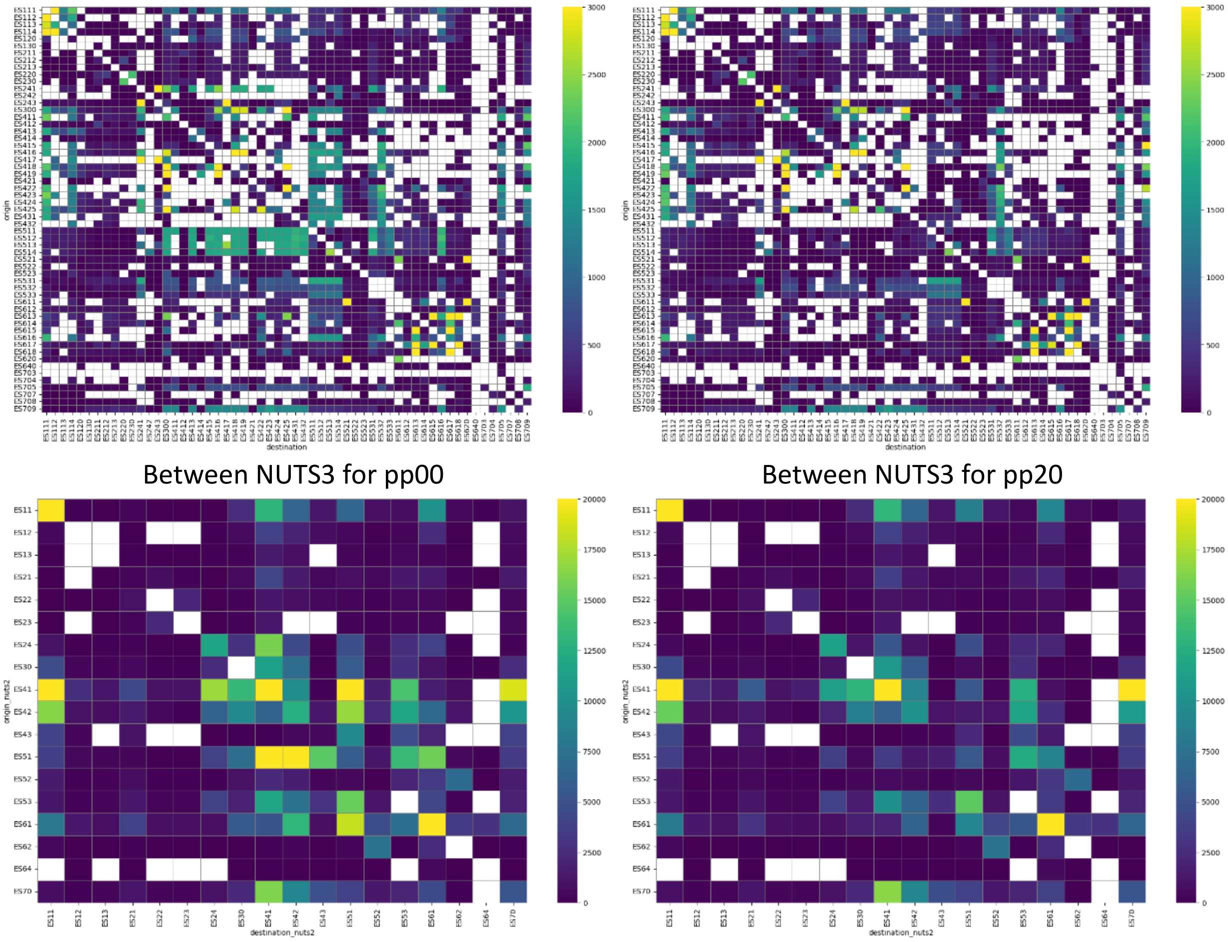
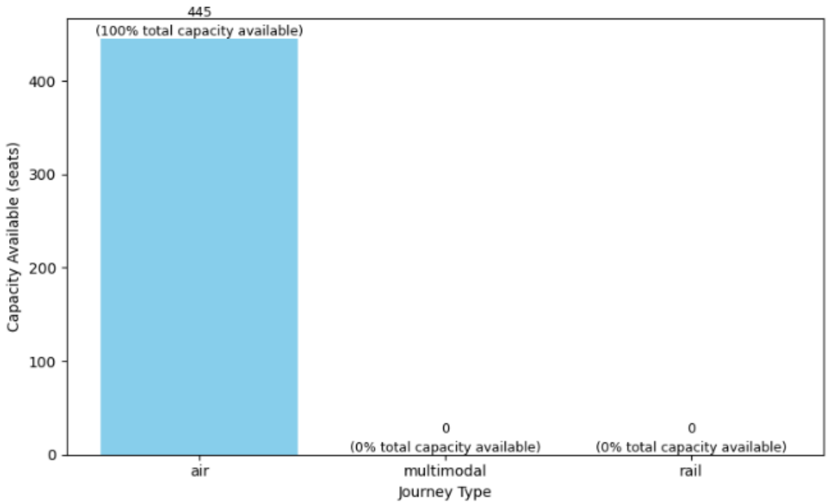


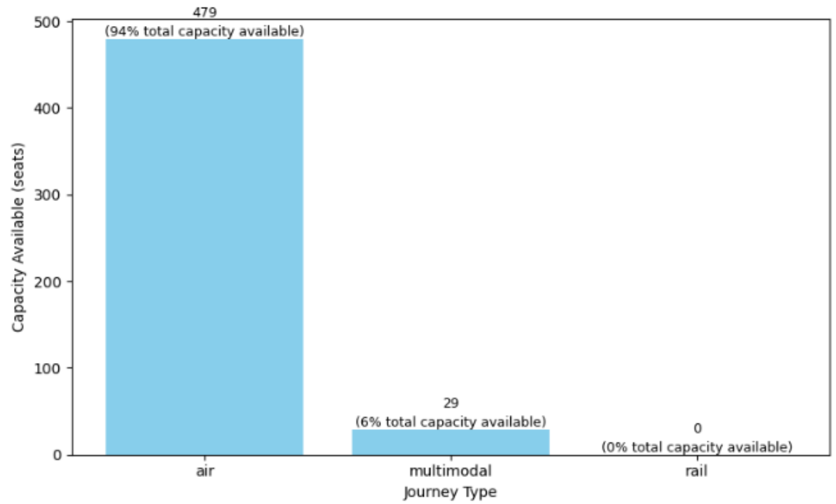
Figure B19: Capacity available between NUTS (levels 2 and 3) for baseline (pp00) and enforced policies (pp20) cases.

Figure B19 shows how when the enforcing policies are in place, the capacity available between different origin-destination pairs is reduced. It is worth noticing how this limitation in capacity is not spread uniformly across all the origin-destination pairs. For example, the connections between ES51 (Catalonia) and ES41, ES42, and ES43 (Castille-Leon, Castille-La Mancha and Extremadura) reduce significantly.

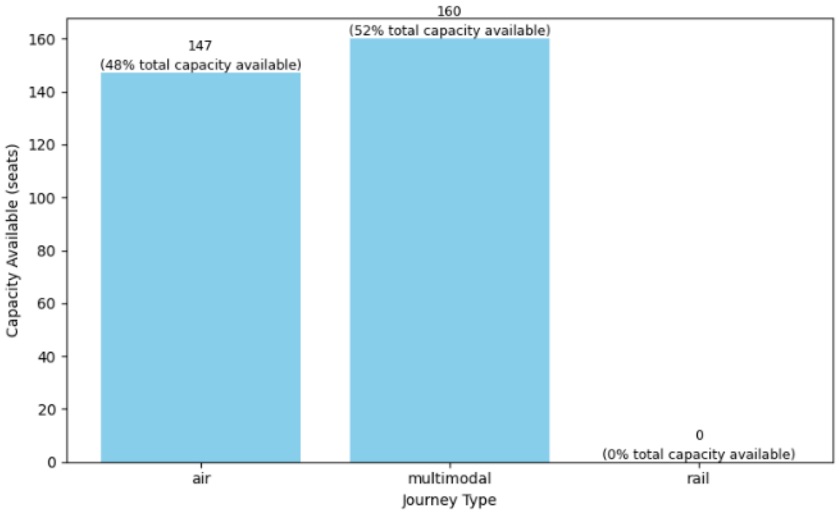


ES1

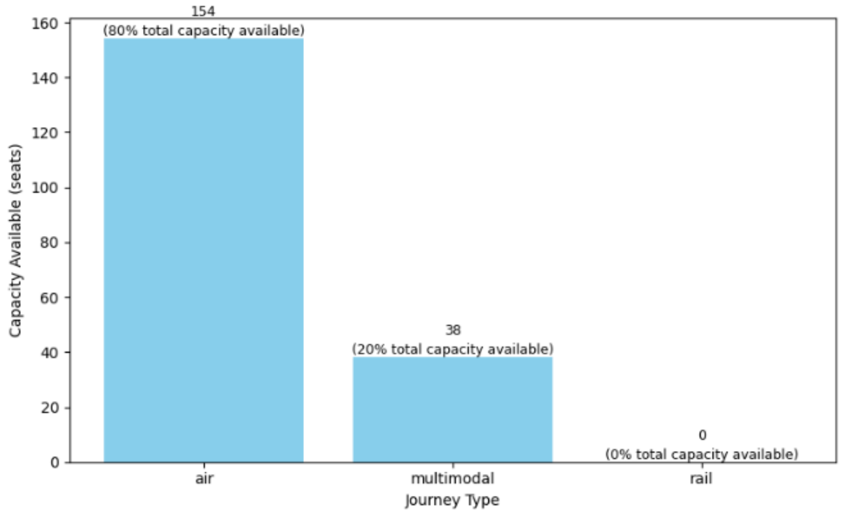
11 - ES512 (A Coruna - Girona) for pp00



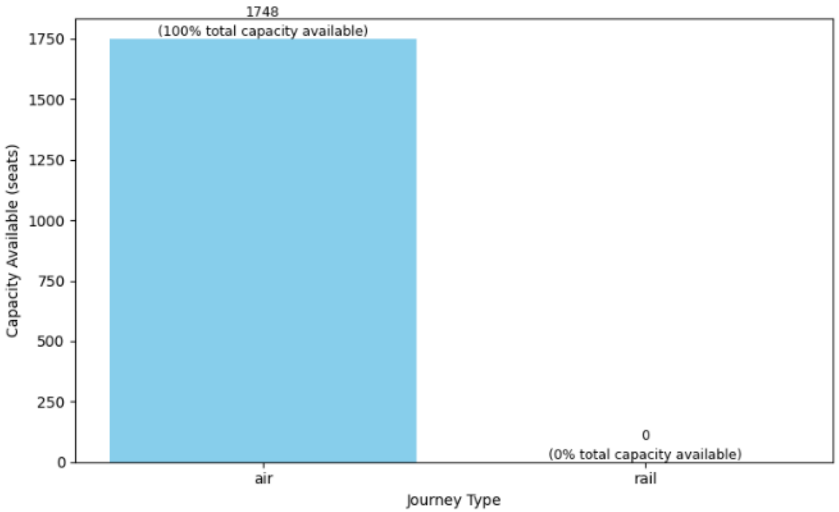
ES111-ES512 (A Coruna - Girona) for pp20



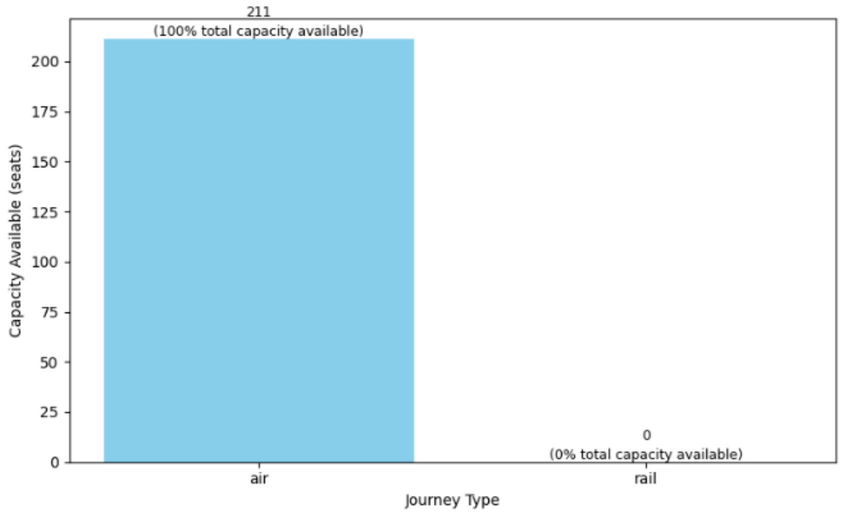
ES617-ES511 (Malaga - Barcelona) for pp00



ES617-ES511 (Malaga - Barcelona) for pp20



ES511 - ES300 (Barcelona to Madrid) for pp00



ES511 - ES300 (Barcelona to Madrid) for pp20

Figure B20: Capacity available between selected NUTS3 for baseline (pp00) and enforced policies (pp20)

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Figure B20 shows the capacity available between a selection of origin-destination NUTS3 for the baseline (pp00) and enforced policies (pp20) cases. Once again, the reader is reminded that this is estimated considering the possible itineraries between those regions and the seats available on those services independently.

The first example (ES111 - ES512) shows the seats available from A Coruna to Girona (crossing from the North-West to the North-East of Peninsular Spain). As observed, the capacity available by air is similar, this could be due to the fact that flights from A Coruna and from Girona airport are not affected by the flight ban. However, in pp20 extra capacity appears with multimodal options. These options were not present in the baseline case (pp00). In the baseline case, a passenger could fly from A Coruna (or surrounding airports) to Madrid and change to a flight to Barcelona; in the enforcing policy case (pp20), the Madrid to Barcelona segment is banned. Therefore, now a multimodal trip (involving a flight to Madrid and a train service) appears as a possibility. This option was possible in the baseline case but was disregarded as not suitable and, hence, not presented/considered by the passengers.

The Malaga to Barcelona (ES617 - ES511) case shows a significant reduction of multimodal options. This could be due to the saturation of the rail network, which does not provide the capacity, and by the fact that Madrid to Malaga flights are also banned in pp20.

Finally, the Barcelona to Madrid (ES511 - ES300) is presented as an example where, in the baseline, there is significant spare capacity in the air system (1,748 seats), while the rail is already to capacity (0 seats available). However, as shown in the Demand served indicator, only 62% of the demand is served (there are 3,555 passengers who would like to travel but are not accommodated). The reason is that the logit model has assigned those passengers to the HSR alternative which does not have any capacity. It is expected that scheduling solutions (such as SOL400/SOL2) could consider this to identify where extra services should be provided.

In the multimodality enforced case (pp20), the Madrid to Barcelona (ES300 - ES511) (not presented in Figure B20 does not have any capacity left. Flights are banned between Madrid and Barcelona, and therefore, no seats in air mode are available. The rail was already full in the pp00 case, so removing the flights only intensifies this over-demand. In the Barcelona to Madrid case (depicted in Figure B20), there is a capacity of 211 seats available in air mode even if the flights between Barcelona and Madrid are banned. These are connecting flights from Barcelona to the Balearic Island and then to Madrid. A few passengers select this option, but, as observed, the demand for this type of itinerary is low, and hence there is some spare capacity.

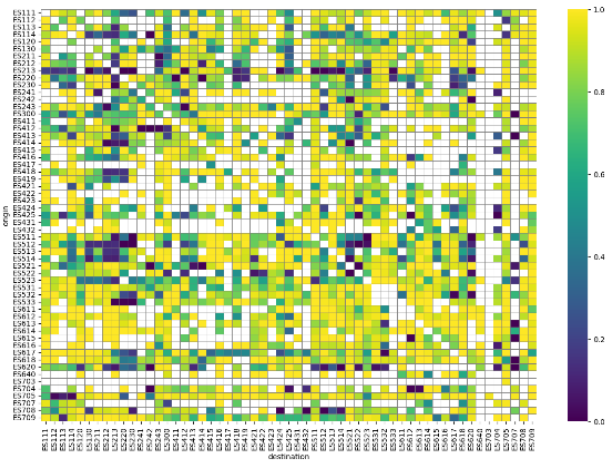
<u>Demand served</u>

At aggregated level, the demand served is similar in the three scenarios (0.81% for pp00 and pp10 and 0.79 for pp20).

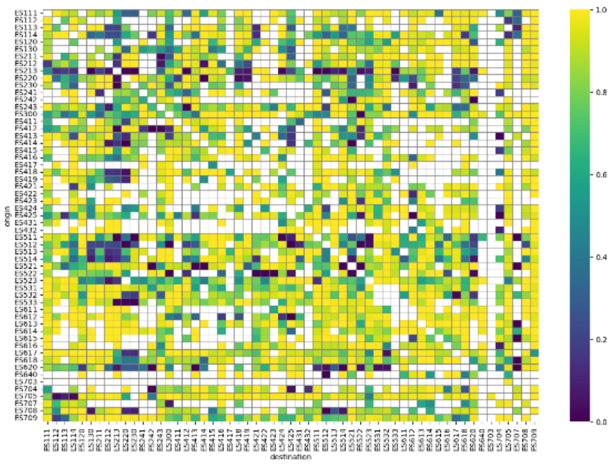
Figure B19 shows how when the enforcing policies are in place, the capacity available between different origin-destination pairs is reduced. It is worth noticing how this limitation in capacity is not spread uniformly across all the origin-destination pairs. For example, the connections between ES51 (Catalonia) and ES41, ES42, and ES43 (Castille-Leon, Castille-La Mancha and Extremadura) reduce significantly.

PP00

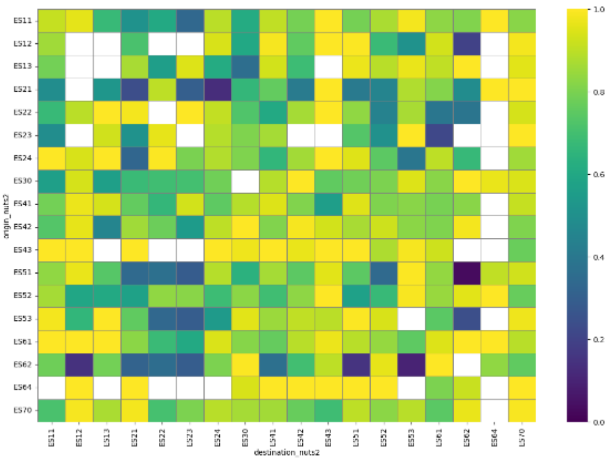
PP20



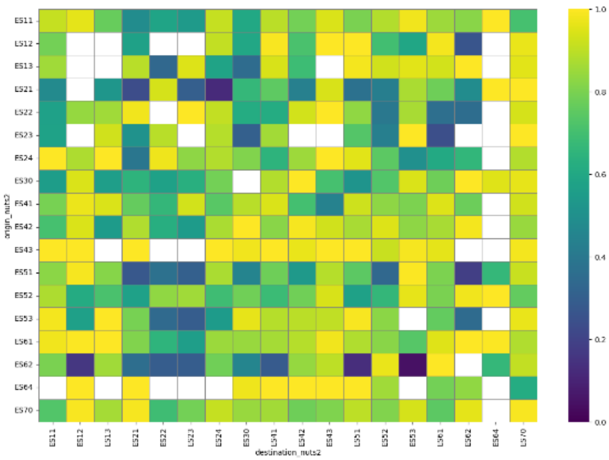
Between NUTS3 for pp00



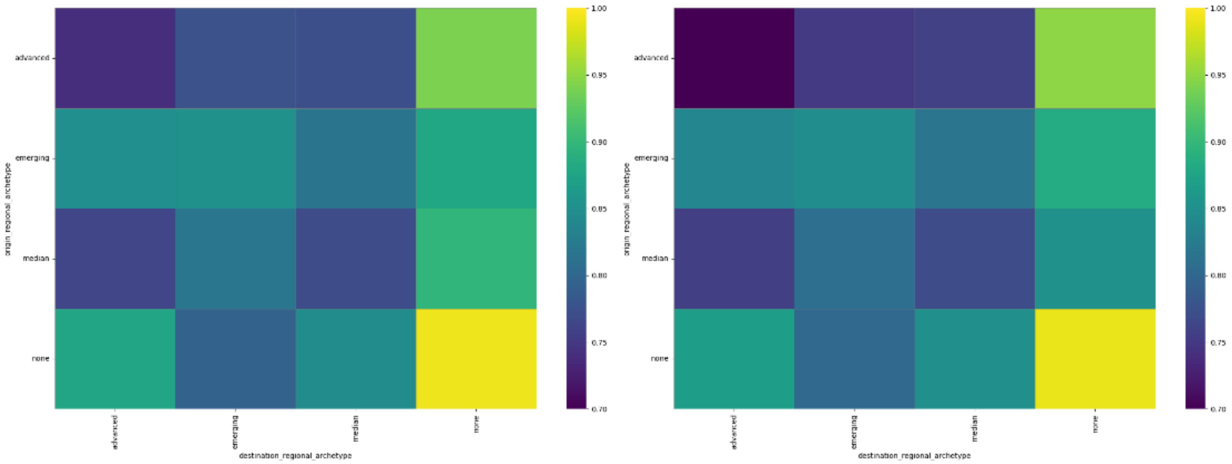
Between NUTS3 for pp20



Between NUTS2 for pp00



Between NUTS2 for pp20



Between region archetypes for pp00 Between region archetypes for pp20

Figure B21 Demand Served

As with the other indicators presented, a disaggregation of this indicator focusing on a particular origin-destination pair provides a deeper understanding of the mobility characteristic and the impact (or not) of the different policies implemented.

Figure B21 presents the demand served aggregated at different levels (between NUTS3, NUTS2 and regional archetypes) for the baseline and enforced policies scenario.

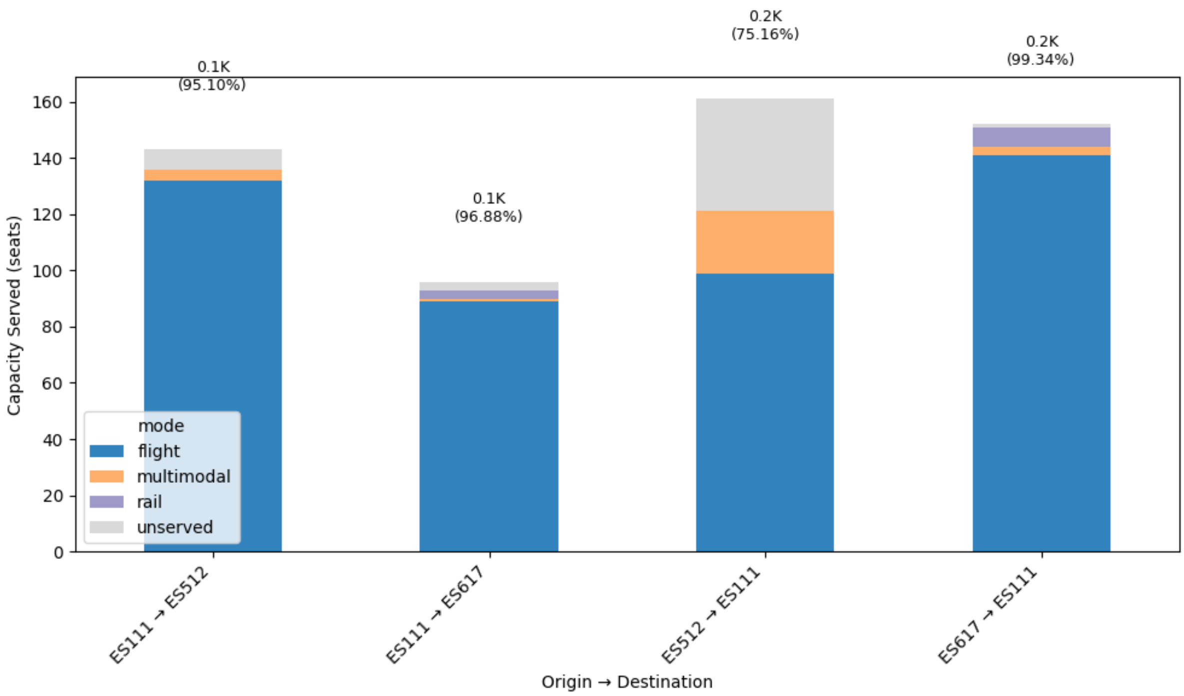


Figure B22: Example of demand served per mode for baseline pp00

Figure B22 shows an example of different origin-destination pairs and how the demand is served by different modes (air (flight), rail or multimodal). These pairs are selected due to the distance

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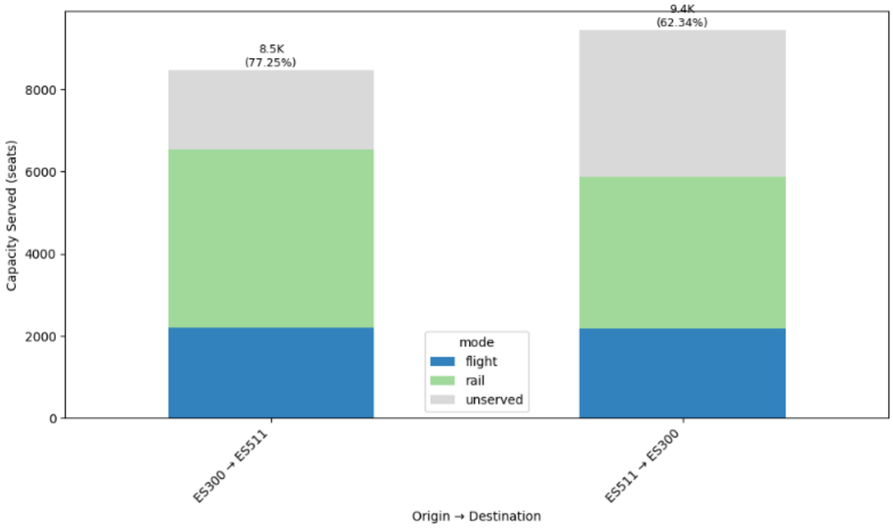
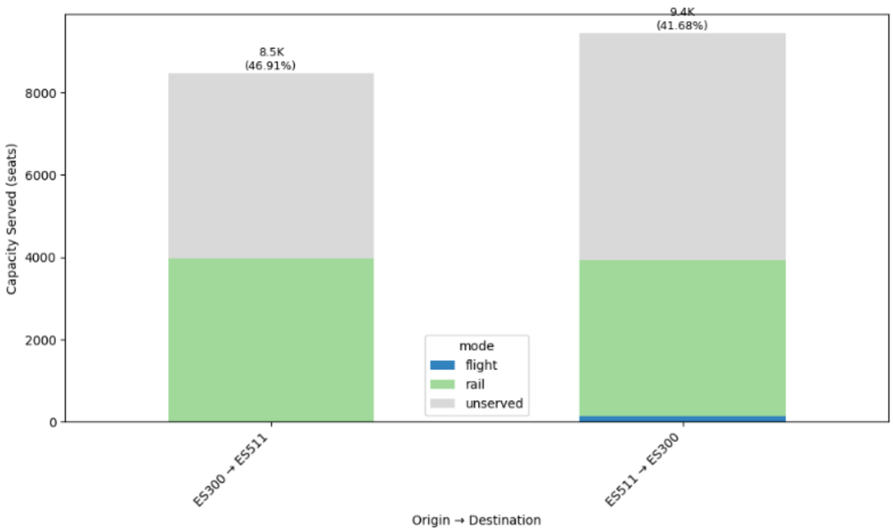
between them (ES111-ES512 (A Coruna - Girona), ES511-ES617 (A Coruna - Malaga)). It is worth noticing how the demand might be non-symmetrical between a pair of regions (e.g. more passengers have demand between ES617 to ES111 than between ES111 and ES617). Also, the modes used might be different; see, for example, the relatively high multimodal proportion of passengers between ES512 (Girona) to ES511 (A Coruna), but the lack of those in the other sense. This could be due to the synchronisation of schedules.



Baseline (pp00)



Policy enforced case (pp20)

Figure B23: Demand served between ES300 and ES511 (Madrid - Barcelona) for baseline and policy enforced cases.

Figure B23 shows with a bit more detail the example between Barcelona and Madrid for the baseline and the policy enforced case. It can be observed that in the baseline case, there is a split of around 66% of the demand being served by rail and 33% by flight, and only between 62 and 77% of the demand is satisfied. However, as shown previously in the *Capacity available* indicator (Figure B20), there is still capacity in the flights, but passengers do not select that option. Figure B23 showcases

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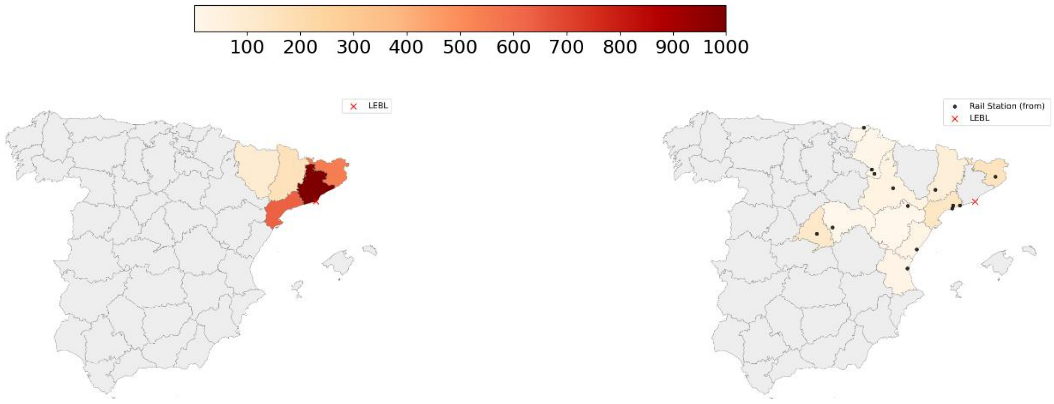
how, in the enforced policy case (pp20), the passengers served by flight practically disappear while there is practically the same (or lower) number of passengers by rail. This leads to a high percentage of demand not being satisfied (nearly 60% of the demand).

<u>Catchment area of airports</u>

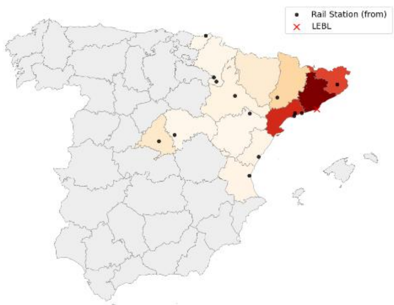
The catchment area of airports can be estimated with different approaches:

- Considering the longer time of the passengers accessing the airport by rail in a multimodal journey. This will provide a view of how multimodal journeys expand the reachability of airports.
- Considering the volume of passengers accessing (egressing) the airport per NUTS3, i.e., passengers who start (or end) a journey at the airport.
- Considering the volume of passengers accessing (egressing) the airport per NUTS3 considering the location of the rail stations with multimodal journeys. This will consider how many passengers are reaching the airport due to multimodality and from which regions.
- Considering the total volume of passengers per NUTS3 either by direct access/egress or multimodal legs.



Access

Access from rail as multimodal



Access total (including rail multimodal)

Figure B24: Access, access with rail as multimodal and access total per NUTS3 for LEBL in the baseline scenario.

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Figure B24 presents an example of the volume of passengers accessing Barcelona airport (LEBL) for the baseline scenario (pp00). It shows that passengers can directly access the airport from adjacent NUTS (Girona, Tarragona, Lleida and Huesca) with a clear higher volume from the Barcelona region itself. The airport can also be accessed as part of a multimodal journey. In this case, the figure shows the rail stations that are further away before reaching the airport. As shown, the demand is relatively low, but many more NUTS are connected in this way to the airport. Note how NUTS who could access directly the airport could also start a multimodal journey by using a rail starting on their NUTS. Finally, the addition of all the demands shows the overall access demand (access catchment area) for the airport. A similar process can be performed for the egress process.

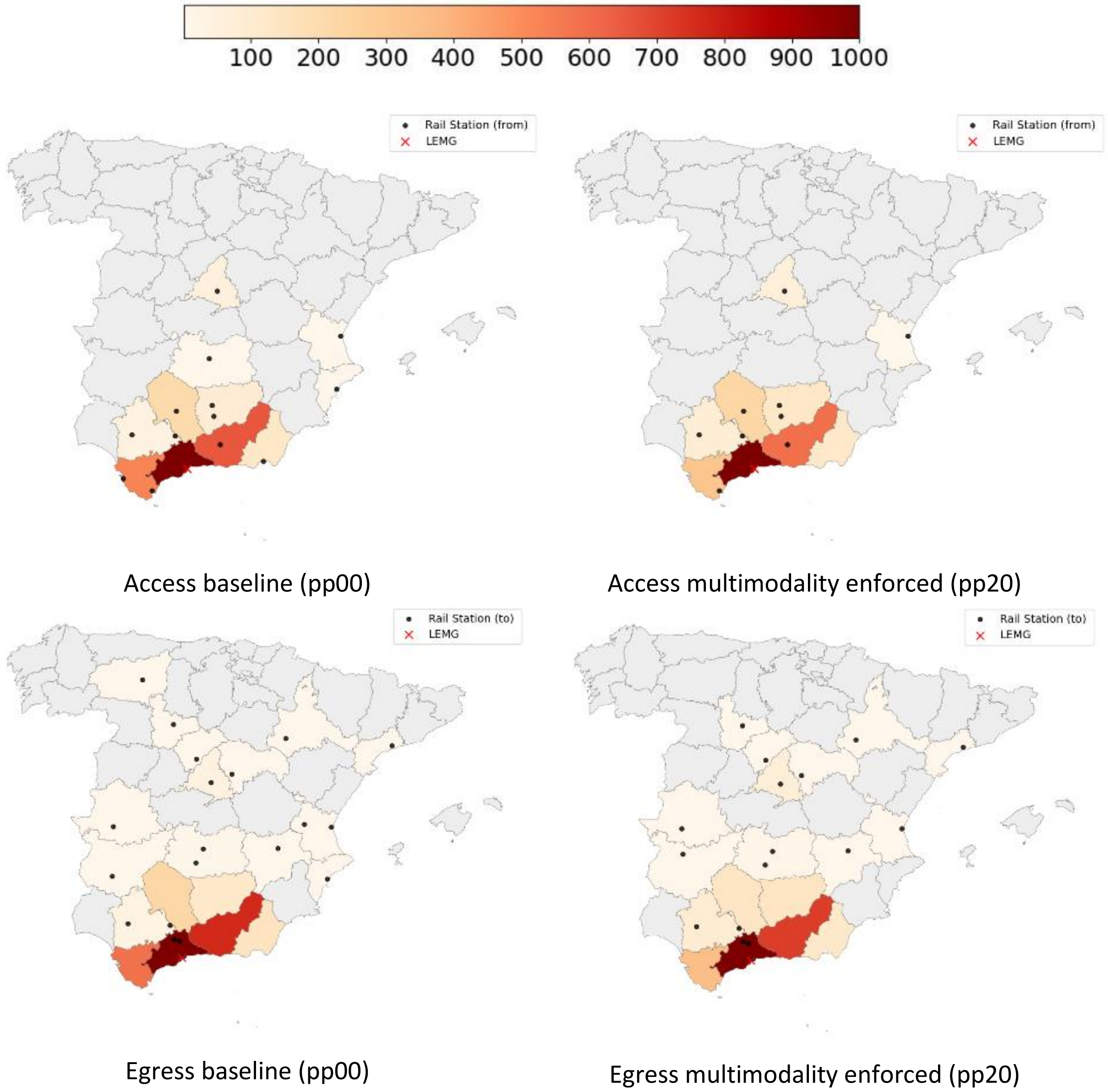

Figure B25: Access and egress for Malaga airport (LEMG) for baseline and multimodality enforced cases.

Figure B25 shows how some airports impacted by the flight ban (flights between Malaga and Madrid are banned) could have some changes in their catchment area. For example, in the baseline case, more passengers access the airport from Cadiz or Granda regions (ES612 and ES614); this could have been demand from those regions to Madrid, which now is rerouted through other alternatives. These airports, therefore, do not necessarily increase their catchment area with multimodal journeys but might reduce their overall demand.

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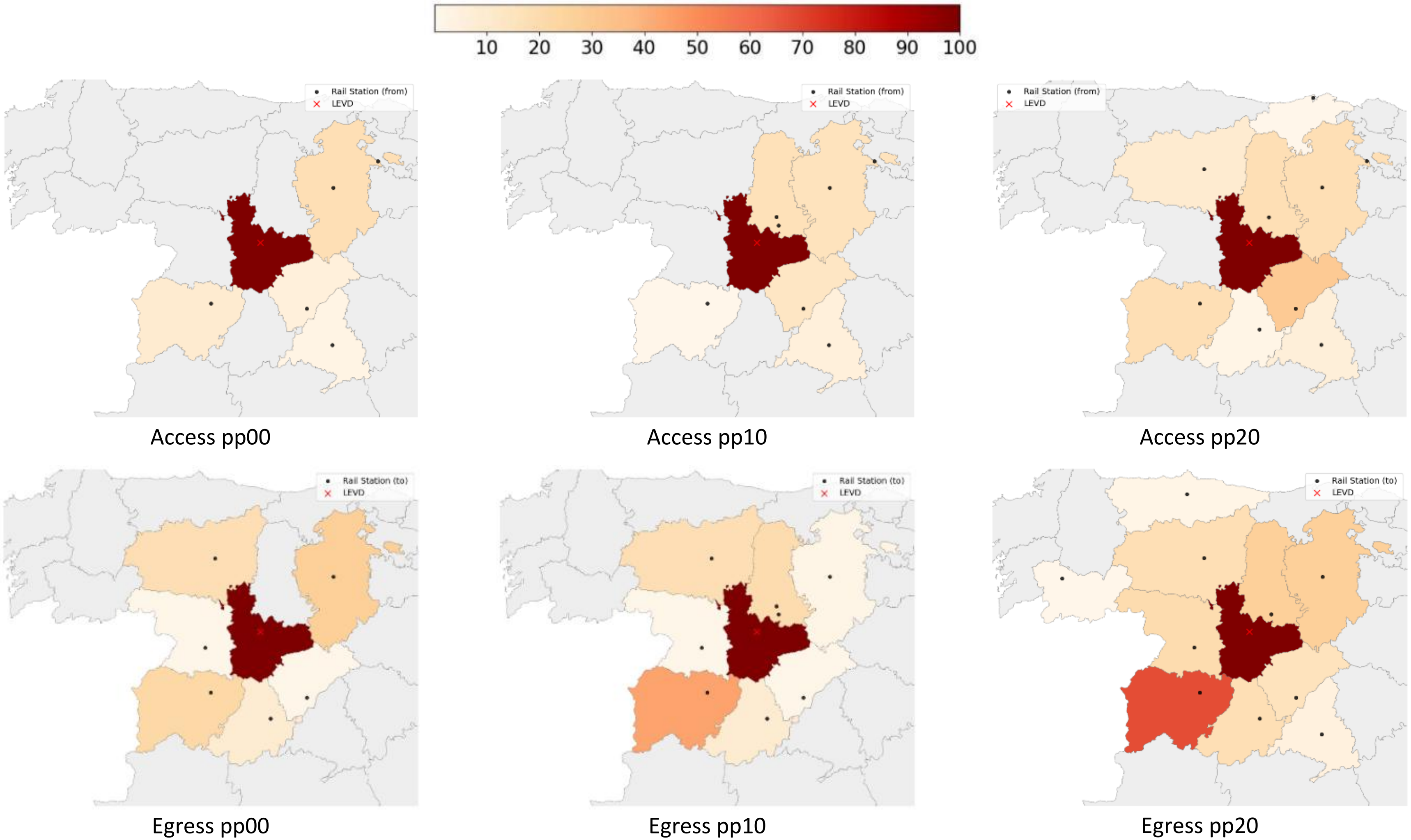

Figure B26: Access and egress (including from/to multimodal journeys) for LEVD for three scenarios.

On the other hand, Valladolid airport (LEVD) experienced an increase in its connectivity and relevance for the wider region where it is located. As incentivised policies are introduced (pp10), the number of multimodal passengers increases (by 29.6%; a similar value is observed in Madrid (LEMD), where an increment of 27.6% of multimodal passengers is observed). This shows the impact of reducing the multimodal connecting times due to integrated ticketing. In contrast, for Madrid airport, when the flight ban is implemented, the total 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, impacting the feeding of the hub toward other intra-Spain destinations. This is similar to the Malaga (LEMG) case previously presented. The intra-Spain flows are rerouted to other alternatives. It is expected that with the consideration of 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 be expected (as now is the case towards regional airports).

With the flight ban, alternatives that before were less appealing are used, and airports such as Valladolid (LEVD), in pp20 provide connectivity to adjacent regions. LEVD is an example of a regional airport that, with the flight ban, experiences a surge in the number of multimodal journeys using the infrastructure (166.1% higher than in pp00 and a 105.4% increase with respect to pp10). In absolute value, the number of multimodal passengers is still, as expected, much lower than in hubs like Madrid, but it is worth noticing that there are only 2 arrivals and 2 departures for LEVD in the day: both with origin/destination Barcelona, one arriving at 15h25 and departing at 16h, and another arriving at 16h50 and departing at 17h15 local time. 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.

When multimodality is incentivised (pp10), the number of regions (and passengers) which use LEVD as their local regional connector increases, and in the case of a flight ban (pp20), the reachability from LEVD increases significantly, reaching Cantabria in the north, and significantly for trips to Salamanca NUTS (ES415) from Barcelona NUTS (ES511): in the baseline scenario, 51 passengers flown to Madrid, 41 passengers went by rail (Barcelona-Sants -- Madrid-Atocha -- Madrid-Chamartín -- Segovia -- Salamanca) and 17 flown to Valladolid to connect with a train to Salamanca; in the flight ban case (pp20), 56 passengers used the rail option, 49 went flying via Valladolid, and 4 decided to fly with a connection in Ibiza. A similar pattern is observed in the Leon (ES413) to Barcelona (ES511) routes, which in pp00 included the option of going by rail to Madrid to fly to Barcelona, and in pp20 replace that option with flying from LEVD, or in the Segovia (ES416) to Lleida (ES513), which also trades the option of rail and flight from Madrid to rail and flight from Valladolid. These examples showcase how these regional airports, which are not directly affected by the flight ban, such as LEVD, are indirectly affected by the patterns of their demand and multimodality.

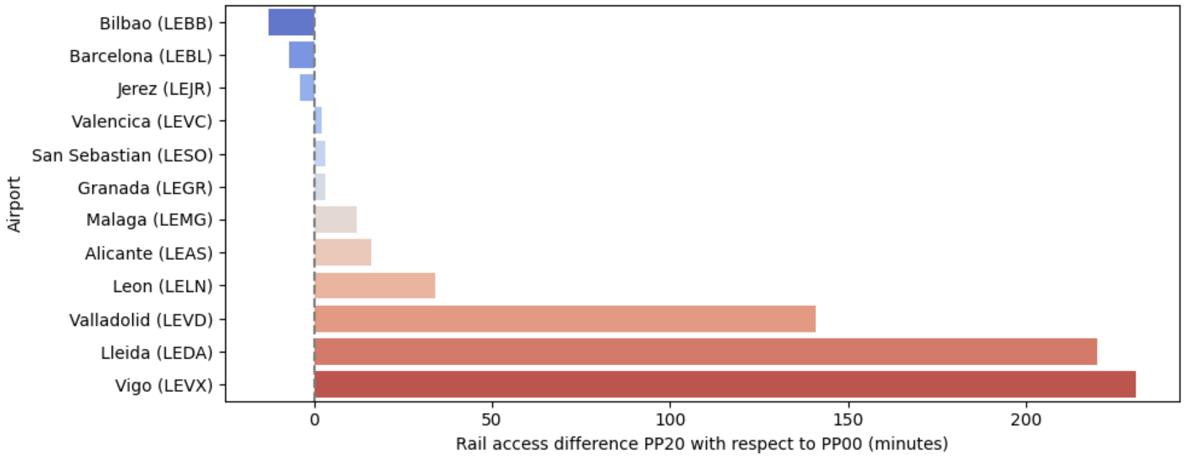

Figure B27: Change in ground time of rail segment of multimodal journeys connecting at the airports between multimodal enforced (pp20) and baseline (pp00).

Figure B27 shows for which airports the distance (in time) of the rail segments as part of a multimodal journey that involves the airport varies. This shows how these regional airports, which are indirectly impacted by the flight ban, increase their catchment area.

SOL399/SOL1 allows the analysis of these infrastructures with more detail, including assessing shifts in flows between nodes.

CO_2 emissions

CO_2 emissions are computed per passenger, as shown the values are similar for the three scenarios (on average around 20-21 Kg CO_2). Once again, further disaggregation (e.g. per origin-destination pair, mode, node) could be considered. It is worth noticing that in the current implementation, the emissions are computed per seat, which might underestimate the emissions per individual passenger if load factors are low.

Tactical evaluation of planned networks

In this experiment, the baseline scenario cs10.pp00.nd00.so00.00 was run with the Tactical Multimodal Evaluator. This Evaluator focuses on air and multimodal connections. Therefore, passengers with rail and flight itineraries, rail-flight, flight-rail and flight-flight itineraries are simulated.

These simulations are performed considering a background *noise* in the system operations, as explained in the Calibration of the Tactical Multimodal Evaluator section (see Section B.3.2.1.2). These are modelled as delay for trains using a normal distribution centred at 0 minutes with a standard deviation of 10 minutes, a standard deviation of 5 ground mobility centre around the nominal time to do these transfers (airport-to-rail_station and rail_station-to-airport), and previously calibrated *nominal* amount of delay in the air system (ATFM and other causes).

As the simulations are stochastic, the results presented are average for 10 runs of the simulator.

Finally, 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 as part of Appendix C.

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 B7: Tactical indicators for the baseline scenario

Table B7 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 compared to the strategic results.

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.

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

Table B8: Delayed flights and passengers with arrival delay larger or equal to the threshold.

Table B8 shows the ratio of delayed flights, 73% of flight had some delay and 37% had a delay of 15 minutes or more.

The average arrival delay for passengers was 3.69 minutes. As can be seen in Table B3, 55% of passengers arrived late, 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 indicates that passenger and service delays (in particular flights) can be different and highlight the need for dedicated passenger-centric metrics.

Conclusions on Experiment 3

The activities conducted in Experiment 3 satisfy the criteria EXE02-CRT-0399-ERP-030.3 as the Strategic Multimodal Evaluator has been executed successfully for baseline (cs10.pp00.nd00.so00.00), incentivised policies (cs10.pp10.nd00.so00.00), and enforced policies (cs10.pp20.nd00.so00.00) together with a range of PIs computed.

The Tactical Multimodal Evaluator has been executed with the baseline (cs10.pp00.nd00.so00.00) scenario thus satisfying the criteria EXE02-CRT-0399-ERP-030.4.

As shown, the Multimodal Evaluators enable the estimation of a range of indicators which can be disaggregated (or analysed) at different levels. When indicators are considered at network-level, the vision tends to be partial, but by combining the findings of different indicators, it is possible to capture the impact of policies (and different planned networks) from a mobility, passenger, service (flight and rail), infrastructure (airports and rail stations) and regions perspective.

B.3.2.2 OBJ-0399-TRL2-ERP-040 Results

Objective: Evaluate the performance of the Schedule Design Solution (SOL400/SOL2).

Validation: The validation of this Objective is achieved through the implementation of Experiment 4, described in Section B.1.1.

This experiment addresses the SESAR solution success criteria EXE02-CRT-0399-ERP-040.1 (evaluate SOL400/SOL2).

As mentioned in this document, the objective of the validation provided in this ERR is not to show the benefits and/or drawbacks of SOL400/SOL2 per se. For that, the reader is referred to the ERR of SOL400/SOL2 [17]. Therefore, the results presented here focus on: showing the capabilities of SOL399/SOL1 to analyse the network optimised by SOL400/SOL2 with a particular emphasis on the PIs defined in the Multimodal Performance Framework. To see how SOL399/SOL1 could more deeply analyse the planned network, please see the results provided in Experiment 3 (Section B3.2.1.3).

The capabilities of SOL399/SOL1 for the tactical evaluation of the network have been shown in Experiment 3 (Section B3.2.1.3). In this Section, results are presented to showcase how SOL399/SOL1 is able to analyse the robustness of SOL400/SOL2 with respect to multimodal connections. Therefore, results focus on the multimodal connections (rail-air) and (air-rail), and on aviation-related connections (air-air). The tactical evaluator of SOL399/SOL1 is not able to assess rail-rail connections yet.

Finally, as explained in Section B.1.3, due to the limitations of SOL400/SOL2 which considers valid connections between flight services independently of the operator (and alliances), the results presented in this experiment are based on the evaluation of *network definition* 02 (nd02). This definition of the network enables the connections between services regardless of the operator and assigns passengers to services aiming at maximising first the total demand served. Note that the results presented here without SOL400/SOL2 will be similar but different from the ones in Experiment 3 where alliances are respected for flight connections. Therefore, for the strategic evaluation of the networks the following scenarios are defined:

- cs10.pp00.nd02.so00.00: Baseline intra-Spain mobility without particular multimodal policies with network definition 02.
- cs10.pp00.nd02.so10.02: Based on the outcome of cs10.pp00.nd02.so00.00, SOL400/SOL2 has been executed iteratively twice. This means that the schedules have been optimised by SOL400/SOL2, then evaluated by the Strategic Multimodal Performance Framework, and considering the output obtained re-optimised once more. For more details on this process see the ERR of SOL400/SOL2 [19].
- cs10.pp20.nd02.so00.00: Same as cs10.pp00.nd02.so00.00 but with the application of multimodality enforced policies (in particular, flight ban along with integrated ticketing and CO2 charges for flight emissions).
- cs10.pp20.nd02.so10.01: Application of SOL400/SOL2 over the outcome of cs10.pp20.nd02.so00.00.

All these scenarios are also evaluated by the Tactical Multimodal Evaluator with a deeper analysis of the sensitivity of missed connections with respect to ground mobility delay for the pp20 cases.

B.3.2.2.1 Experiment 4

Strategic evaluation of networks with SOL400/SOL2

PI	Short definition	KPA	Variant	pp00.so00	pp00.so10.02	pp20.so00	pp20.so10.01
Total journey time	Door-to-door total travel time [min]	Efficiency	sum	88,109,665	88,105,422	86,086,170	85,986,947
			avg for connecting passengers	417.09	405.28	416.23	411.50
Passengers time efficiency	Best possible journey time (from schedules)/planned time travel (from planned operations) [percentage]	Efficiency	total	0.88	0.88	0.88	0.88
Buffers in itineraries (min)	Total waiting time between all connections in itineraries [min]	Efficiency	sum	380,028	314,866	399,760	353,479
			avg for connecting passengers	20.39	15.72	19.63	16.83
Seamless of travel	Transition time (between services) [mins]	Interoperability	avg	83.11	74.85	83.04	80.70

Modal share	Share of transport modes in passenger itineraries [number passengers per mode and percentage]	Interoperability	total	• air: 104,837 (0.27) • rail: 284,758 (0.72) • multimodal: 4,066 (0.01)	• air: 104,745 (0.27) • rail: 285,191 (0.72) • multimodal: 4,060 (0.01)	• air: 93,653 (0.24) • rail: 287,957 (0.74) • multimodal: 5703 (0.01)	• air: 93,384 (0.24) • rail: 287,606 (0.74) • multimodal: 6011 (0.02)
Demand served	Number of passengers assigned to itineraries over demand between origin-destination [percentage]	Capacity	total	0.82	0.82	0.80	0.80
			total connecting passengers	0.04	0.04	0.04	0.04

Table B9: Selected strategic performance indicators defined in the multimodal performance framework for the networks with SOL400/SOL2

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Table B9 lists the most relevant PIs for evaluation of the benefits of SOL400/SOL2. As we can see, the improvement in total time in connecting itineraries is significant. This decrease in total time is not totally reflected when looking at the total network because the percentage of connected itineraries is quite low. However, the average total time for connecting passengers has decreased. The passengers' time efficiency, demand served and modal share remained stable.

The results regarding buffer times are more telling: In all the analysed scenarios buffer times decrease significantly. This makes sense, as one of the objective functions of SOL400/SOL2 is to minimise buffer times. This makes the network more efficient and, subsequently, the seamless of travel PI decreased as well.

Note that besides this analysis shown here, a deeper analysis as the one described in Experiment 3 could also be performed. For example, analysing the catchment area of airports when SOL400/SOL2 is put in place and comparing that with the case without it.

Tactical evaluation of networks with SOL400/SOL2

In this experiment, scenarios with baseline (pp00) and multimodality enforced (pp20) policies have been evaluated. The results focus on PIs relevant for connecting passengers, as the tactical simulation has the most significant effect on these. For non-connecting passengers, the results, such as total travel time, are similar to the strategic itineraries with an added noise of total arrival delay due to the delayed services.

Indicator	variant	cs10.pp00.nd02.so00.00	cs10.pp00.nd02.so10.02
total arrival delay	average	3.6	3.6
	average for passengers missing connections	266.0	261.2
stranded passengers	percentage of stranded passengers over the total number of passengers	<0.1%	<0.1%
	percentage of stranded passengers with air-to-rail connections over total number of stranded passengers	<0.1%	<0.1%
	percentage of stranded passengers with rail-to-air connections over total number of stranded passengers	37.6%	32.0%
	total number of stranded passengers	110.7	104.4
	percentage of stranded passengers over the total number of passengers with missed connections	9%	6.4%
missed connections	percentage of passengers with missed connections over the total number of passengers	• total 0.33% • air-to-air 0.30% • air-to-rail 0.02% • rail-to-air 0.01%	• total 0.42% • air to air 0.38% • air to rail 0.03% • rail to air 0.01%
	total number of passengers missing connections	• total 1,309 • air-to-air 1,171 • air-to-rail 90 • rail-to-air 48	• total 1,654 • air-to-air 1,490 • air-to-rail 124 • rail-to-air 40
total journey time	Addition of the total journey time of all passengers	87,343,707.0	87,361,484.4

Table B10: Tactical evaluation of scenarios with pp00

Table B10 presents the results of the scenarios with baseline policies (pp00). The number of stranded passengers is very similar between the optimised and the baseline case. The number of passengers with missed connections has increased in the scenario with SOL400/SOL2. This is in line with expectations, as SOL400/SOL2 tightens the buffers in itineraries, making the passengers more likely to miss their connections.

Indicator	variant	cs10.pp20.nd02.so00.00	cs10.pp20.nd02.so10.01
total arrival delay	average	3.4	3.4
	average for passengers missing connections	258.9	285.1
stranded passengers	percentage of stranded passengers over the total number of passengers	<0.1%	<0.1%
	percentage of stranded passengers with air-to-rail connections over the total number of stranded passengers	<0.1%	<0.1%
	percentage of stranded passengers with rail-to-air connections over the total number of stranded passengers	30.7%	54.9%
	total number of stranded passengers	192.000	178.700
	percentage of stranded passengers over the total number of passengers with missed connections	11.7%	11.5%
missed connections	percentage of passengers with missed connections over the total number of passengers	• total 0.46% • air-to-air 0.32% • air-to-rail 0.12% • rail-to-air 0.02%	• total 0.39% • air-to-air 0.25% • air-to-rail 0.10% • rail-to-air 0.04%
	total number of passengers missing connections	• total 1,763 • air-to-air 1,230 • air-to-rail 458 • rail-to-air 75	• total 1,501 • air-to-air 955 • air-to-rail 393 • rail-to-air 153
total journey time	Addition of the total journey time of all passengers	85,349,881.1	85,406,089.1

Table B11: Tactical evaluation of scenarios with pp20

connecting passengers	air-to-air	air-to-rail	rail-to-air	total
cs10.pp20.nd02.so00.00	4,393	2,055	3,050	9,498
cs10.pp20.nd02.so10.01	4,264	2,294	3,234	9,792

Table B12: Number of connecting passengers in tactical simulation

Table B11 presents the results of the experiments with the multimodality enforced policy (pp20). In this case, the number of stranded passengers and passengers with missed connections is slightly larger in the scenario without SOL400/SOL2. This can be explained by a slightly different structure of the scenarios, i.e., the proportion of passengers with different connections (air-to-air, air-to-rail and rail-to-air). As shown in Table B12, scenario cs10.pp20.nd02.so00.00 has a higher number of passengers with air-to-air connections. This type of connection is more likely to be missed due to the higher delay of flights compared to trains. Similarly, rail-to-air connections are less likely to be missed, and scenario cs10.pp20.nd02.so00.00 has fewer passengers with this type of connection compared to cs10.pp20.nd02.so10.01.

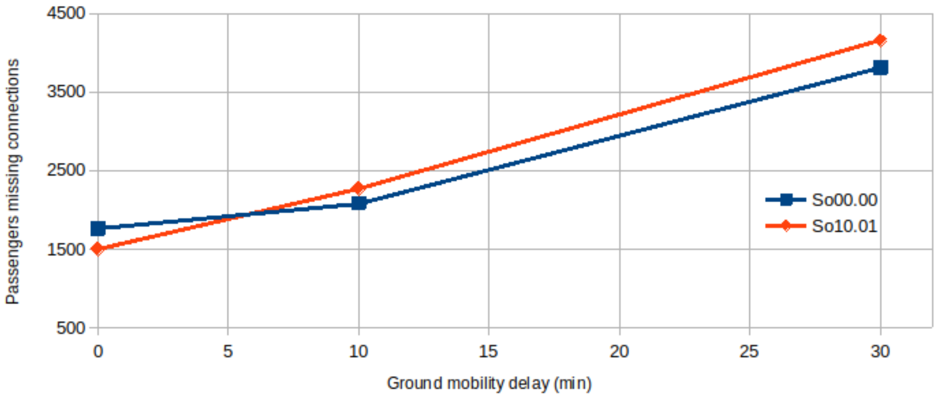
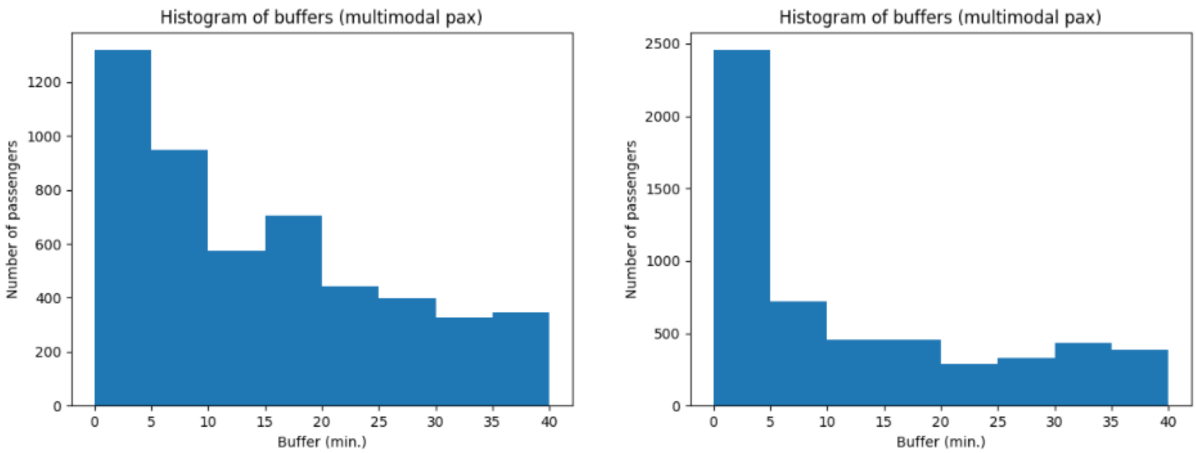


Figure B28: Number of passengers missing connections as a function of ground mobility delay



cs10.pp20.nd02.so00.00 cs10.pp20.nd02.so10.01

Figure B29: Buffers in itineraries

Finally, the Tactical Multimodal Evaluator enables the introduction of an additional delay (in this case, a delay of ground mobility), which can test the robustness of connecting itineraries. Figure B28 shows the number of passengers with missed connections with increased additional delay. While the number of passengers with missed connections increased for both scenarios (with and without SOL400/SOL2), the scenario with SOL400/SOL2 degraded faster with higher delay. This result is expected as SOL400/SOL2 tightens the buffers in itineraries, as can be seen in the histograms in Figure B29.

Conclusions on Experiment 4

The activities conducted in Experiment 4 satisfy the criteria EXE02-CRT-0399-ERP-040.1 as the scenarios for baseline policies (pp00) and enforced policies (pp20) have been executed without and with SOL400/SOL2 (cs10.pp00.nd02.so00.00, cs10.,pp20.nd02.so00.00, and cs10.pp00.nd02.so10.02, cs10.,pp20.nd02.so10.01). The scenarios have been compared in terms of both strategic and tactical performance.

Appendix BB Unexpected behaviours/results

No major unexpected results were encountered.

Appendix CC Confidence in results of validation exercise #02

B.3.4.1 Level of significance/limitations of validation exercise results

We acknowledge that the Spanish air and rail networks offer some limitations in showcasing multimodality. Due to the size of the country and the availability of options, most trips are single-mode with a strong prevalence of rail itineraries. This is mitigated by the use of policy packages that force multimodality, e.g. with the ban of short-haul flights and with the consideration of longer distance trips such as to-from the Canary Islands from the peninsular regions in Spain.

The capacity of the indicators to capture the effect of multimodality is, therefore, limited in some aspects. However, interesting trends and patterns emerge that can be captured by the model (e.g. the relevance of regional airports as connecting nodes when flight bans are in place). The inclusion of international trips will support a deeper analysis of the impact of multimodality, showcasing the relevance of international hubs. This is, therefore, a priority for future work. However, the cases analysed are sufficient to show the capabilities of SOL399/SOL1 to analyse the mobility scenarios both strategically and tactically.

B.3.4.2 Quality of validation exercises results

We consider that there are no issues regarding the quality and accuracy of the results.

Some of the results show that further work might be required to adjust some of the model input parameters. For example, the unsatisfied demand between selected origin-destination pairs seems too high; this could be due to the use of a subset of trains available (Renfe) or an overestimation of the demand between the regions. Likewise, as shown, the logit model might select in high numbers an option with limited capacity (leading to unsatisfied demand), while extra capacity is provided by different alternatives which are not used. This could be considered by SOL400/SOL2 to adjust the supply with additional services (or reallocation of services) on those over-demanded paths; a different iterative approach to assign demand to alternatives could also be explored in the future.

The Tactical Multimodal Evaluator could be extended to include rail-rail connections, even thought the current focus is on air and multimodal mobility.

These highlighted aspects are not significant to, once again, show how SOL399/SOL1 is able to assess a planned network (with and without SOL400/SOL2) both strategically and tactically.

B.3.4.3.Significance of validation exercises results

Operational significance has already been discussed in section B.3.4.1. (Level of significance/limitations of validation exercise results).

Appendix DD Conclusions

Appendix EE Conclusions on concept clarification

With this validation exercise, SOL399/SOL1 has proven to fulfil the research objectives proposed in the ERP (EXE02-OBJ-0399-TRL2-ERP-030 and EXE02-OBJ-0399-TRL2-ERP-040).

This exercise validated the Strategic Multimodal Evaluator and Tactical Multimodal Evaluator for Strategic Multimodal Evaluation and Tactical Multimodal Evaluation when assessing a planned multimodal mobility network, including the integration of optimised schedules (i.e., from SOL400/SOL2). The experiments showed that the proposed framework is capable of a performance assessment of a Schedule Optimiser solution.

Appendix FFConclusions on technical feasibility

SOL399/SOL1 fulfils all the functional requirements outlined in the FRD.

Appendix GG Conclusions on performance assessments

As discussed in the ECO-EVAL, the Performance Assessment Solution (SOL399/SOL1) aims to evaluate the performance of a planned multimodal mobility network and other multimodal Solutions (such as SOL400/SOL2). This was demonstrated through PIs of the multimodal performance framework, which showed the performance in the KPAs such as a positive impact of SOL400/SOL2 on efficiency, reducing buffer times and total journey times.

The exercise shows how SOL399/SOL1 can provide estimations of the indicators defined in the multimodal performance framework.

Finally, it is worth reminding the reader that results show the importance of disaggregating the indicators on specific cases to fully understand the impact of mechanisms (e.g. policies, schedulers (such as SOL400/SO2)). Otherwise, network-wise indicators tend not to vary in a significant way while mobility patterns are actually emerging in selected sub-operational environments (e.g. hub airports, airports affected by flight bans, and regional airports).

Appendix HH Recommendations

Future work could address shortcomings mentioned in section B.3.2.1.2:

- The Strategic Multimodal Evaluator should consider more accurate emissions and costs associated with access and egress,

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- The Tactical Multimodal Evaluator should include rail-rail connections in the simulation.

As described in B.3.4.2., further work could be done to produce improved inputs for the model (adjusting the demand and supply for selected origin-destination pairs).

Appendix II Validation exercise #03 report

Appendix JJ Summary of the validation exercise #03 plan

The validation exercise follows in its principles the one presented in the ERP SESAR solution SOL399/SOL1.

Appendix KK Validation exercise description and scope

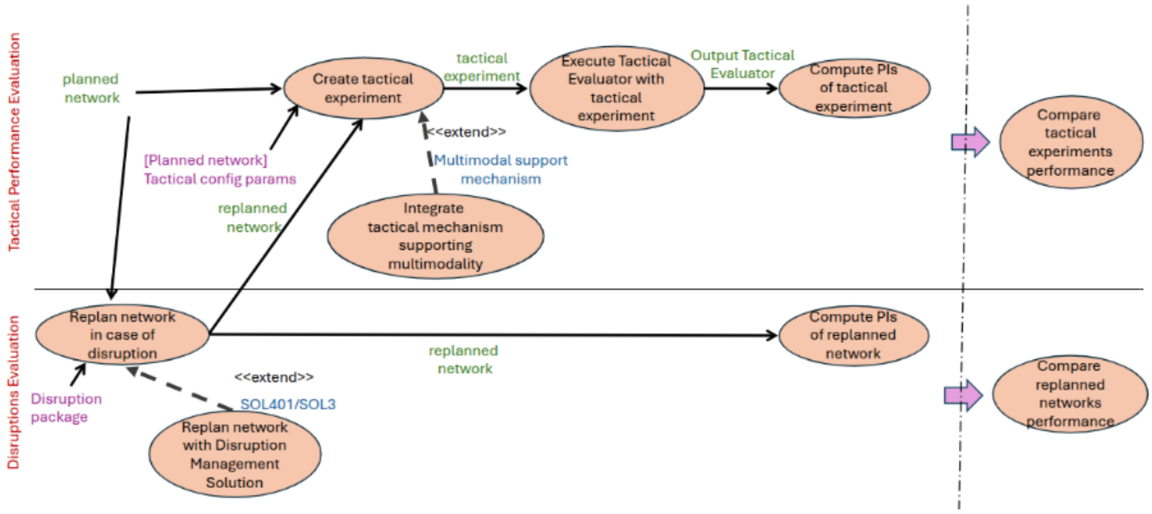

Figure C1: Use cases validated in Validation exercise TVAL.03.1-MultiModX-0399-TRL2

The operational scope of the validation exercise covers the use case, as shown in Figure C1, performed by the actors 'Disruption Management Performance Assessment Expert' and 'Tactical Performance Assessment Expert' as described in OSED [15]. The validation exercise flow follows:

- The Disruption Evaluation of the network by means of:
  - The Use Case 'Replan network in case of disruption' with either the outcome of SOL401/SOL3 or from historical data (*planned network*),
  - The Use Case 'Compute PIs replanned network' to compute multimodal replanning performance indicators.
  - The Use Case 'Compare replanned networks' performance' can be used to compare the performance of different replanned networks (e.g. with or without the schedules being adjusted by SOL401/SOL3).
- The Tactical Multimodal Evaluation of the replanned network by means of:
  - The Use Case 'Create tactical experiment' translates the replanned network into the input required by the Tactical Multimodal Evaluator (among the configuration of other required parameters). This could include the incorporation of mechanisms to

support multimodality (Integrate tactical mechanism supporting multimodality use case extension).

- The 'Execute Tactical Evaluator with tactical experiment' Use Case uses the information from the tactical experiment to execute the Tactical Evaluator.
- The outputs of the Tactical Evaluator can then be used by the 'Compute PIs of tactical experiment' Use Case to generate the required multimodal performance indicators.
- A comparison of the result of different tactical experiments can be carried out with the 'Compare tactical experiments performance' Use Case.

The same geographical, policy and infrastructure scope as for TVAL.02.1-MultiModX-0399-TRL2 is used for this validation exercise. See B.1.1 for a justification of the scope. In addition, the multimodal networks are impacted by disruptions, as explained in OSED [15]. These disruptions are grouped into disruption packages, which represent different representative operational environments.

The validation exercise will consist of the following experiments:

Experiment 1: Replanning network in case of disruption

Step 1: Replan a planned network which has been generated in TVAL.02.1-MultiModX-0399-TRL2 by applying a disruption package. Compute multimodal replanning performance indicators.

Step 2: Replan a planned network with SOL401/SOL3 Disruption Management Solution to modify the flight and/or rail timetables and reallocate passengers impacted by these changes (subject to availability) to alternative itineraries (services). Compute multimodal replanning performance indicators for this replanned network.

Step 3: Compare the performance of the replanned networks based on indicators computed in Steps 1 and 2.

Experiment 2: Tactical evaluation of the replanned network

Step 1: Define a Tactical Experiment for the replanned networks from Experiment 2, which is then executed with the Tactical Evaluator pipeline to compute multimodality tactical performance indicators.

Step 2: Compare the performance of tactical experiments based on indicators computed in Step 1.

Note that the computation of tactical indicator by the Tactical Multimodal Evaluator given a (re)planned network has already been shown in Experiment 3 of Validation Exercise 2 (see Section B3.2.1.3 and EXE02-CRT-0399-ERP-030.4). In addition, the Tactical Multimodal Evaluator focuses on single connections, while the replanning of operations modelled by SOL401/SOL3 produces significant replanning on the rail layer. These changes are more suitable to be explored by the assessment of the replanned network itself as done in Experiment 1 of this Validation Exercise. Therefore, this materialisation of the replanned network is not considered required to show the underlying capabilities of the model; EXE03-CRT-0399-ERP-050.1 (EXE03-OBJ-0399-TRL2-ERP-050) can succeed without the tactical execution of the replanned network.

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Experiment 3: Evaluation of Mechanism to support multimodality

Step 1: Define a Tactical Experiment including the mechanism to support multimodality (fast-track for multimodal connecting passengers at the airport) for the considered scenario, which is then executed with the Tactical Evaluator pipeline to compute multimodality tactical performance indicators.

Step 2: Compare indicators for the tactical experiment from Step 1 with the tactical experiment for the same scenario without including the mechanism to support multimodality.

This experiment is required to satisfy EXE03-CRT-0399-ERP-060.1 (EXE03-OBJ-0399-TRL2-ERP-060). This could be applied to any planned (or replanned) network, and it is in addition to the original scope of MultiModX.

The validation exercise technique is simulations run/modelling using Python and the pipeline of SOL399/SOL1 for experiments 1 to 3. The validation platform is the computer(s) used to perform the models.

Appendix LL Summary of validation exercise #03 validation objectives and success criteria

Validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
EXE03-OBJ-0399-TRL2-ERP-050	EXE03-CRT-0399-ERP-050.1	Fully covered	Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries. More generally, evaluate the replanning of a network to consider disruptions computing PIs on the network with an operation and passengers' itineraries perspective.	• Set two experiments to replan the network considering the disruptions, with and without the use of a Disruption Management Solution (e.g. SOL401/SOL3) and use the replanning capabilities of the Multimodal Evaluator to reassign passengers in the network. • Compute PIs on the replanned networks with a focus on replanned multimodal indicators. This computation is to be done on the replanned network obtained from the previous step. • Compare the results of the PIs of the two related networks to assess the benefit of the Disruption Management Solution.
EXE03-OBJ-0399-TRL2-ERP-060	EXE03-CRT-0399-ERP-060.1	Fully covered	To use the Tactical Multimodal Evaluator to assess the impact on the performance of a mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports.	• Two tactical experiments are set up, one with and one without the mechanism activated, and are executed with the Tactical Evaluator and tactical multimodality-related PIs computed. • The performance of the system, with a focus on passenger-centric metrics, is compared across the two experiments to assess the benefit of the mechanism.

Table C1: Validation objectives for the exercise #03

Appendix MM Summary of validation exercise #03 validation scenarios

The same geographical (CS10), policy packages (PP00-PP20) and infrastructure apply to this validation exercise as for TVAL.02.1-MultiModX-0399-TRL2 (see Section B.1.3). Note that only a nominal network (prior disruption) is required. Therefore, the use of SOL400/SOL2 is not needed for this validation exercise (so00.00 is sufficient, and the network definition could be set as *baseline* (nd00). See Section B.1.1 for a justification of these modelling choices and a better understanding of the representativeness of these experiments.

Two different types of scenarios are defined:

- For the evaluation of disruptions and replanned networks (to satisfy EXE03-CRT-0399-ERP-050.1), and
- For the evaluation of a mechanism to support multimodality (to satisfy EXE03-OBJ-0399-TRL2-ERP-060).

Slightly different criteria have been applied to select the reference and solution scenarios as explained in the subsequent sections.

C.1.3.1 Reference and solution scenarios for disruptions and replanned networks

C.1.3.1.1 Reference networks prior to disruption

Two reference scenarios are defined (prior to the application of the disruptions):

- cs10.pp00.nd00.so00.00 for 'nominal' representative conditions, and
- cs10.pp20.nd00.so00.00 for the multimodality enforced case (flight-ban), as that is the scenario which the most multimodal initial journeys.

These two reference scenarios have been selected based on the previous consideration and on the results obtained in the evaluation of the planned networks (see Section B.3.2.1.3).

C.1.3.1.2 Disruption packages

Disruption package	Network impacted	Definition
dp100	Rail	The rail link between Madrid Atocha and Barcelona Sants was removed.
dp210	Air	Closure of LEMG airport
dp300	Air	ATFM at LEMD due to industrial action
dp310	Air	Reduction of capacity at LEMD

Table C2: Disruptions considered for the validation exercise

Different disruptions have been evaluated by applying them to the reference networks, for these the cases summarised in Table C2 are used in this validation exercise, and further detailed in the subsequent sections.

C.1.3.1.2.1 Dp100 - Closure rail link Barcelona - Madrid

Dp100 represents the closure of the Madrid-Barcelona rail link. This cancels 57 train services, not only between these two cities but also to stops along the line (e.g. Girona to Madrid), as shown in Figure C2. Note that the figure shows the rail cancelled but sampled only at the stops considered in the network.

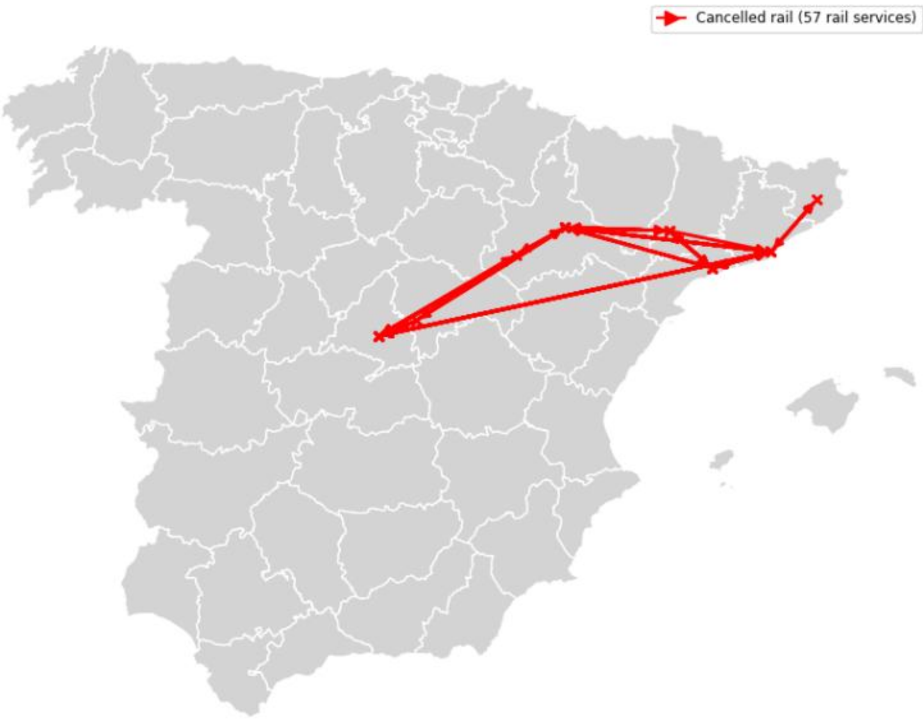

Figure C2: Rails cancelled in dp100.

The rail link between Madrid Atocha and Barcelona Sants is one of the most used in Spain, and therefore, it is interesting to observe how demand could be accommodated in the system.

C.1.3.1.2.2 Dp210 - Closure Malaga airport (LEMG)

Dp210 is a critical case of closure of all air connections to-from Malaga (LEMG) airport. Similar to the closure of the rail link, we expect a significant amount of passengers to be impacted needing to be accommodated in the network.

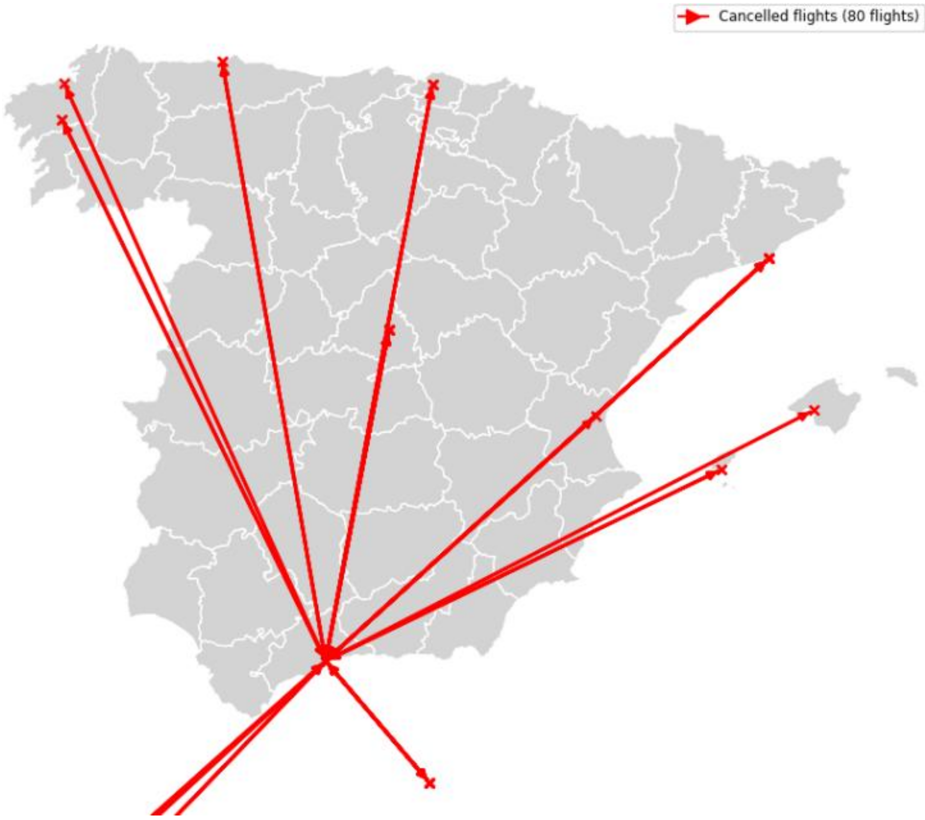

Figure C3: Flights cancelled in dp210 applied to cs10.pp00.nd00.so00.00.

As shown in Figure C3, a total of 80 flights are cancelled in the pp00 case.

C.1.3.1.2.3 Dp300 - Industrial Action ATFM regulation at Madrid (LEMD)

Dp300 models the impact of an ATFM regulation spanning all day in Madrid airport (LEMD) due to industrial action. Industrial action has been selected as the reason for the regulation due to the severe impact of these types of regulations on traffic in terms of cancellations and delays [25].

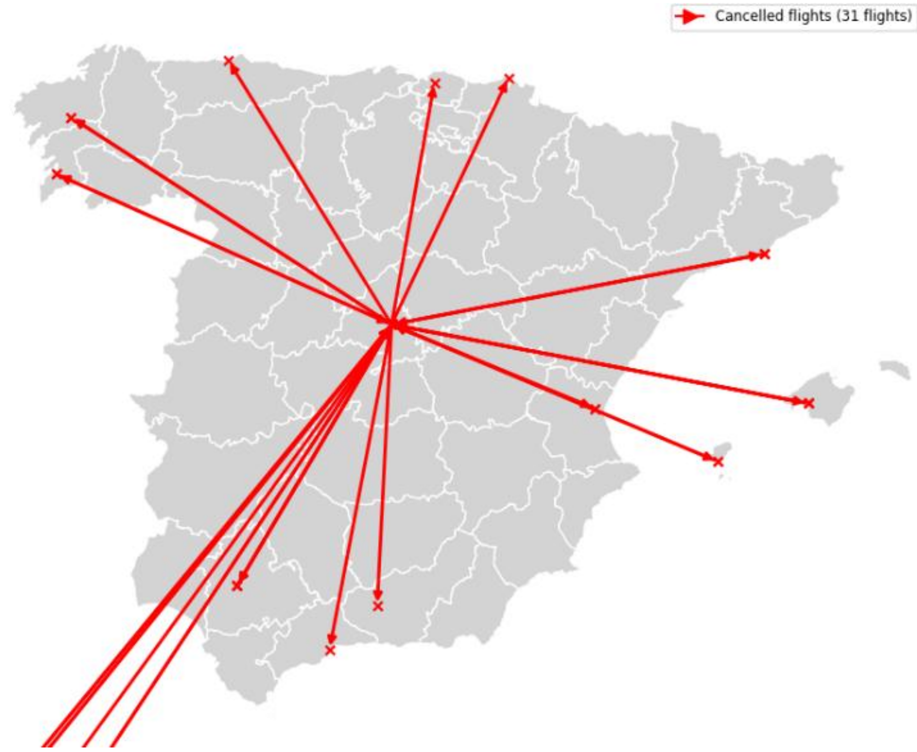

Figure C4: Flights cancelled dp300 applied to cs10.pp00.nd00.so00.00.

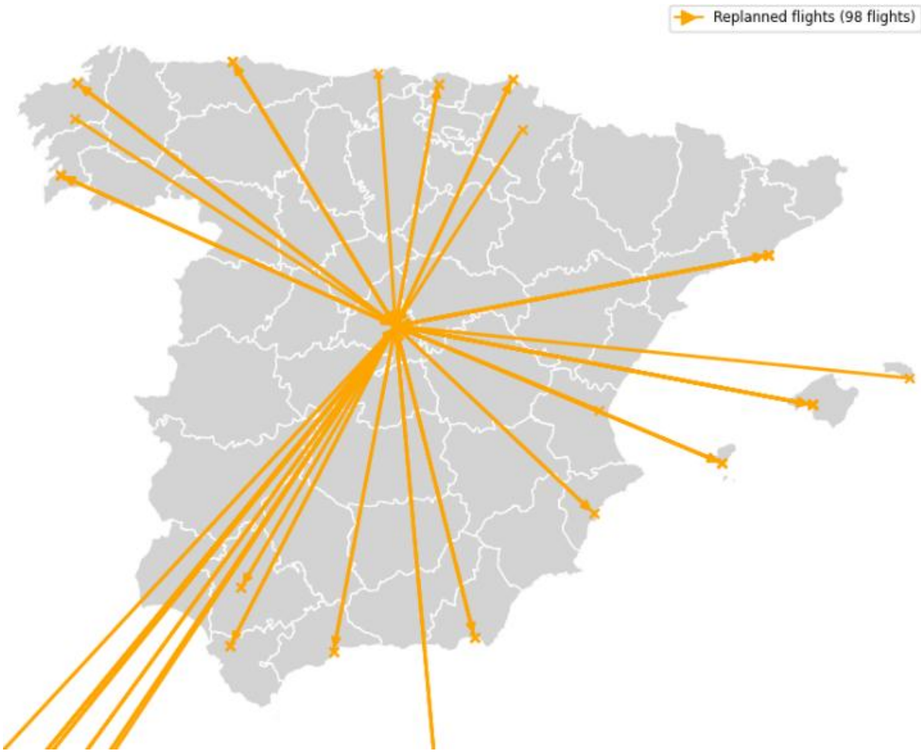

Figure C5: Flights delayed due to ATFM in dp300 applied to cs10.pp00.nd00.so00.00.

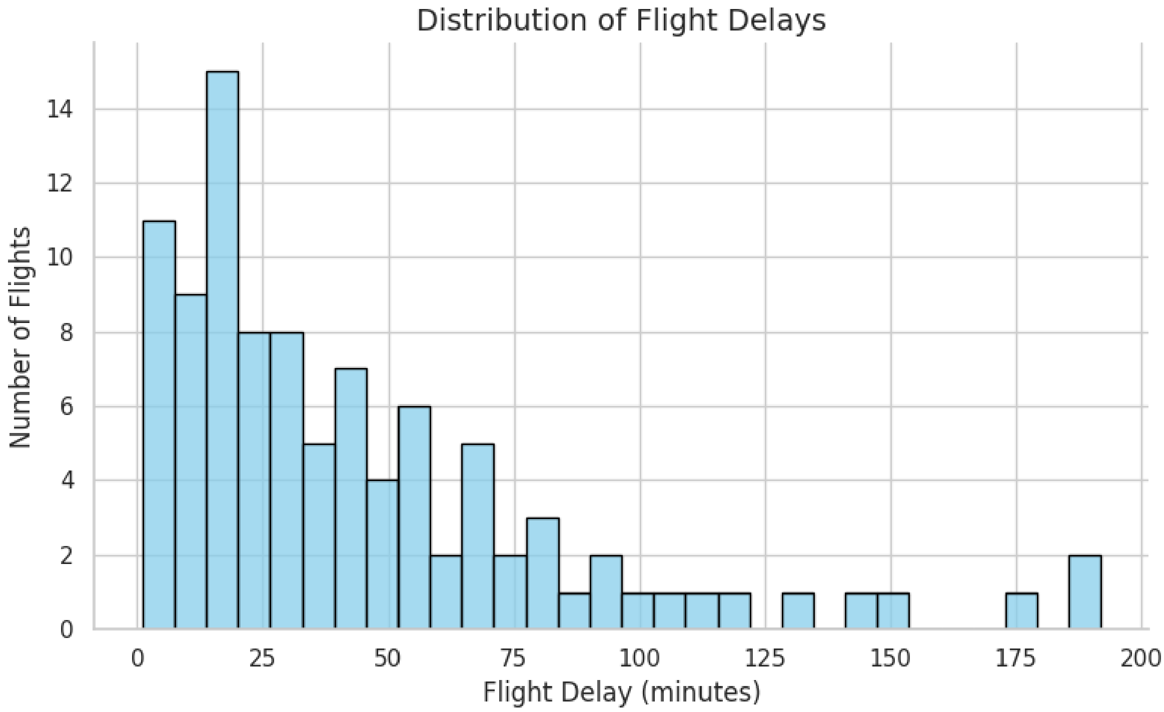

Figure C6: Distribution of delay for delayed flights due to ATFM in dp300 applied to cs10.pp00.nd00.so00.00.

The modelling approach used to replan the network considering the disruption is as follows:

1. According to the EUROCONTROL's Performance Review Report for June 2023, between June and September 2022, 5.5% of schedules were not operated on average [24]; and according to [28] strikes increase the ratio of cancellations by up to 37%. Therefore, a probability of 7.5% is used for all flights operating in LEMD to be cancelled. As shown in Figure C6, a total of 31 flights are therefore cancelled in this disruption package when applied to cs10.pp00.nd00.so00.00.

2. For the remaining flights, it is assumed that some delay due to ATFM will be applied. This is done considering the analysis and findings from [25] where ATFM regulations for AIRACs 1313–1413 and 1702, 1709 were analysed. All regulations due to industrial action from that period were processed obtaining the probability of being assigned zero minutes of delay and the distribution of the historically observed delay if positive. For the flights that are delayed in our model, a random ATFM delay following these probabilities is drawn. As shown in Figure C4, a total of 98 flights are delayed when applying this to cs10.pp00.nd00.so00.00, with a positive delay with a distribution of delay as depicted in Figure C5.

In summary, out of 410 flights operating to-from LEMD in cs10.pp00.nd00.so00.00, 31 (7.5%) are cancelled, and 98 (23.9% with respect to originally planned, 31.4% with respect to operating (non-cancelled)) are replanned with some positive delay. As shown in Figure C4 and Figure C5, flights from a range of airports in Spain are impacted.

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C.1.3.1.2.4 Dp310 - Reduced capacity at Madrid (LEMD)

Finally, SOL401/SOL3 uses as validation in their ERR a reduction of capacity at Madrid (LEMD) for the entire day at 10 flights/hour [26]. Therefore, this will be considered as a final disruption package when evaluating the possibility of SOL399/SOL1 to assess the outcome of SOL401/SOL3.

C.1.3.1.3 Disruption management

Disruption management	Short description
dm00	The replanning of the network considering the disruption but not optimising operations: for cancellations, removal of services from schedules; for delay, a shift of schedules by the amount of expected delay (e.g. ATFM delay)
dm10	An ad-hoc solution to compensate for the reduction in supply for dp100 in the pp20 case, consisting of reintroducing the banned flights between the origin-destination impacted by the rail cancellations.
dm20	Replanning of operations if no optimisation is implemented to minimise passengers stranded as provided by SOL400/SOL3 (baseline of disruption according to SOL400/SOL3).
dm21	Application of SOL400/SOL3 in a centralised manner.

Table C3: Different alternatives to manage disruptions evaluated

Table C3 Different alternatives to manage disruptions evaluated

In order to show the capabilities of SOL399/SOL1 to assess a network impacted by disruptions (replanned), the usage of SOL400/SOL3 is not required. As it will be presented in C.1.3.1.4., different passenger assignment alternative already enables the evaluation of policies and operational aspects on the impact of passengers even if only the disruption is just considered (cancelling and delaying services (dm00)), but no optimisation of the remaining services (further adjusting their schedules) is considered.

Dm10 is the ad-hoc solution to compensate for the reduction of supply in the case of rail cancellation of services in the case of the multimodality enforced policy (pp20). This considers the reintroduction of those cancelled flights for the origin-destination impacted by the rail limitations. Note that this is done to show how SOL399/SOL1 can consider the introduction of new services besides the cancellation and the replanning (delay) of services as part of the replanning of a network.

Finally, dm21 is a version of SOL401/SOL3 as described in [26]; these are validated against the replanning of the network if no optimisation is produced as provided by SOL401/SOL3 (dm20).

C.1.3.1.4 Passenger assignment alternatives

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Passengers replanning alternative	Short description	Constraints for new itineraries for passengers
pa01	Close to planned	• To Respect the alliances of services used • To respect alliances of original itineraries • To maintain the original path • To maintain the original modes • Start the journey in the same infrastructure as originally planned • End the journey in the same infrastructure as originally planned • Do not allow to depart from home before initially planned
pa02	Allow different path	• To Respect the alliances of services used • To respect alliances of original itineraries • Allow a different path than the original path • To maintain the original modes • Allow to start the journey in a different infrastructure than originally planned • Allow to end the journey in a different infrastructure than originally planned • Do not allow to depart from home before initially planned
pa03	Allow different path and mode swap	• To Respect the alliances of services used • To respect alliances of original itineraries • Allow a different path than the original path • Allow different modes than originally planned • Allow to start the journey in a different infrastructure than originally planned • Allow to end the journey in a different infrastructure than originally planned • Do not allow to depart from home before initially planned
pa04	Allow different path, mode swap and different operators	• To Respect the alliances of services used • Allow different operators (alliances) than originally planned • Allow a different path than the original path • Allow different modes than originally planned • Allow to start the journey in a different infrastructure than originally planned • Allow to end the journey in a different infrastructure than originally planned • Do not allow to depart from home before initially planned

pa05	Allow different path, mode swap, different operators and leave 'home' earlier than initially planned	• To Respect the alliances of services used • Allow different operators (alliances) than originally planned • Allow a different path than the original path • Allow different modes than originally planned • Allow to start the journey in a different infrastructure than originally planned • Allow to end the journey in a different infrastructure than originally planned • Allow to depart from home before initially planned

Table C 4: Passenger assignment alternatives

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Finally, when reassigning passengers impacted by the disruption into the capacity available in the replanned network, different alternatives are possible: from restrictive conditions when passengers can only be accommodated in 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.

SOL399/SOL1 provides parameters to configure these aspects. These individual constraints to consider when reassigning passengers are grouped into five alternatives as shown in Table C4.

A lexicographic optimisation is used to perform the reassignment of passengers to potentially suitable alternatives. How this optimisation is performed could also be adjusted if desired. For the validation, 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.

C.1.3.1.5 Summary of validation exercise scenarios for disruptions and replanned networks

Disruption package	Reference scenario	Disruption scenario	Solution scenario	Rationale
dp100	cs10.pp00.nd00.so00.00	cs10.pp00.nd00.so00.00.dp100	dm00.pa01 to dm00.pa05	Baseline case with the closure of Madrid-Barcelona rail link (dp100) cancelling rail services affected (dm00). Different alternatives for how to reallocate impacted passengers analysed (from pa01 to pa05)
	cs10.pp20.nd00.so00.00	cs10.pp20.nd00.so00.00.dp100	dm00.pa01 to dm00.pa05	Same as previous but with enforced policies (pp20 – integrated ticketing, CO_2 tax for aviation and flight ban) cancelling rail services affected (dm00). Different alternatives for how to reallocate impacted passengers analysed (from pa01 to pa05)
			dm10.pa01 to dm10.pa05	Same as previous, but in this case, the disruption management action is to reintroduce the banned flights. These flights will be put back as usable services to compensate the drop in rail capacity and support the passengers affected by the rail disruption.
dp210	cs10.pp00.nd00.so00.00	cs10.pp00.nd00.so00.00.dp210	dm00.pa02 to dm00.pa05	Closure of Malaga airport (LEMG). At least the flexibility of pa02 – allowing different paths is required, as the airport is closed, and therefore, no alternative maintaining the original path will be possible.
dp300	cs10.pp00.nd00.so00.00	cs10.pp00.nd00.so00.00.dp300	dm10.pa01 to dm10.pa05	Instead of closure of LEMD, assume delay due to ATFM is known beforehand. There is not enough time to justify departing earlier, but there is possible alternative paths for connecting passengers.

dp310	cs10.pp00.nd00.so00.00	cs10.pp00.nd00.so00.00.dp310.dm20.pa04	dm21.pa03	Reduced capacity at LEMD as assumed by SOL401/SOL3 and application of SOL401/SOL3 as in SOL401/SOL3 ERR (see [26]). Replanning in a centralised manner, therefore allowing the change of mode and operator.

Table C5: Scenarios evaluated for Experiment 1 – Evaluation of replanned network in case of disruptions.

With all the previous considerations, the scenarios defined in Table C5 are evaluated. Note that we differentiate between 'reference scenario' as the case without the disruption, 'disrupted scenario' where the disruption is applied, and 'solution scenario' where a disruption management mechanism is in place with a passenger replanning alternative. Finally, these scenarios are grouped by the disruption applied to them, as it might be interesting to show in the validation results how passengers are reaccommodated as a function of the other characteristics when a disruption with the same characteristics arises.

These scenarios show a range of types of disruptions: rail, air, full closures (closer to crisis management situation), ATFM-related, and significant throughput reduction. These will satisfy Experiment 2 showcasing how SOL399/SOL1 can assess the impact of the disruptions (and replanned network) on the initial passenger itineraries and their potential replanning. As explained in [18], it is considered that cs10 is sufficient for the validation of SOL399/SOL1, i.e., to demonstrate the capabilities of SOL399/SOL1 to assess the impact of the disruption and the replanned network (with or without SOL401/SOL3). Therefore cs11 (intra-Spain mobility with international flights) will not be discussed in this document and will be analysed as future work.

As previously discussed these scenarios will be used for the evaluation of disruption and replanned networks at a planning/pre-tactical phase. The tactical evaluation of the replanned network is not considered fully required to assess the benefits of the replanning (as it would focus on the robustness of that replanning). The capabilities of SOL399/SOL1 to assess tactically a network was presented in Experiment 3 of Validation Exercise 2 (see Section B.3.2.1.3 and EXE02-CRT-0399-ERP-030.4). Moreover, the tactical evaluation of a network under different levels of disturbance are shown in Experiment 3 of this Exercise (see Section C.1.3.2).

C.1.3.2 Reference and solution scenario for a mechanism to support multimodality

For the assessment of a mechanism to support multimodality a fast-track to process passengers at the airport pre-departure is considered. This mechanism will reduce the kerb-to-gate time for multimodal passengers expecting to reduce potential missed inter-mode connections. The airport could implement this in different ways, such as reducing the processing time at security checks (dedicated lane, more staff) as in [7], faster baggage drop or tactical gate change to shorten walking distance. In this simplified version, multimodal delayed passengers can use a dedicated Fast-track, which reduces their kerb-to-gate processing times at the airport by a specified ratio.

As shown in Section B.3.2.2., the tactical evaluation of s10.pp20.nd02.so10.01 showed that when there is a large ground mobility delay a significant amount of passengers miss their connections. These missed connections are worsened with respect to the so00.00 case as the optimisation of the schedules by SOL400/SOL2 tightens the buffers. A trade-off between shorter planned operations and their robustness arises.

Therefore, for the evaluation of the mechanisms to support multimodality the reference scenario is set to be the s10.pp20.nd02.so10.01 with 30 minutes of ground mobility delay without any particular mechanisms. Then the solution scenarios are the same case but with reductoins of the kerb-to-gate passenger processing time between 0.1 to 0.5 speed-up coefficient (reduction of kerb-to-gate between 10 and 50%).

Appendix NN Summary of validation exercise #03 validation assumptions

No extra assumptions are needed for this exercise.

C.2 Deviation from the planned activities

The main deviation with respect to the planned activities is that the replanning of passenger itineraries in case of disruption provided by SOL399/SOL1 can already evaluate different alternatives to manage disruptions without the introduction of SOL401/SOL3. Therefore, the assessment of the replanning capabilities focuses on different types of representative disruptions. The combined disruption of air and rail in the network is not presented, but the capabilities of the model to evaluate both are discussed.

Finally, Experiment 2 has not been executed for this Validation Exercise. Note that this was already considered as a possibility in the original plan (see ERP [18]), and it is not a limitation on the validation of SOL399/SOL1 overall, as explained previously and in Section C.3.2.1.2.

C.3 Validation exercise #03 results

C.3.1 Summary of validation exercise #03 results

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Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion	Sub-operating environment	Exercise #03 validation results	Exercise #03 validation objective status
EXE03-OBJ-0399-TRL2-ERP-050	Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries.	EXE03-CRT-0399-ERP-050.1	• Set two experiments to replan the network considering the disruptions, with and without the use of a Disruption Management Solution (e.g. SOL401/SOL3) and use the replanning capabilities of the Multimodal Evaluator to reassign passengers in the network. • Compute PIs on the replanned networks with a focus on replanned multimodal indicators. This computation is to be done on the replanned network obtained from the previous step. • Compare the results of the PIs of the two related networks to assess the benefit of the Disruption Management Solution.	N/A	• Scenarios with different type of disruptions: rail links and airport closures, industrial actions, and reduced capacity have been evaluated by SOL399/SOL1. • Different replanning of passengers alternatives are considered. • Disruption management initiatives by introducing new services and by applying SOL401/SOL3 have been assessed. • Mobility PIs with a focus on passenger-centric are estimated for the different scenarios enabling the comparison of alternatives.	OK

EXE03-OBJ-0399-TRL2-ERP-060	A mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports, is evaluated by the Tactical Evaluator.	EXE03-CRT-0399-ERP-060.1	• Two tactical experiments are set up, one with and one without the mechanism activated, and are executed with the Tactical Evaluator and tactical multimodality-related PIs computed. • The performance of the system, with a focus on passenger-centric metrics, is compared across the two experiments to assess the benefit of the mechanism.	N/A	• Scenario cs10.pp20.nd02.so10.01 with 30-minute ground mobility delay executed with an airport pre-departure fast-track mechanism. • PIs for passengers with missed connections have been calculated to assess the benefit of the mechanism.	OK
Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion	Sub-operating environment	Exercise #03 validation results	Exercise #03 validation objective status

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EXE03-OBJ-0399-TRL2-ERP-050	Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries.	EXE03-CRT-0399-ERP-050.1	• Set two experiments to replan the network considering the disruptions, with and without the use of a Disruption Management Solution (e.g. SOL401/SOL3) and use the replanning capabilities of the Multimodal Evaluator to reassign passengers in the network. • Compute PIs on the replanned networks with a focus on replanned multimodal indicators. This computation is to be done on the replanned network obtained from the previous step. • Compare the results of the PIs of the two related networks to assess the benefit of the Disruption Management Solution.	N/A		

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EXE03-OBJ-0399-TRL2-ERP-060	A mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports, is evaluated by the Tactical Evaluator.	EXE03-CRT-0399-ERP-060.1	• Two tactical experiments are set up, one with and one without the mechanism activated, and are executed with the Tactical Evaluator and tactical multimodality-related PIs computed. • The performance of the system, with a focus on passenger-centric metrics, is compared across the two experiments to assess the benefit of the mechanism.	N/A	• Scenario cs10.pp20.nd02.so10.01 with 30 minute ground mobility delay executed with an airport pre-departure fast-track mechanism. • PIs for passengers with missed connections have been calculated to assess the benefit of the mechanism.	OK

Table C6: Validation exercise #03 results

Table C6 presents the summary of the objective status of the validation exercise #03

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C.3.2 Analysis of validation exercise #03 results per validation objective

C.3.2.1OBJ-0399-TRL2-ERP-050 Results

Objective: Evaluate the efficiency of a Disruption Management Solution (e.g. SOL401/SOL3) to deal with disruptions by replanning the network by computing PIs on the network considering the replanned operations and passengers' itineraries.

Validation:

C3.2.1.1 Experiment 1

The results of replanning the network under different disruption conditions are presented in this section. As presented in C.1.3.1, there are several reference and solution scenarios. In this experiment, results will be presented per disruption package, i.e., disruption applied to the network, as presented in Table C5.

C3.2.1.1.1 DP100 – Madrid Atocha - Barcelona Sants rail link closure

This first set of scenarios considers a breakage on the rail line between Madrid Atocha and Barcelona Sants stations. This is one of the rail links with higher demand within Spain. Note that this will not only affect passengers travelling between those two cities but also passengers between cities along the line (e.g. between Madrid and Zaragoza), passengers in the line before or after the breakage (as the whole trains are cancelled) (e.g. Girona - Barcelona in trains that keep their journey to Madrid), and of course, on connecting passengers which use services on that line.

cs10.pp00.nd00.so00.00.dp100.dm00 – Baseline network

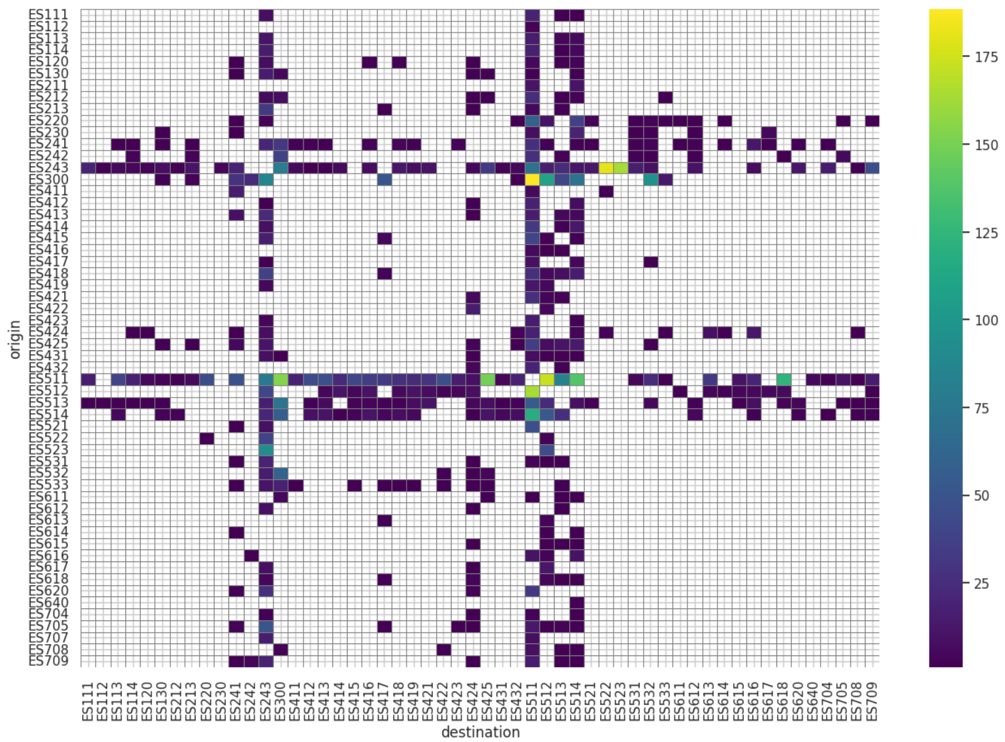


Figure C7: Need replanning

We start by considering the baseline network (cs10.pp00.nd00.so00.00). A total of 25,356 passengers out of 389,191 passengers in the case study (7.0%) are affected by this breakage. As depicted in Figure C7 the ES300-ES511 (Madrid to Barcelona) are the regions affected the most (as expected). It is worth seeing how ES243 (Zaragoza), ES512 (Girona), ES513 (Lleida) and ES514 (Tarragona), all regions within the broken line, are particularly impacted in their connectivity with many different regions within Spain (which indicates that these regions are directly (but also indirectly) connected by these trains to the rest of Spain).

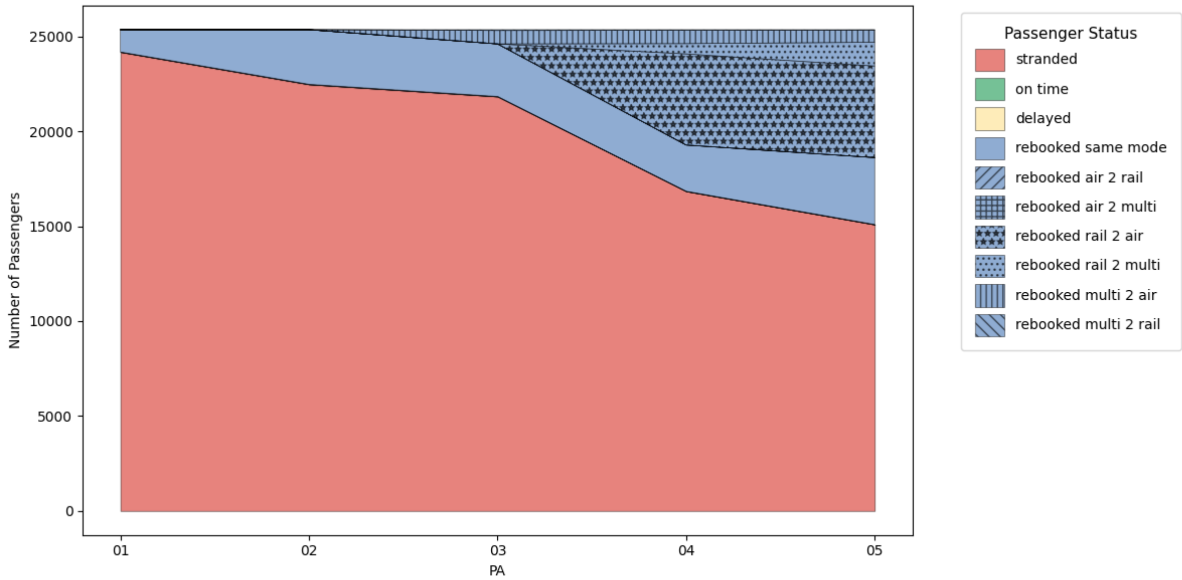


Figure C8: Passengers impacted for cs10.pp00.nd00.so00.00.dp100.dm00

pp00.dp100.dm00	pa01	pa02	pa03	pa04	pa05
Unaffected [pax (% total pax)]	363,835 (93.5%)	363,835 (93.5%)	363,835 (93.5%)	363,835 (93.5%)	363,835 (93.5%)
Stranded [pax (% total / % affected pax)]	24,180 (6.2% /95.4%)	22,475 (5.8% / 88.6%)	21,834 (5.6% / 86.1%)	16,843 (4.3% / 66.4%)	15,090 (3.9% / 59.5%)
Delayed [pax (% total / % affected pax)]	0	0	0	0	0
On-time [pax (% total / % affected pax)]	0	0	0	0	0

Replanned [pax (% total / % affected pax)]	1,176 (0.3% / 4.6%)	2,881 (0.7% / 11.4%)	3,522 (0.9% / 13.9%)	8,513 (2.2% / 33.6%)	10,266 (2.6% / 40.5%)

Table C7: Passengers affected by dp100.dm00 in cs10.pp00.nd00.so00.00

Figure C8, with values depicted in Table C7 shows the number of passengers affected by the disruption and how different policies to manage them impact their final status:

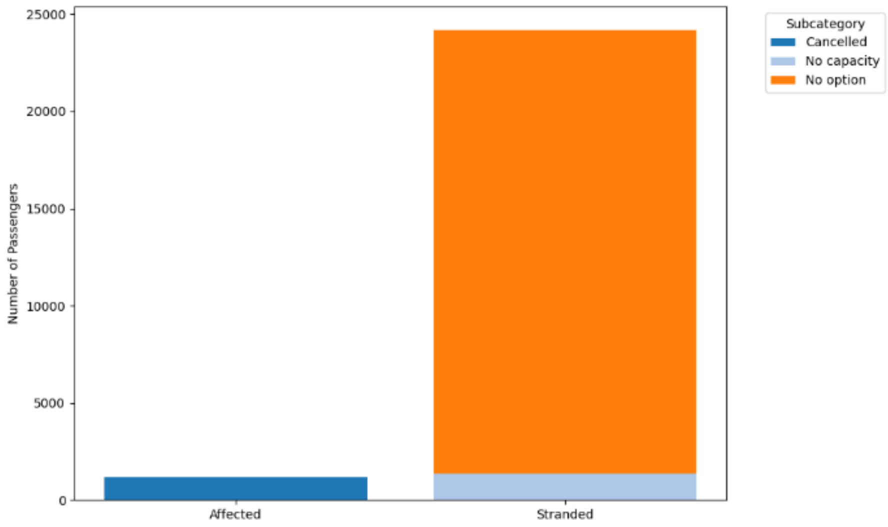
- pa01 forces passengers to keep their initial path and operators (alliances). This means that only 4.6% of affected passengers are reaccommodated. These will be passengers who can use alternative rail services which are not cancelled (i.e. trains not passing via Madrid-Atocha and Barcelona-Sants). Of course, if their origin or destination is any of these affected stops, no alternatives will be possible.

- pa02 allows the use of alternative paths, including changing the starting and end nodes. As shown, this extra flexibility means that an additional 1,705 passengers can be reaccommodated.

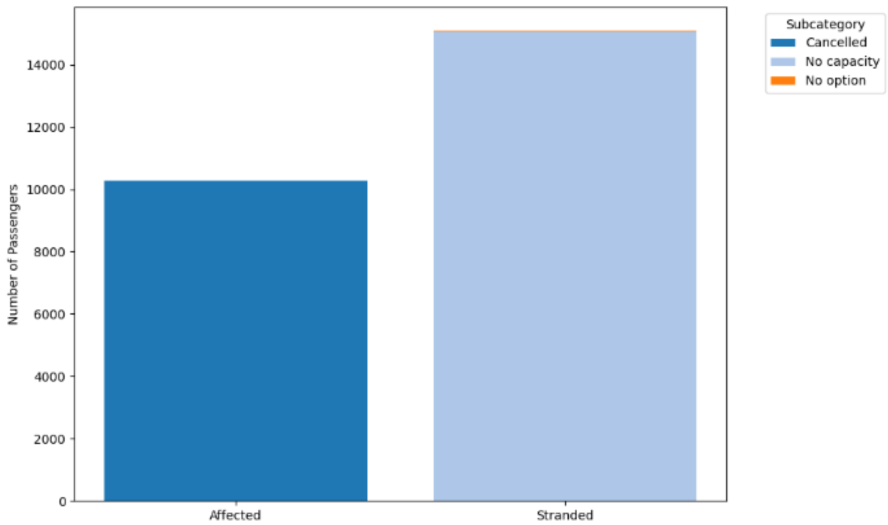
- pa03 enables the usage of alternative modes. In this case, as the disruption is on the rail network, we expect passengers to be able to switch to suitable air alternatives. However, the operators (alliances) must be the same as originally planned. This means that only multimodal passengers could be reaccommodated into flights, i.e. they were planning to get a train (which is now cancelled) and a flight with a given airline (alliance), and now they are allowed to use flights from that airline (or alternative trains). This enables the reallocation of additional 641 passengers, having 13.9% of impacted passengers reaccommodated (with 86.1% of affected passengers still stranded).

- pa04 allows further flexibility including the swap of operator. This is particularly relevant in this case, as passengers who were only using rail now can use flights instead. Now the number of passengers reaccommodated increased significantly to 8,513 (33.6% of affected passengers). This shift to air is observable in Figure C8 (see 'rebooked rail 2 air' case).

- pa05 finally allows also to depart their initial 'home' earlier than planned. This means that passengers can get a service that departs before they originally intended. This could be considered if the disruption is known with a sufficient look-ahead time. With this extra flexibility, 10,266 passengers are reaccommodated, reaching up to 40.5% of affected passengers being accommodated. As shown in Figure C11 there is an increase in the number of passengers being re-routed from rail to multimodal alternatives (from 546 passengers rebooking pa04 to 1,254 passengers in pa05) and able to use the same mode but using earlier departures (from 2,434 passengers in pa04 to 3,524 in pa05).



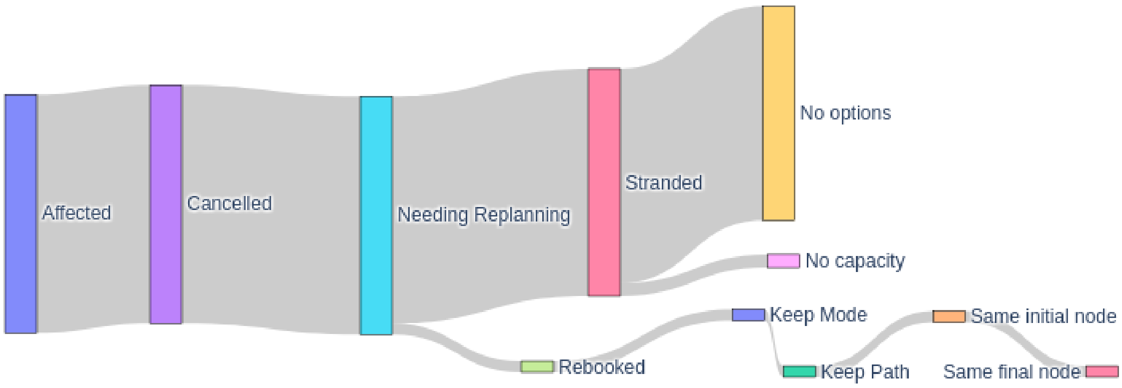
a) pa01



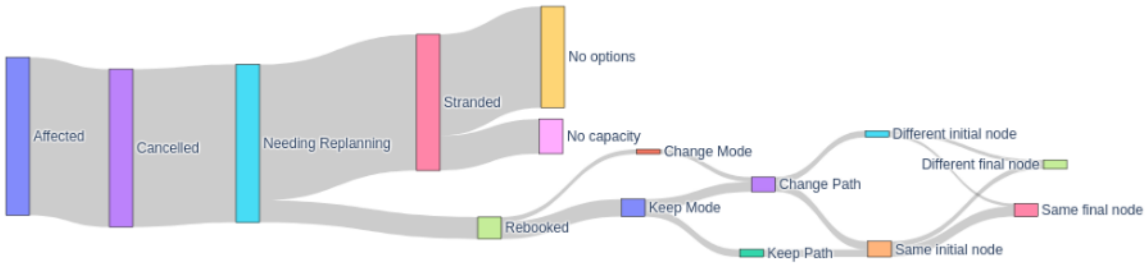
b) pa05

C9: Passengers affected by the disruption and their status for pp00.dp100.dm00

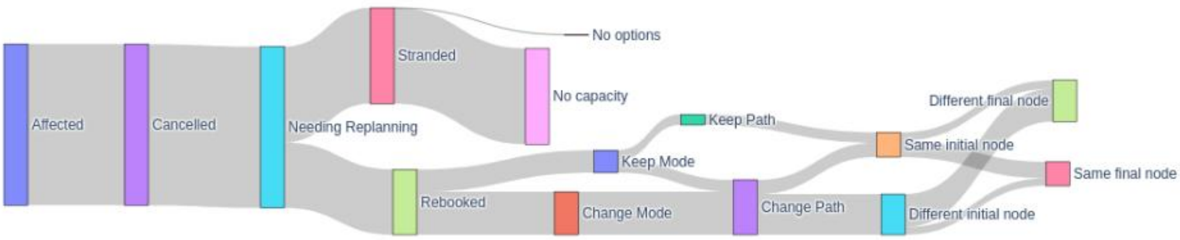
As depicted in Figure C9, in the pa01 case, most of the passengers end up stranded, and the main reason for being stranded is a lack of alternatives (options) to fulfil their journey. With the additional flexibility incorporated in pa05, the number of affected passengers (that can be rebooked, delayed, etc) increases significantly, while conversely, the number of stranded passengers reduces significantly (to 15,090 from 24,180 as previously presented in Table C7) (note the different y-axis in the two subfigures). And, as observed, the main reason for those remaining stranded passengers is not a lack of alternatives but a lack of capacity on those alternatives, i.e., all alternatives are full, at least in some of the services needed to fulfil the itineraries.



a) pa01



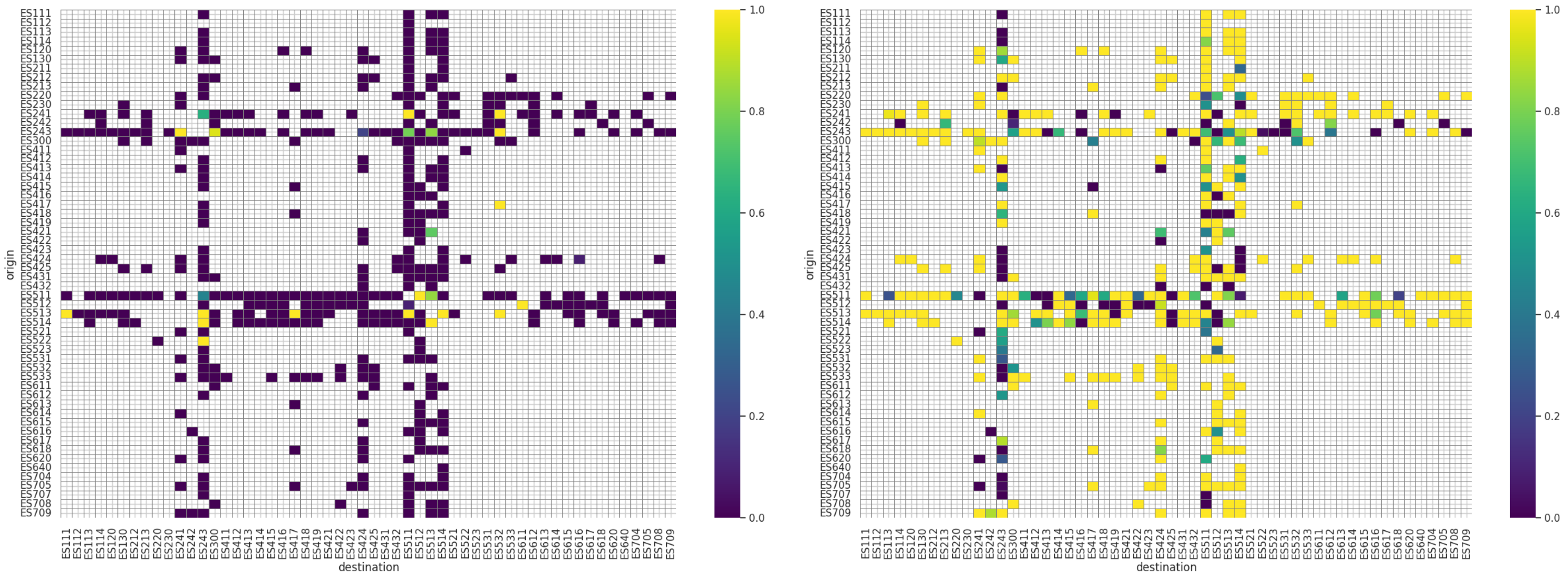
b) pa03



b) pa05

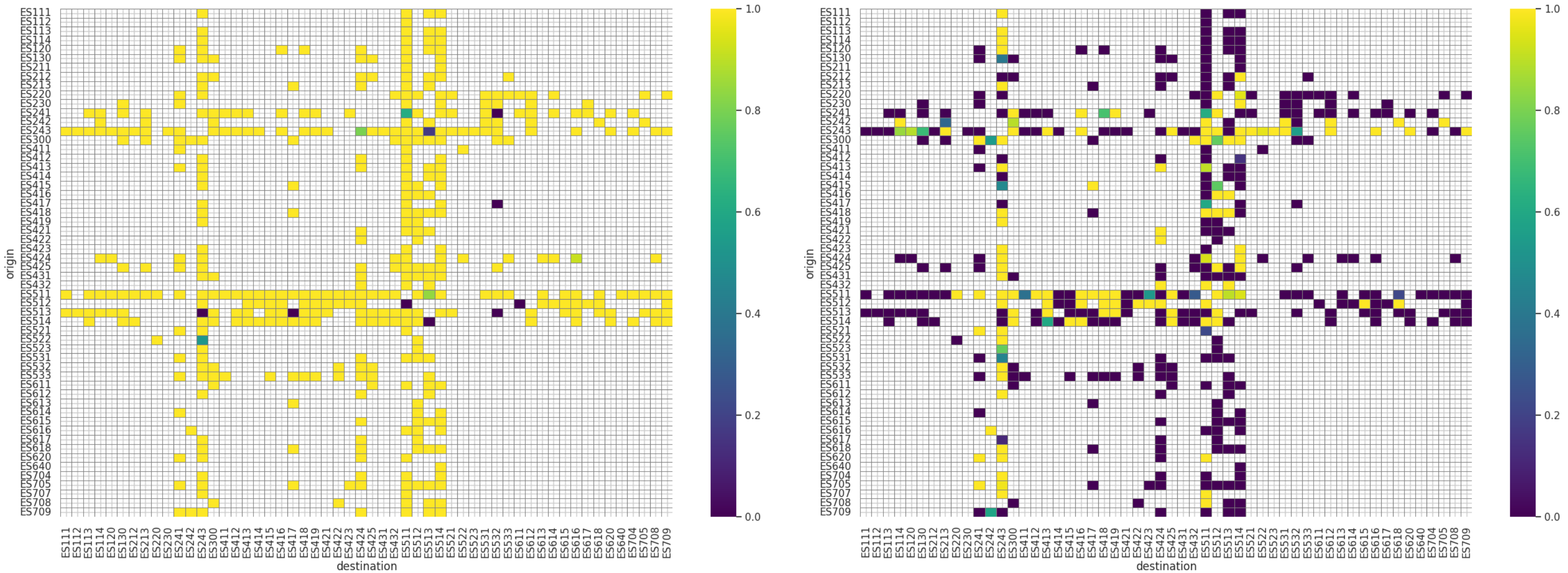
Figure C10: Distribution of itineraries status for pp00.dp100.dm00

Figure C10 represents for pa01, pa03 and pa05 the status of the different itineraries affected by the disruption in this scenario. It is possible to observe how, as the flexibility to rebook passengers increases, there is a change in the number of stranded and rebooked passengers. It is worth seeing how in pa03 the majority of stranded passengers do not have available alternatives (options) while in pa05 the lack of sparre capacity is the limiting factor. Also, note how in pa05, most of the passengers arrive (and start their journey) at a different node (airport/rail station) than initially planned.



a) Percentage of passengers reassigned for pa01 case

b) Percentage of passengers reassigned for pa05 case



c) Percentage of passengers stranded for pa01 case
d) Percentage of stranded passengers for pa05 case

Figure C11: Passengers reassigned and stranded per origin-destination NUTS3 for pp00.dp100.dm00

Figure C11 delves further into the analysis of the impact of flexibility when replanning the itineraries considering the origin-destination connectivity. The figure contraposes the percentage of passengers reassigned (and the complementary percentage of passengers stranded) with respect to the total number of passengers affected (see Figure C7) for the pa01 and pa05 cases.

As shown, for the pa01 case, only 26 origin-destination pairs benefit from the reassignment, with most connectivity being stranded. The origin-destination pairs that replan the maximum number of passengers are ES511 (Barcelona) to ES513 (Lleida) and ES243 (Zaragozaa) to ES300 (Madrid). These can find alternatives to other rail services that are not cancelled. On the contrary, in the pa05 case, almost all origin-destination pairs manage to reaccommodate most of their affected demand. Notable exceptions are trips to-from ES243 (Zaragoza) and, not surprisingly, ES511 (Barcelona). This shows how these regions (particularly Zaragoza) rely on the rail link closed for their connectivity with the remaining of Spain.

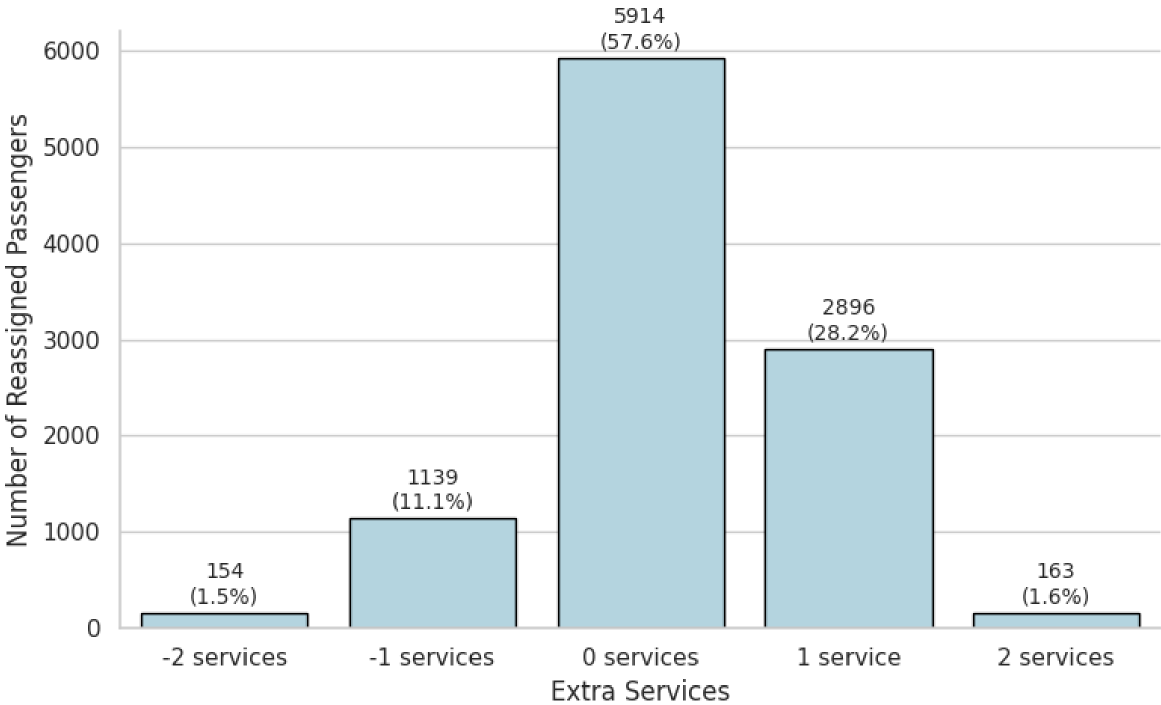


Figure C12: Number of additional services used with respect to planned itineraries for replanned passengers in pa05 for pp00.dp100.dm00

When alternative itineraries are used, in some cases a different number of services than initially planned could be used. Figure C12 shows the number of additional services used with respect to the original itineraries for passengers that are replanned in the network for pa05. We have selected pa05 as this is the most flexible case. As shown, most passengers maintain the number of services from their original itinerary (57.6% of the cases) or higher (29.8%). This is expected as rerouting might involve more connections to reach their final destination. However, as shown, in some cases (12.9%), alternatives are found that use fewer services, in some cases by departing or arriving at adjacent NUTS that are reachable from the actual origin and destination regions (some examples of this are shown below).

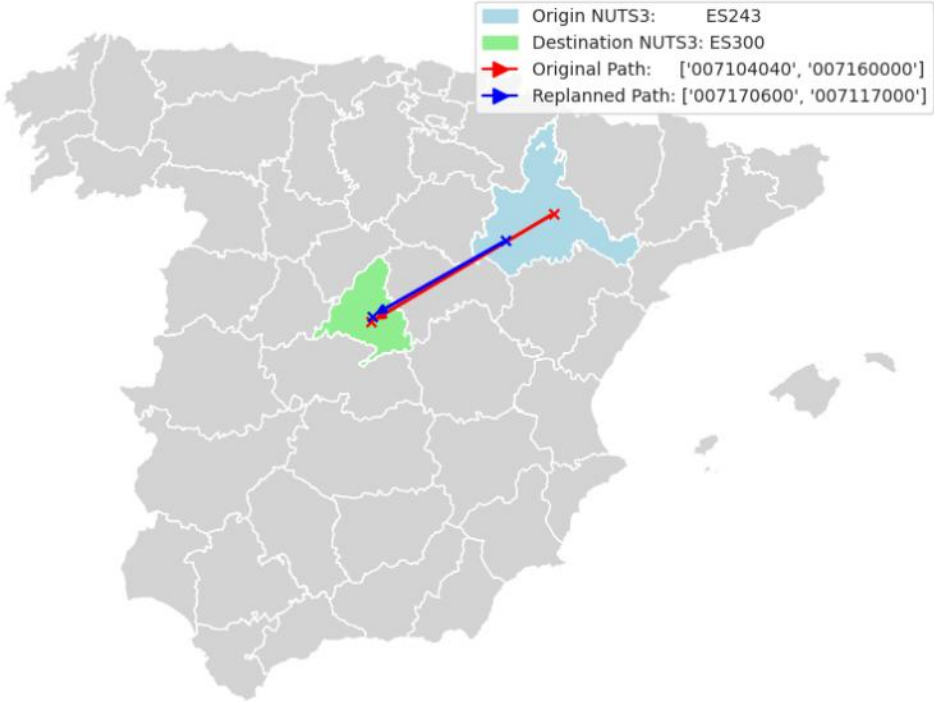


Figure C13: Example of replanning of itinerary from ES243 to ES300 in cs10.pp00.nd00.so00.00.dp100.dm00.pa03

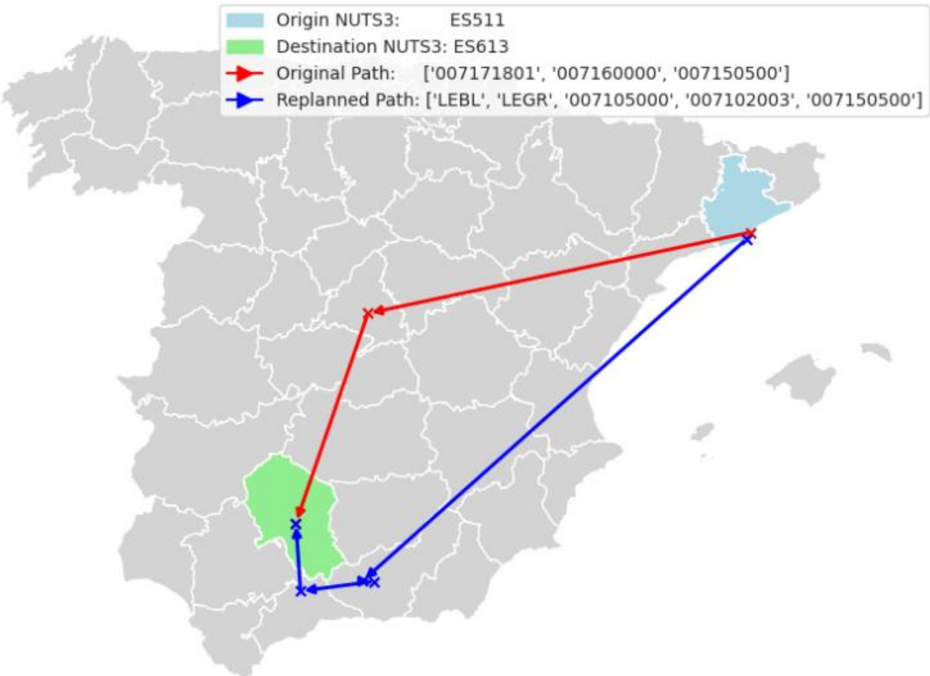


Figure C14: Example of replanning of itinerary from ES511 to ES613 in cs10.pp00.nd00.so00.00.dp100.dm00.pa05

Figure C 15: Comparison of Original and Replanned Air Traffic Routes Between NUTS3 Regions in Spain

Figures C13, C14 and C15 show three examples of reassigned passengers for the pp00.sp100.dm00 case. Figures C13 shows for pa03 how an alternative path with different origin and destination rail stations is used to travel between ES243 (Zaragoza) and ES300 (Madrid). In the original path, the passenger was travelling from Zaragoza Delicias (007104040) to Madrid Atocha (007160000). This route is in the HSR line which is closed in dp100. As shown, the alternative is a different rail service from Calatayud (007170600) to Madrid Chamartín used by the regional train.

Figure C14 shows how in pa05, a rail itinerary from ES511 (Barcelona) to ES613 (Córdoba). In this case, the planned trip was a rail journey from Barcelona Sants (00717801) to Madrid Atocha (007160000) to then change to a train to Córdoba Central (007150500), i.e. two HSR services. In the replanned alternative, the passenger flies from Barcelona (LEBL) to Granada (LEGR) and then continues by train to Córdoba, with a train from Granda (007105000) to Antequera in the region of Malaga (007102003) to then a final train to Córdoba Central (007150500). This is an example of a replanning which changes modes and the initial infrastructure node to reach the final destination as planned.

Finally, Figure C15 is an interesting example for passengers travelling from ES616 (Jaén) to ES511 (Barcelona). The original journey was a rail trip from Espeluy (007150400) in Jaén's NUTS to Córdoba Central (007150500) and then to Barcelona Sants (007171801) via Madrid Atocha (007160000). As the Madrid to Barcelona train is closed, the alternative is a direct flight from Malaga (LEMG) to Barcelona (LEBL). This shows how the alternative could require fewer services than originally planned and shows the effect of the larger catchment areas (in terms of access/egress) of airports, as LEMG can be reached from ES616 even if the airport is in an adjacent NUTS (ES617). The passenger will have a longer access journey but won't be stranded.

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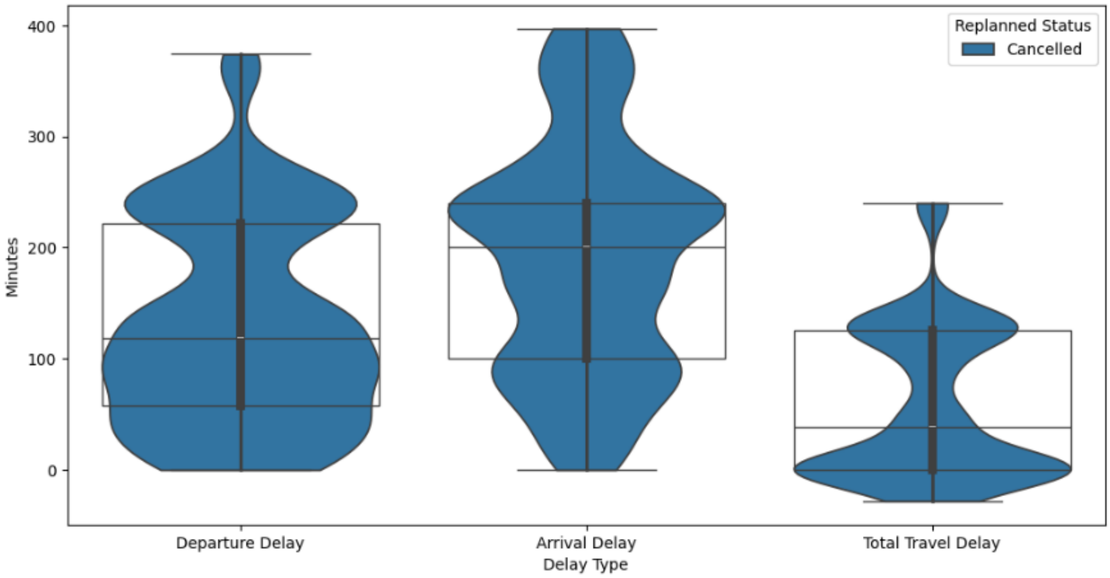
pp00.dp100.dm00	pa01	pa02	pa03	pa04	pa05
Mean departure delay	131.8	113.3	105.9	62.8	-275.8
Mean arrival delay	191.5	237.1	182.5	122.6	-164.6
Mean total travel time deviation	59.7	123.8	76.6	59.8	111.2

Table C8: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp00.nd00.so00.00.dp100.dm00



a) pa01

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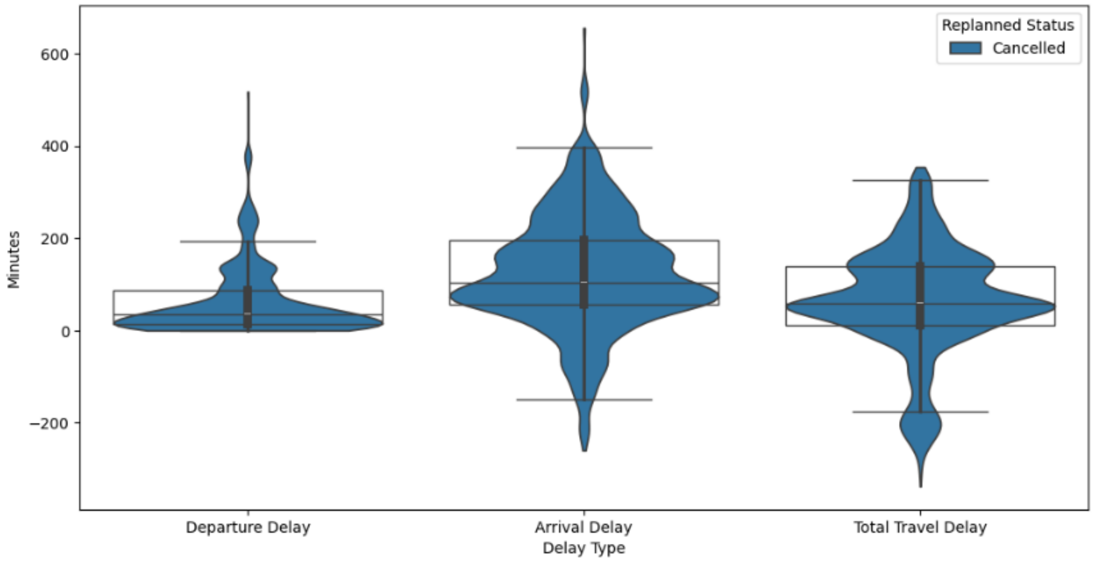
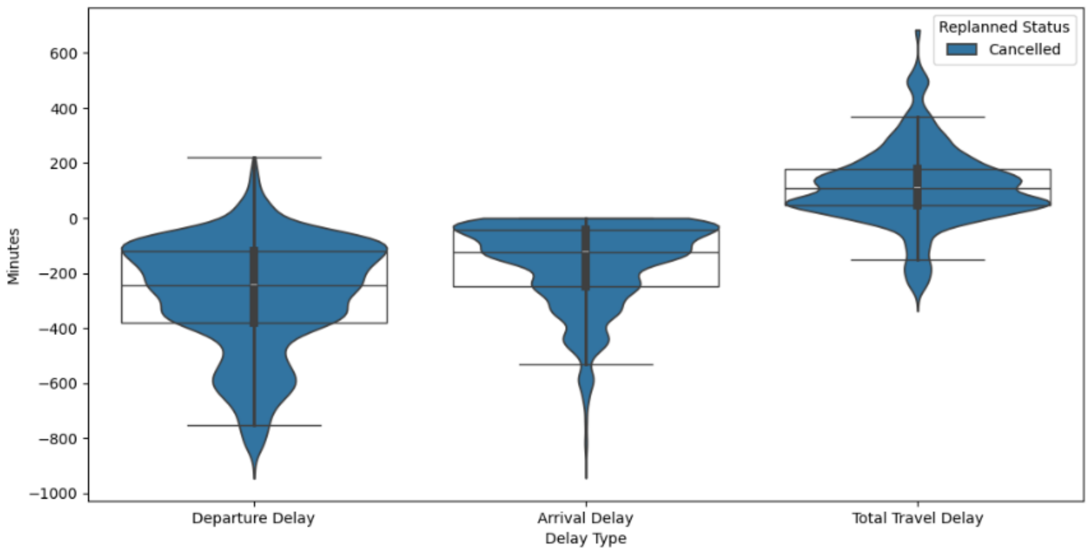


b) pa04



c) pa05

Figure C16: Distribution of the departure and arrival delays, and travel time deviation for cs10.pp00.nd00.so00.00.dp100.dm00 for pa01, pa04 and pa05.

The final aspect to consider is the travelling time of passengers. One of the capabilities of SOL399/SOL1 is to evaluate the total travelling time (door-to-door). Therefore, when assessing the departure and arrival delay this is computed from door-to-door. This allows the model to evaluate alternatives for passenger re-routing that consider different infrastructure nodes, even arriving at different NUTS requiring different access and/or egress times (as previously shown in Figure C15).

Table C8 summarises the mean departure and arrival delay of the passenger itineraries, and the difference in travel time of the replanned journeys. First, it is interesting to observe that as the flexibility to replan the itineraries increases, the mean departure delay (from the origin door) tends to decrease. The mean arrival delay increases significantly when alternative paths are allowed but the same mode is maintained (pa02). This indicates that as the rail link is closed, alternatives involve, in general, longer routes avoiding that broken link (as shown by the additional 123.8 minutes required to cover the trip journeys with respect to the originally planned itineraries). Enabling the use of alternative modes (pa03) reduces the mean departure and arrival delay. This reduction is further increased in pa04 when different operators are allowed to be used. This brings the extra travelling time to similar values as pa01 but with a reduced departure and arrival delay. Finally, if passengers are allowed to use a service before the one originally planned, both the departure and arrival delay become negative (-275.8 and -164.6 minutes respectively). This means that, on average, replanned passengers need to leave their 'home' 4h35 minutes before originally planned and end up arriving at their destination 2h45 minutes before planned. Note that this flexibility allows the reallocation of 1,753 additional passengers than in pa04 (as shown in Table C7) but will require passengers to be notified well ahead of their intended departure time. However, the actual travelling time is still, on average, 1h51 minutes longer than planned. This indicates that the extra flexibility comes at the cost of using longer paths, probably with different than the planned infrastructure nodes.

Figure C16 shows the distribution of the departure and arrival delays and the travel time deviation for pa01, pa04 and pa05. As depicted, in pa01 all delays (departure and arrival) are positive, it is worth observing how arrival delay has more samples (itineraries) with larger delay, which correlates with longer travelling times than originally planned, as probably slower services (no HSR) are required to fulfil the itineraries while maintaining the original path (note that the HSR line between Madrid and Barcelona is cut in this scenario). In pa04, it can be observed how even if the departing time is after initially planned, allowing the usage of different modes could lead to earlier arrivals than planned in some cases, but overall to a higher dispersion on both departing and arrival times. Finally, pa05 utilises the capacity available in the system even if that entails departing before initially planned. SOL399/SOL1 could easily limit the maximum deviation that is considered acceptable, to avoid such large changes as the ones observed.

cs10.pp20.nd00.so00.00.dp100.dm00 – Multimodality enforced policy package

This scenario applies the same disruption as the previous case but to the network which has applied policy package pp20. This package improves multimodality by introducing integrated ticketing (which reduces transfer times between modes), a CO_2 charge for flight emissions, and, most importantly, a flight ban for flights with a rail alternative of up to 180 minutes. The strategic impact of such a policy on the planned network was described in Section B.3.2.1.3. In this case, the focus is on assessing the impact of the rail disruption on that network.

Crucially, with the flight ban, the flights between Barcelona (LEBL) and Madrid (LEMD) are among the 104 flights banned. This means that when the rail HSR link between the two cities is disrupted, the possibility to reaccommodate passengers is more limited. First, the rail network is operating with a higher load factor (and has a lower spare capacity that could be used to accommodate disrupted passengers); second, some passengers who were previously travelling with air alternatives (e.g. flying to LEMD to connect to an onward flight) are, in pp20, multimodal passengers, who are therefore impacted when the rail network is disrupted; and third, even when the possibility to swap to air operators (pa04) the alternatives are still reduced. SOL399/SOL1 is able to assess all these aspects.

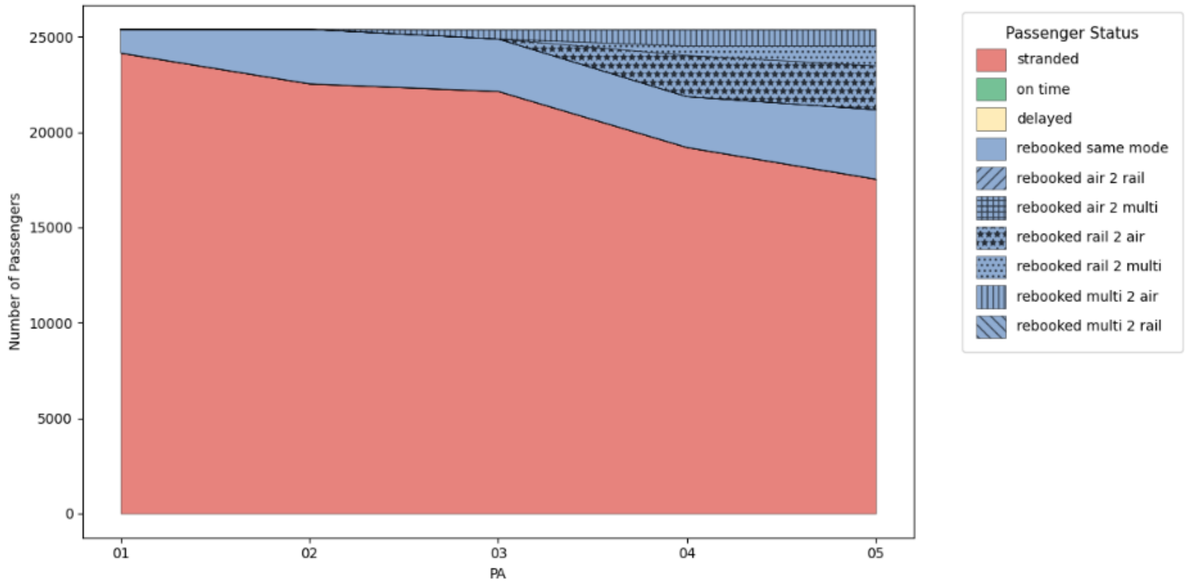


Figure C17: Passengers impacted for cs10.pp20.nd00.so00.00.dp100.dm00

pp20.dp100.dm00	pa01	pa02	pa03	pa04	pa05
Unaffected [pax (% total pax)]	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)
Stranded [pax (% total / % affected pax)]	24,164 (6.3% /95.1%)	22,554 (5.9% / 88.8%)	22,154 (5.8% / 87.2%)	19,212 (5.0% / 75.6%)	17,550 (4.6% / 69.1%)
Delayed [pax (% total / % affected pax)]	0	0	0	0	0
On-time [pax (% total / % affected pax)]	0	0	0	0	0
Replanned [pax (% total / % affected pax)]	1,233 (0.3% / 4.9%)	2,843 (0.7% / 11.2%)	3,243 (0.9% / 12.8%)	6,185 (1.6% / 24.4%)	7,847 (2.1% / 30.9%)

Table C9: Passengers affected by dp100.dm00 in cs10.pp20.nd00.so00.00.

Table C9 presents the passenger status for the different passenger assignment (pa) alternatives, as depicted in Figure C17. These results can be compared with the pp00 case (see Table C7). In pa01 and pa02 a similar number of passengers are stranded and reaccommodated in both pp00 and pp20.

In these two alternatives, passengers are kept in their original modes and paths (pa01), and mod (pa02), and the capacity of the rail system is limited in both cases. Similarly, if alternative modes are possible but operators are kept (pa03), the amount of reaccommodated passengers is only 12.8% of all disrupted passengers (slightly lower but similar to the 13.9% observed in the pa03 case). The highest difference between the replanning of passengers in the pp00 and the pp20 is for pa04 and pa05. In the first case, pp00 reaccommodated 33.6% of the passengers by using the spare air capacity. This is reduced to 24.4% in the pp20 case. Finally, when passengers are allowed to depart before originally planned, pp00 achieves 40.5% of rebooked passengers, while pp20 reaccommodates only 30.9% of the disrupted passengers. Values are compared in percentage with respect to affected passengers as the total number of passengers in the network is also different between pp20 and pp00.

In summary, the results obtained are as expected: if the network has lower capacity in the system (as flights are removed), the network is less resilient, as fewer suitable alternatives are available for passengers in case of disruption. SOL399/SOL1 is able to quantify this with passenger-centric indicators.

pp20.dp100.dm00	pa01	pa02	pa03	pa04	pa05
Mean departure delay	135.8	106.0	104.1	89.4	-328.3
Mean arrival delay	192.4	233.4	191.5	160.2	-176.2
Mean total travel time deviation	56.6	127.4	87.4	70.9	152.1

Table C10: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp20.nd00.so00.00.dp100.dm00

Table C10 shows the mean departure and arrival delay, and the travel time deviation of the replanned itineraries with respect to the original network for this scenario. As with the passengers reassigned, comparing the results with the ones obtained in the pp00 case (see Table C8) indicates that results are similar for pa01, pa02 and p03; while the fact that passengers need to find longer alternative paths when allowed to shift to air, is observed for pa04 and pa05 with longer travel time deviations (i.e., longer total trips), higher average delays for pa04 and the need for even earlier departures (and arrivals) for pa05 to be able to ensure the possible needed further air connection.

cs10.pp20.nd.so00.00.dp100.dm10 – Multimodality enforced policy package with reintroduction of flights

This scenario is designed so that we can show how SOL399/SOL1 is able to assess disruption management solutions which introduce additional new replacement services. In this case, the simple approach used is to reintroduce the banned flights.

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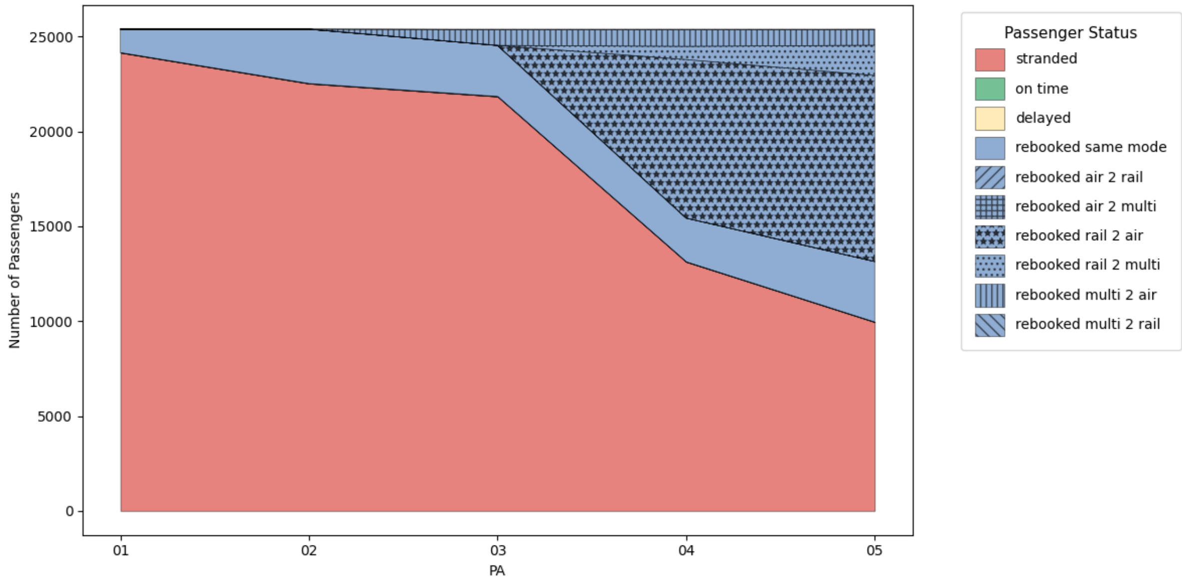

Figure C18: Passengers impacted for cs10.pp20.nd00.so00.00.dp100.dm10

pp20.dp100.dm10	pa01	pa02	pa03	pa04	pa05
Unaffected [pax (% total pax)]	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)	355,657 (93.3%)
Stranded [pax (% total / % affected pax)]	24,164 (6.3% /95.1%)	22,533 (5.9% / 88.7%)	21,852 (5.7% / 86.0%)	13,132 (3.4% / 51.7%)	9,956 (2.6% / 39.2%)
Delayed [pax (% total / % affected pax)]	0	0	0	0	0
On-time [pax (% total / % affected pax)]	0	0	0	0	0
Replanned [pax (% total / % affected pax)]	1,233 (0.3% / 4.9%)	2,864 (0.8% / 11.3%)	3,545 (0.9% / 14.0%)	12,265 (3.2% / 48.3%)	15,441 (4.1% / 60.8%)

Table C11: Passengers affected by dp100.dm10 in cs10.pp20.nd00.so00.00.

As expected, the results presented in Figure C18 and Table C11 show that having these extra flights does not provide any significant benefit for pa01 and pa02, as the modes used in the original itineraries are maintained. For pa03, when the alternative flights could be used for multimodal passengers if using the same airline as initially planned, few additional passengers are reaccommodated, but the biggest benefit is observed in pa04 and pa05. As passengers are no longer required to maintain the operator(s) they had in their original itineraries and the additional flights have full spare capacity. As shown, 48.3% and 60.8% of disrupted passengers are reaccommodated for pa04 and pa05. These values, again as expected, exceed the ones for pp00 (33.6% and 40.5%), as the flights are fully available.

pp20.dp100.dm10	pa01	pa02	pa03	pa04	pa05
Mean departure delay	136.2	106.8	97.4	62.4	-251.7
Mean arrival delay	192.5	231.8	167.7	114.7	-152.6
Mean total travel time deviation	56.2	125.0	70.3	52.4	99.12

Table C12: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp20.nd00.so00.00.dp100.dm10.

Also, as shown in Table C12, the departure and arrival delay (and travel time deviation) are significantly improved for pa04 and pa05 (across this scenario and in comparison with the previous one (dm00)).

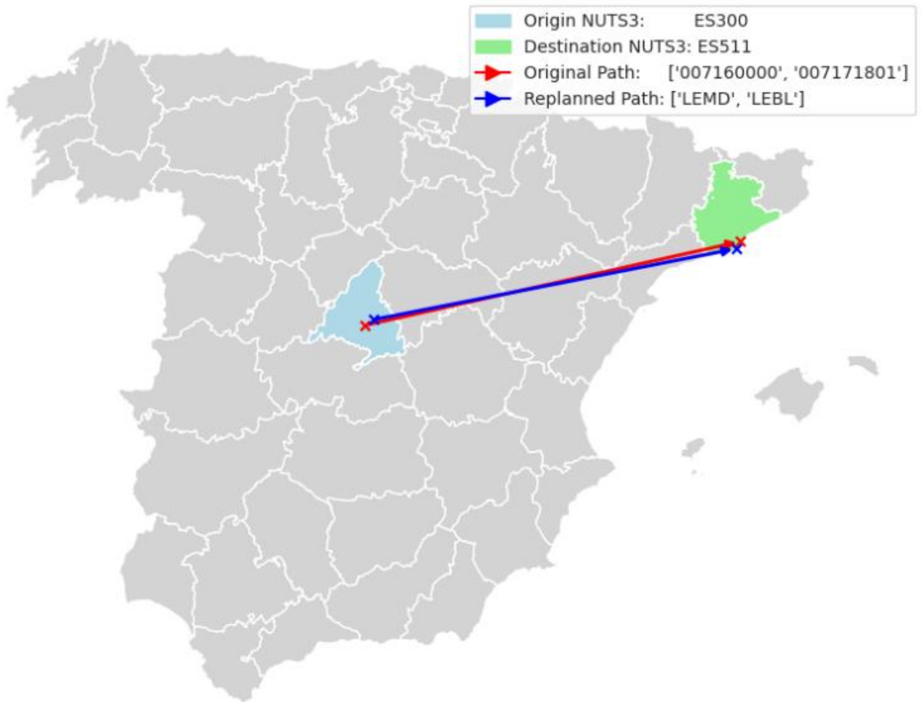

Figure C19: Example replacement of passengers in an itinerary in cs10.pp20.nd00.so00.00.dp100.dm10.pa04.

Figure C19 shows an example when passengers are shifted from rail (Madrid Atocha (007160000) to Barcelona Sants (007171801)) to equivalent air alternatives (Madrid (LEMD) to Barcelona (LEBL)) in pa04.

C3.2.1.1.2 DP210 – Malaga airport (LEMG) closure

In this scenario, instead of a disruption in the rail network, a closure of Malaga airport (LEMG) is considered.

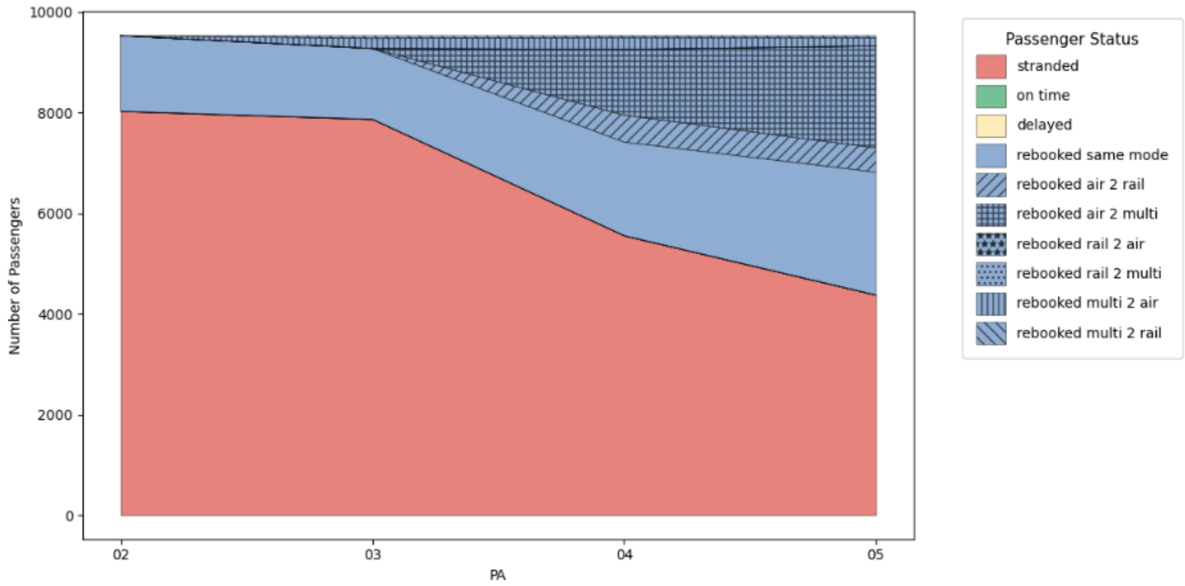

Figure C20: Passengers impacted for cs10.pp00.dn00.so00.00.dp210.dm10

pp00.dp210.dm00	pa01	pa02	pa03	pa04	pa05
Unaffected [pax (% total pax)]	379,666 (97.6%)	379,666 (97.6%)	379,666 (97.6%)	379,666 (97.6%)	379,666 (97.6%)
Stranded [pax (% total / % affected pax)]	9,525 (2.4% / 100.0%)	8,026 (2.1% / 84.3%)	7,868 (2.0% / 82.6%)	5,555 (1.4% / 58.3%)	4,376 (1.1% / 45.9%)
Delayed [pax (% total / % affected pax)]	0	0	0	0	0

On-time [pax (% total / % affected pax)]	0	0	0	0	0

Table C13: Passengers affected by dp210.dm00 in cs10.pp00.nd00.so00.00.

Figure C20 shows the status of the disrupted passengers. As described in Table C13, with pa01, 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 alternative paths are possible, 15.7% of disrupted passengers are already 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 C21: Example of itinerary replanned in cs10.pp00.nd00.so00.00.dp210.dm00.pa02.

Figure C21 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 original NUTS was 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 will be longer than initially planned (connecting itinerary instead of direct flight), but now it is possible, and the passenger is no longer stranded.

Allowing to change operator (pa04) increases the number of reaccommodated passengers significantly to 41.7%. Finally, the enabling of departing before originally planned (pa05) ensures that 1,179 additional passengers are served (with a total of 54.1% of disrupted passengers reaccommodated).

pp00.dp210.dm00	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 C14: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp00.nd00.so00.00.dp210.dm00.

Figure C22: Example itinerary replanned in cs10.pp00.nd00.so00.00.dp210.dm00.pa05 change mode.

As shown in Table C14, the possibility to change mode represents a larger increment in the total travel time of disrupted passengers, as slower and with more connection alternatives could be used, as shown in Figure C22 where the flow with maximum reaccommodated passengers is shown for the pa05 case. The original itinerary was just a flight from Malaga (LEMG) to Madrid (LEMD), which becomes a train journey from Malaga Maria Zambrano (007154413) to Madrid Atocha (007160000) connecting in Córdoba Central (007150500).

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Figure C23: Example itinerary replanned in cs10.pp00.nd00.so00.00.dp210.dm00.pa05 change infrastructure nodes

Figure C23 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 to get a flight from Alicante (LEAL) to Madrid (LEMD) and connect to Asturias (LEAS). The passenger has a different access as instead of getting to Malaga airport needs to travel to Alicante and connect in Madrid. This might mean an earlier departure than originally planned, as allowed by pa05. The example is illustrative of the effect of airport access/egress connectivity.

C3.2.1.1.3 DP300 – ATFM industrial action in Madrid Barajas (LEMD)

This scenario is illustrative of the replanning of a network not only for the closure of infrastructure links and nodes but for a significant (expected) reduction in capacity. This would 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.

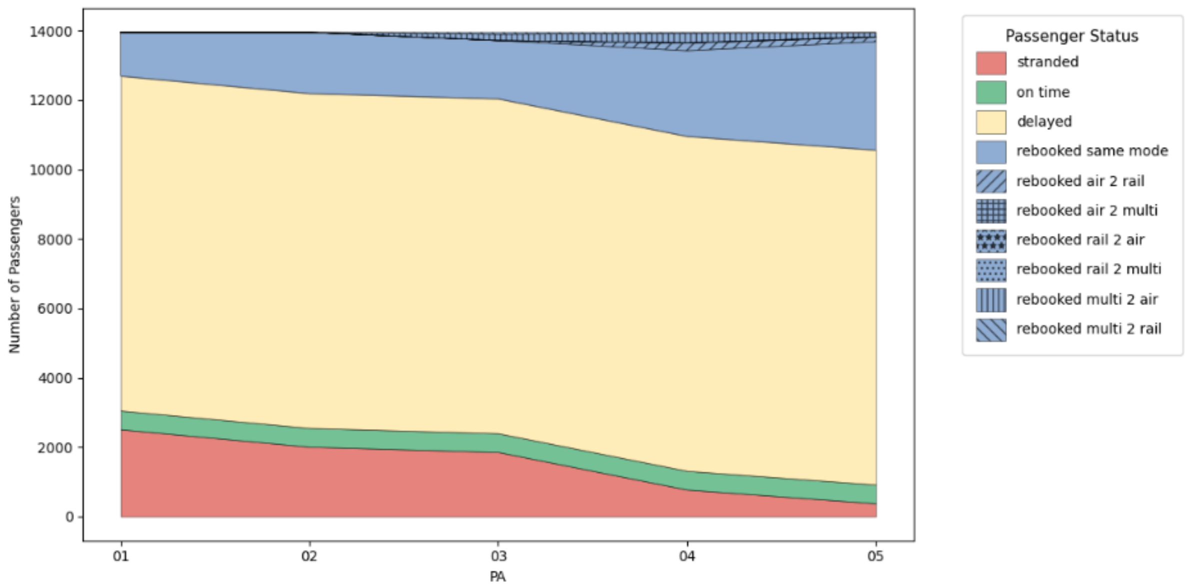


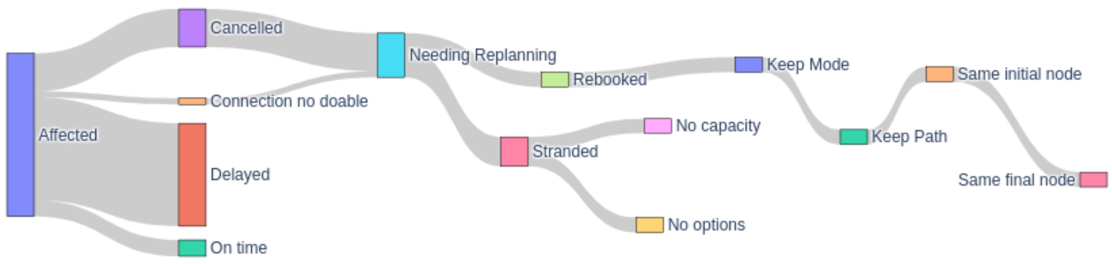
Figure C24: Passengers impacted for cs10.pp00.nd00.so00.00.dp300.dm00

pp00.dp300.dm00	pa01	pa02	pa03	pa04	pa05
Unaffected [pax (% total pax)]	375,238 (96.4%)	363,835 (93.5%)	363,835 (93.5%)	363,835 (93.5%)	363,835 (93.5%)
Stranded [pax (% total / % affected pax)]	2,510 (0.6% / 18.0%)	2,008 (0.5% / 14.4%)	1,855 (0.5% / 13.3%)	772 (0.2% / 5.5%)	376 (0.1% / 2.7%)
Delayed [pax (% total / % affected pax)]	9,644 (2.5% / 69.1%)	9,644 (2.5% / 69.1%)	9,644 (2.5% / 69.1%)	9,644 (2.5% / 69.1%)	9,644 (2.5% / 69.1%)
On-time [pax (% total / % affected pax)]	541 (0.1% / 3.9%)	541 (0.1% / 3.9%)	541 (0.1% / 3.9%)	541 (0.1% / 3.9%)	541 (0.1% / 3.9%)
Replanned [pax (% total / % affected pax)]	1,258 (0.3% / 9.0%)	1,760 (0.5% / 12.6%)	1,679 (0.5% / 13.7%)	2,996 (0.8% / 21.5%)	3,392 (0.9% / 24.3%)

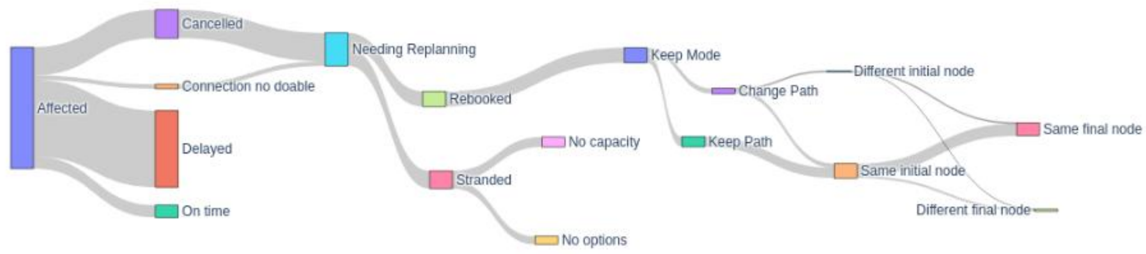
Table C15: Passengers affected by dp300.dm00 in cs10.pp00.nd00.so00.00

A total of 13,953 passengers are affected by the replanning of operations due to the ATFM regulation. As shown in Table C15 and Figure C24, most of them are due to delays on their flights (9,644 69.1% of affected passengers). These are passengers who arrive at their final destination with some delay with respect to the planning. 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. This could be connecting passengers whose inbound flight is delayed but still made the connection (either to another on-time flight or rail service).

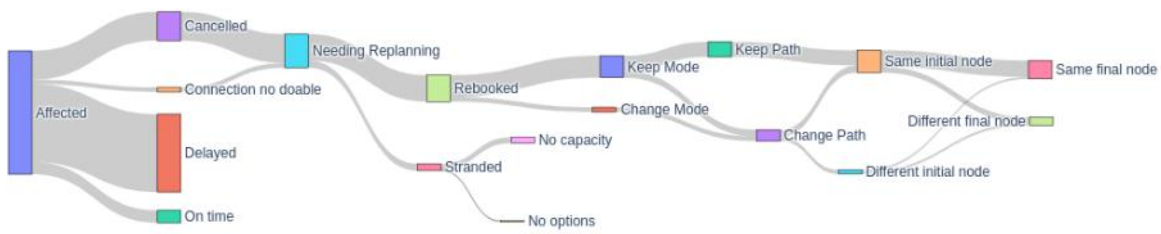
In pa01, when the same operator, mode and path must be maintained, a total of 1,258 (9.0% of affected passengers) can be rebooked on alternative flights. Enabling the use of alternative paths (pa02) has a small improvement (12.6% of passengers are reassigned), enabling the mode swap but maintaining the modes only improves original multimodal passengers who might be replanned as just rail in pa03. When changes between modes are allowed to all passengers (pa04) 21.5% of affected passengers are replanned and only 5.5% of passengers are stranded. See, however in Figure C15 how the number of passengers rebooked across modes is still very limited. Finally, if enough anticipation is available and passengers can be reaccommodated into earlier than originally planned services, only 376 passengers end up stranded (2.7% of the originally planned ones). As depicted in Figure C25, most of these are achieved by ensuring that air connections are still possible by selecting earlier flights. It is worth reminding that the cancellation rate used for the flights departing-arriving to Madrid is 7.5% in this disruption (see Section C.1.3.1.2.3).



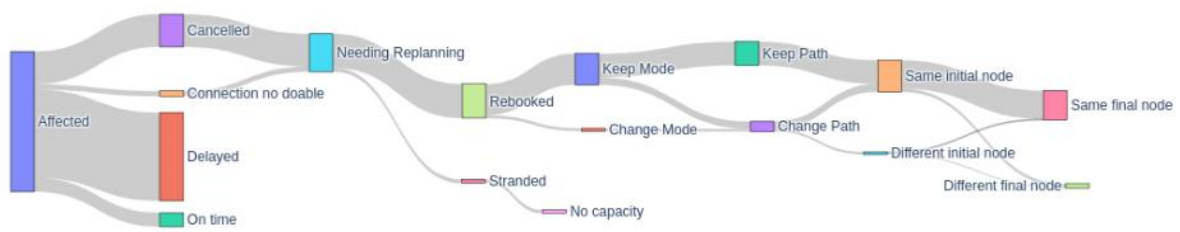
a) pa01



b) pa03



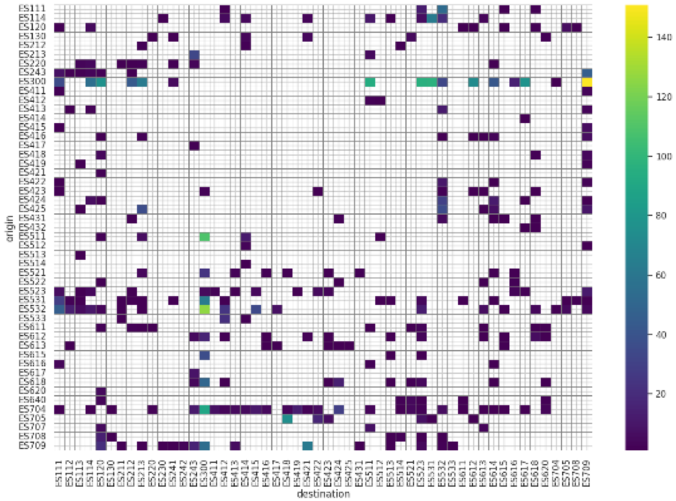
c) pa04



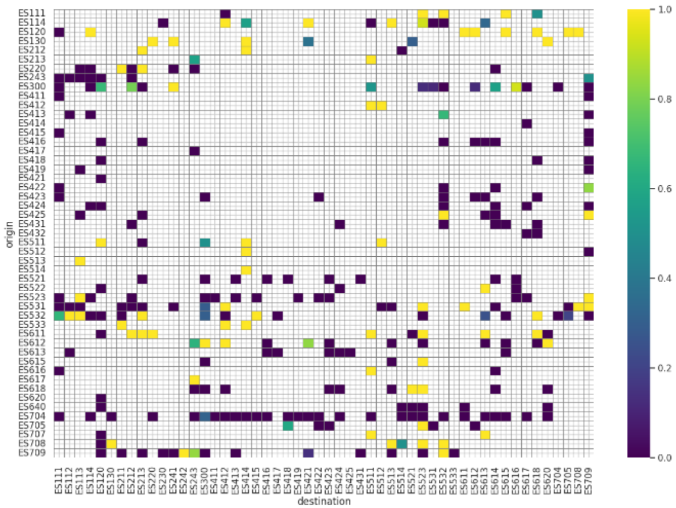
d) pa05

Figure C25: Distribution of itineraries status for pp00.dp300.dm00

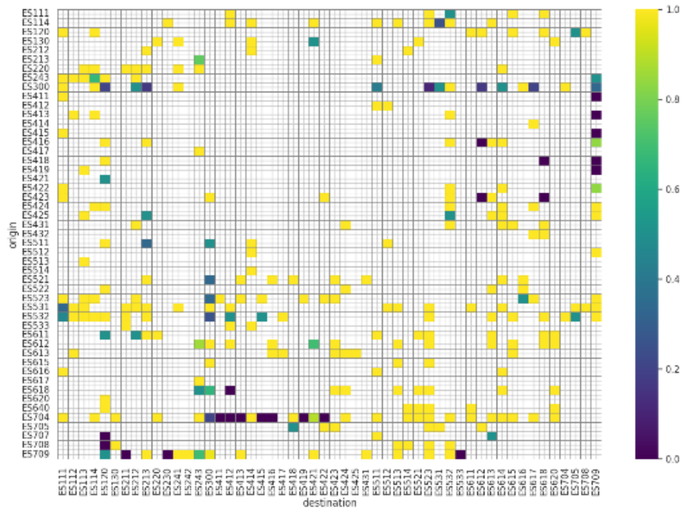
Figure C25 represents for pa01, pa03 and pa05 the status of the different itineraries affected by the disruption in this scenario. Once again, as the flexibility to reaccommodate passengers increases, the number of stranded passengers gets reduced and in contrast with dp100, where the rail link between Barcelona and Madrid was closed (see Figure C26), 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 overall rebooked (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.



a) Passengers needing replanning



b) Percentage of passengers reassigned for pa01



c) Percentage of passengers reassigned for pa05

Figure C26: Passengers impacted and reassigned per origin-destination NUTS3 for pp00.dp300.dm00

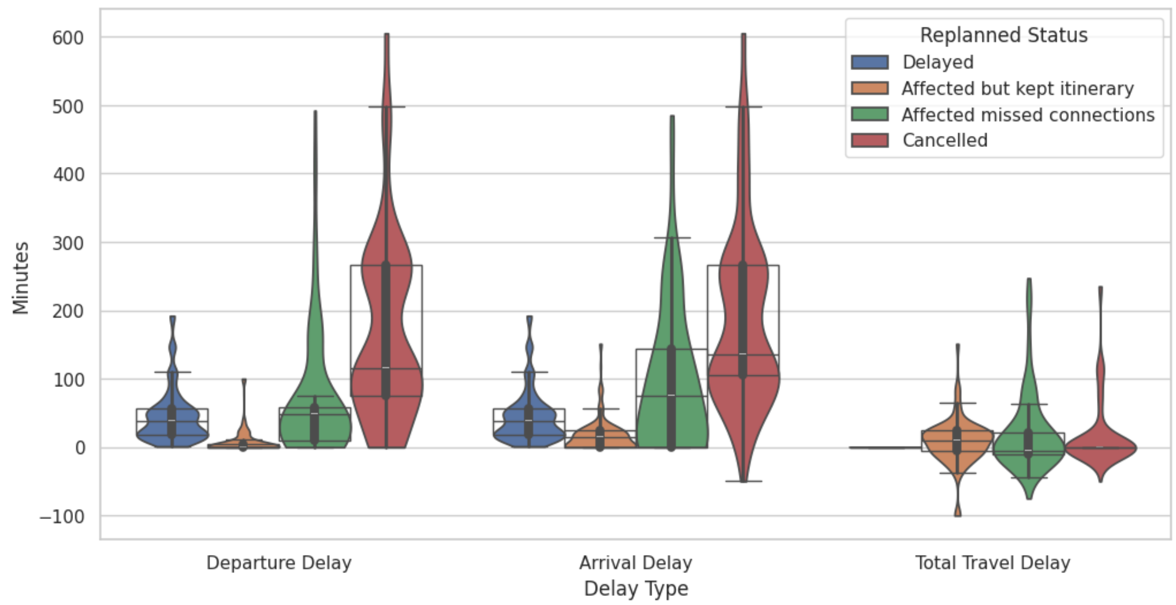
Figure C26 Passengers impacted and reassigned per origin-destinatin NUTS3 for pp00.dp300.dm00

Figure C26 shows how one of the particularities of this type of disruption is that it affects the connectivity of regions in Spain in a more spread manner. This is due to the centrality of Madrid to connect peripheral regions (and islands) between them. This can be observed in the case of the impact on the connectivity of the Canary Islands (ES70x) and Balearic Islands (ES53x) with the rest of Spain, particularly Castille-Leon (ES41x) for the Canary Islands and Galicia (ES11x) for the Balearic Islands.

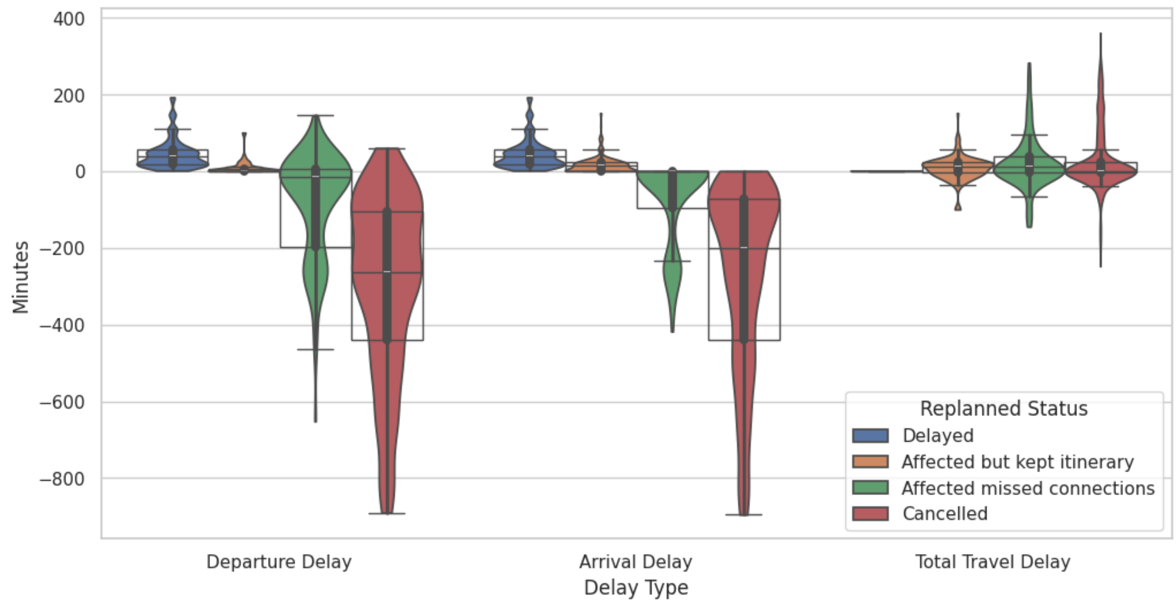
pp00.dp300.dm00		**pa01**	**pa02**	**pa03**	**pa04**	**pa05**
Mean departure delay	cancelled	172.0	122.5	116.7	78.2	-298.1
	delayed	45.5	45.5	45.5	45.5	45.5
	replanned doable	8.7	8.7	8.7	8.7	8.7
	replanned not doable	68.5	79.4	72.7	51.4	-91.7
Mean arrival delay	cancelled	190.9	144.7	125.0	71.2	-271.7
	delayed	45.5	45.5	45.5	45.5	45.5
	replanned doable	17.9	17.9	17.9	17.9	17.9
	replanned not doable	88.7	109.2	91.1	33.6	-69.6
Mean total travel time deviation	cancelled	18.9	22.1	8.2	-7.0	26.4
	delayed	0	0	0	0	0
	replanned doable	9.2	9.2	9.2	9.2	9.2
	replanned not doable	20.3	29.7	18.4	-17.8	22.1

Table C16: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp00.nd00.so00.00.dp300.dm00

Table C16 presents the departure and arrival delay and time travel deviation with respect to the originally planned for the different types of passengers for the 5 passenger assignment alternatives. As it can be seen, passengers whose service has been cancelled are the ones with higher delays, while if they have been affected but their connection is still valid the delays are the lowest observed.



a) pa01



b) pa05

Figure C27: Distribution of the departure and arrival delays, and travel time deviation for cs10.pp00.nd00.so00.00.dp300.dm00 for pa01 and pa05

Figure C27 contrasts the delays per type of impact on passengers for pa01 and pa05. As previously discussed, 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 with SOL399/SOL1.

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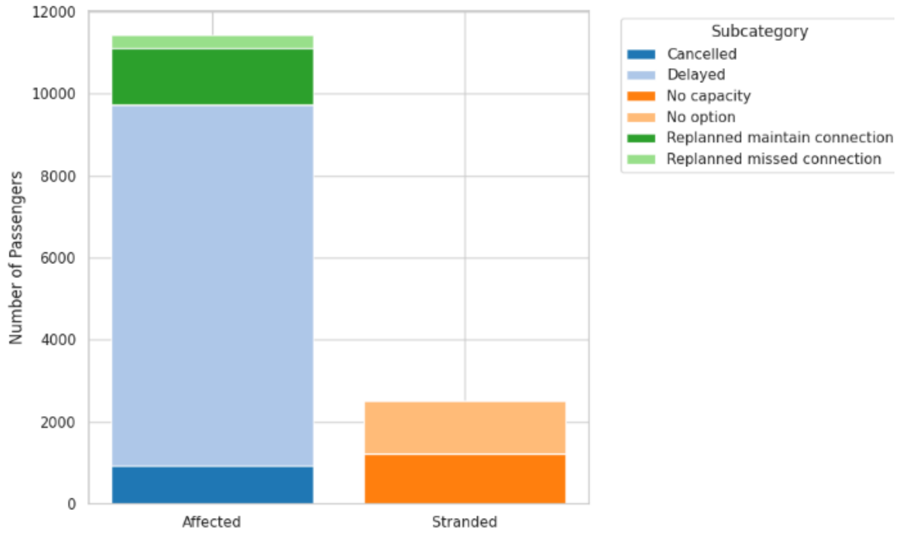
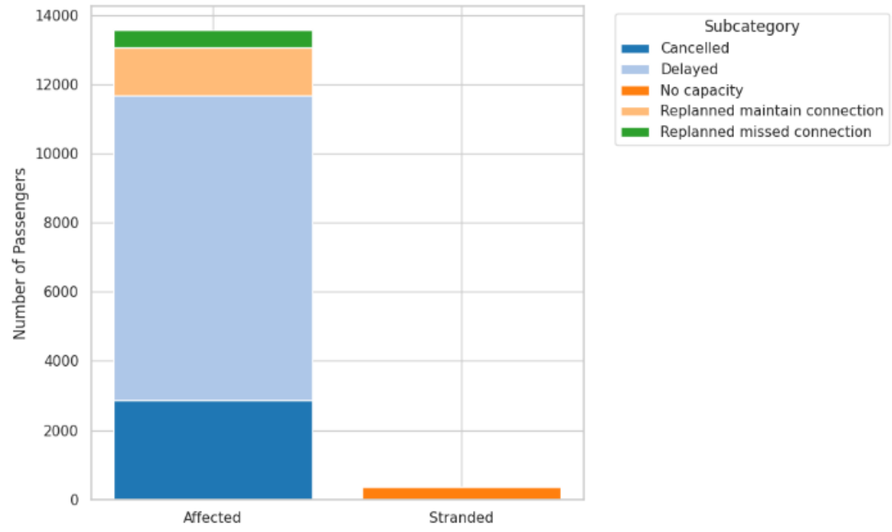


a) pa01



b) pa05

Figure C28: Passengers affected by the disruption and their status for pp00.dp300.dm00

Finally, Figure C28 presents for pa01 and pa05 the number of passengers affected that can make their journey (their original service was cancelled and got rebooked, their original service got delayed, they are affected on one of their legs but still can keep doing the connection, or they were replanned because they missed their connection), 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 amount 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 stranded passengers are just because there is no capacity for them, but all affected passengers have potentially an alternative option.

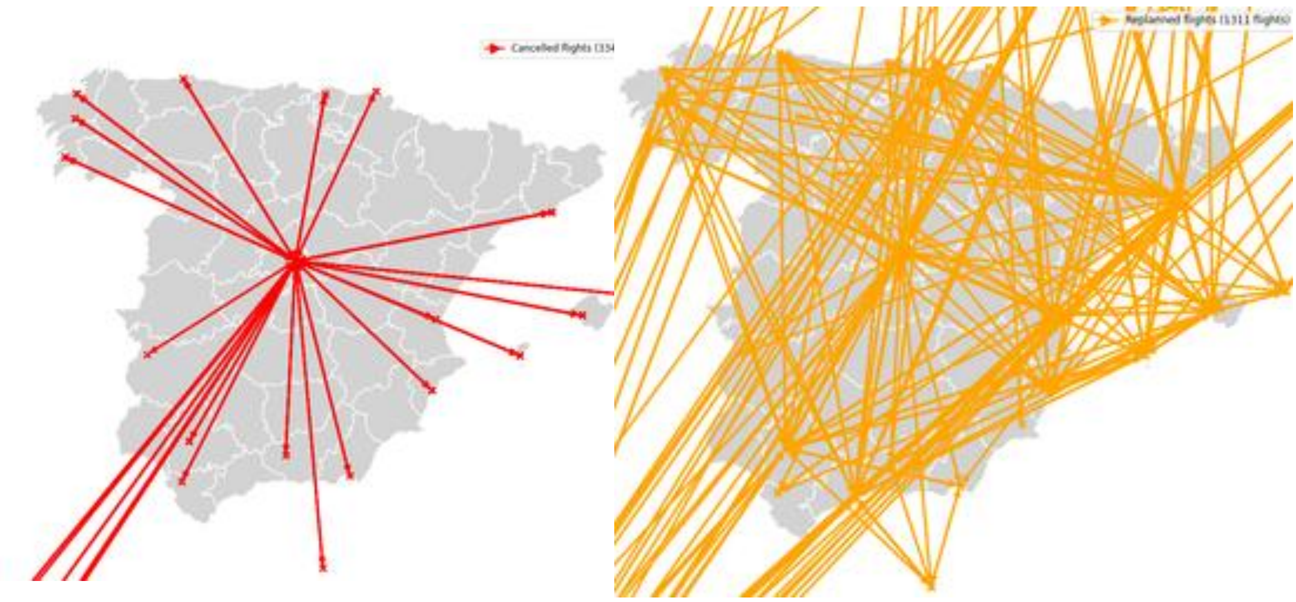
C3.2.1.1.4 DP310 – Reduced capacity at Madrid Barajas (as in ERR SOL401/SOL3)

In this final scenario, SOL399/SOL1 is used to evaluate the outcome of SOL401/SOL3. The results presented here are not to evaluate the benefits of SOL401/SOL3 (for that the reader is referred to SOL401/SOL3's ERR [26]). Instead, this final scenario is just to show that SOL399/SOL1 can use any replanned network to assess the impact on passengers' itineraries (including the replanned network from SOL401/SOL3.

Note that some of the characteristics on the network used by SOL401/SOL3 for their validation are distinct from the ones used for SOL399/SOL1 and SOL400/SOL2. This means that the assessment from SOL399/SOL1 will focus on intra-Spain mobility (CS10), as previously mentioned, while the network from SOL401/SOL3 is slightly different. Once again, this might present some limitations in evaluating the merits of SOL401/SOL3, but it will, in any case, show the capabilities of SOL399/SOL1 to evaluate the outcome of SOL401/SOL3.

In the previous cases, the replanned network is the result of applying the disruption (i.e., cancelling services going through closed links and nodes, cancelling some flights impacted by ATFM regulation and delaying flights according to these ATMF regulations). cs10.pp20.nd00.so00.00.dp100.dm10 presented before showed how, besides modifying supply to account for the disruption, one can adjust the network to mitigate the impact of the disruptions (e.g. reintroducing new flights). If the disruption is very complex, a more complex replanning of the network, which considers what would happen if no services are adjusted, might be needed. This is provided by SOL401/SOL3.

Therefore, SOL401/SOL3 will consider a significant reduction of capacity at LEMD (10 flights/hour) and adjust the network considering what would happen if no optimisation is performed. This first network is the baseline disrupted scenario (dm20). Then, the optimisation will be performed by SOL401/SOL3 in a centralised (dm21) approach. This centralised approach enables the replanning of passengers to any service with capacity available (as with the pa04 limitations). For those reasons cs10.pp0.nd00.so00.00.dp310.dm20.pa04 and cs10.pp0.nd00.so00.00.dp310.dm21.pa04 will be run and compared.

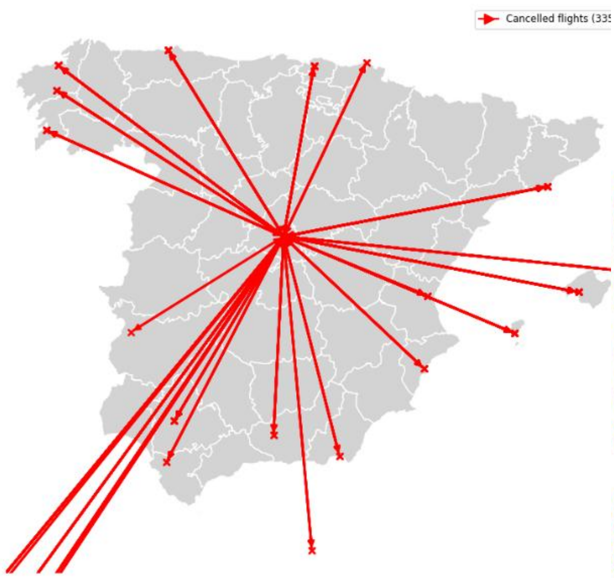


a) Flights cancelled b) Flight replanned/delayed

c) Rail replanned

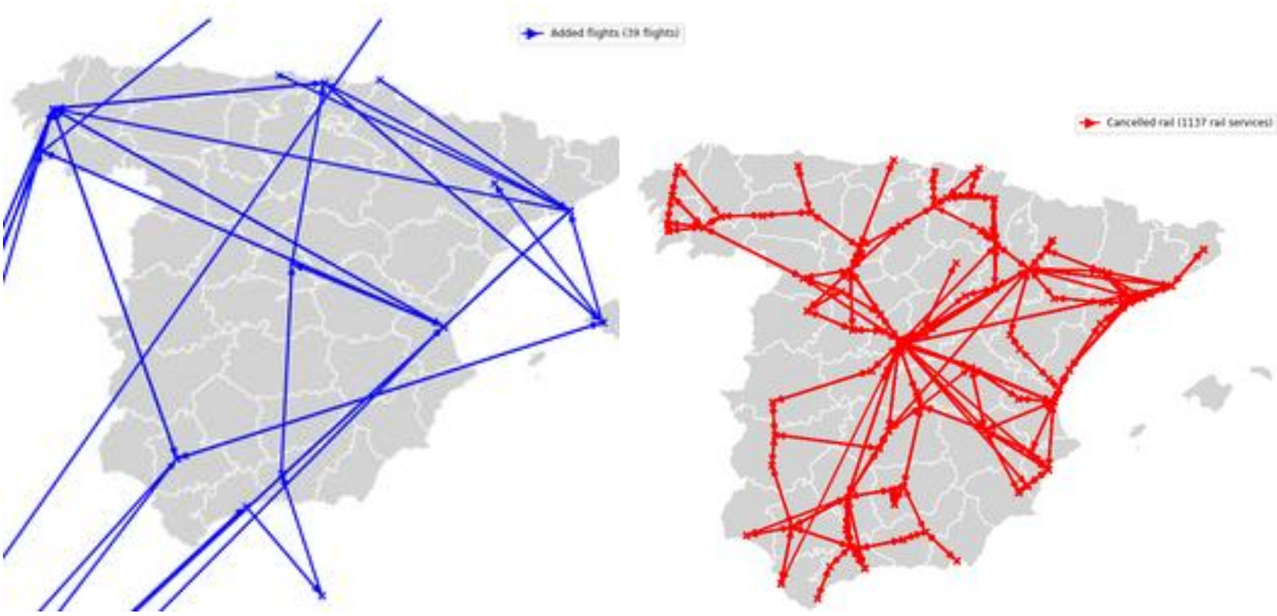
Figure C29: Modifications to network due to dp310 and dm20

Figure C29 shows the effects of the disruption on the network for the dm20 (baseline case). As observed, a total of 334 flights are cancelled, and 1,311 are replanned (delayed). Figure C30 shows how for rail, most of the services are 'cancelled'. This is due to the fact that the current version of SOL401/SOL3 produces replanned rail services which do not respect the stop passage numbering as in the planned network. This is not an issue, but for simplicity, these replanned operations in rail are treated by SOL399/SOL1 as cancellations of the original service and the addition of a new one. Therefore in this instance, the figure shows the rail replanned. As observed SOL401/SOL3 replans most of the rail services.



a) Flights cancelled

b) Flights replanned/delayed



c) Flights added d) Rail replanned

Figure C30: Modifications to network due to dp310 and dm21

As shown in Figure C30, when the Disruption Management Solution is applied, the impact on services is different. First, one additional flight is cancelled (355 in total), 1,308 flights have their schedules adjusted, but an additional 39 flights are operated. A similar number of rail services are replanned as in the baseline case.

pp00.dp310.dmxx.pa04	dm20	dm21
Unaffected [pax (% total pax)]	293 (0.2%)	786 (0.2%)
Stranded [pax (% total / % affected pax)]	47,689 (12.3% / 12.3%)	45,768 (11.6% / 11.8%)
Delayed [pax (% total / % affected pax)]	68,607 (17.6% / 17.6%)	68,881 (17.7% / 17.7%)
On-time [pax (% total / % affected pax)]	1,428 (0.4% / 0.4%)	1,450 (0.4% / 0.4%)

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Replanned [pax (% total / % affected pax)]	271,174 (69.7% / 69.7%)	272,306 (70.0% / 70.1%)

Table C17: Passengers affected by dp100.dm00 in cs10.pp00.nd00.so00.00

Table C17 presents the number of passengers impacted by the replanning of the networks. The first thing that could be surprising is the significant amount of passengers impacted (99.8%). This is the case as shown in Figure C31, most of the services (both air and rail) are cancelled or replanned (delayed). SOL401/SOL3 is modifying most of the schedules. However, the number of replanned passengers (either in their original or new services) is also very high approximately 70% of all passengers. For the remaining, slightly short to 18% are delayed, and 12.3% and 11.6% of the passengers end up stranded in the baseline (dm20) and optimised (dm21) cases, respectively. As shown, the optimised centralised case (dm21) reduces the number of stranded passengers.

pp00.dp310.dmxx.pa04		**dm20**	**dm21**
Mean departure delay	cancelled	6.5	5.0
	delayed	4.4	0.9
	replanned doable	0.1	0.2
	replanned not doable	N/A	72
Mean arrival delay	cancelled	-1.6	-4.8
	delayed	2.7	-0.7
	replanned doable	-1.5	0.0
	replanned not doable	N/A	-202
Mean total travel time deviation	cancelled	-8.0	-9.7
	delayed	-1.7	-1.6
	replanned doable	-1.6	-0.15
	replanned not doable	N/A	-274

Table C18: Mean departure, arrival delay and travel time deviation of replanned journeys in cs10.pp00.nd00.so00.00.dp310

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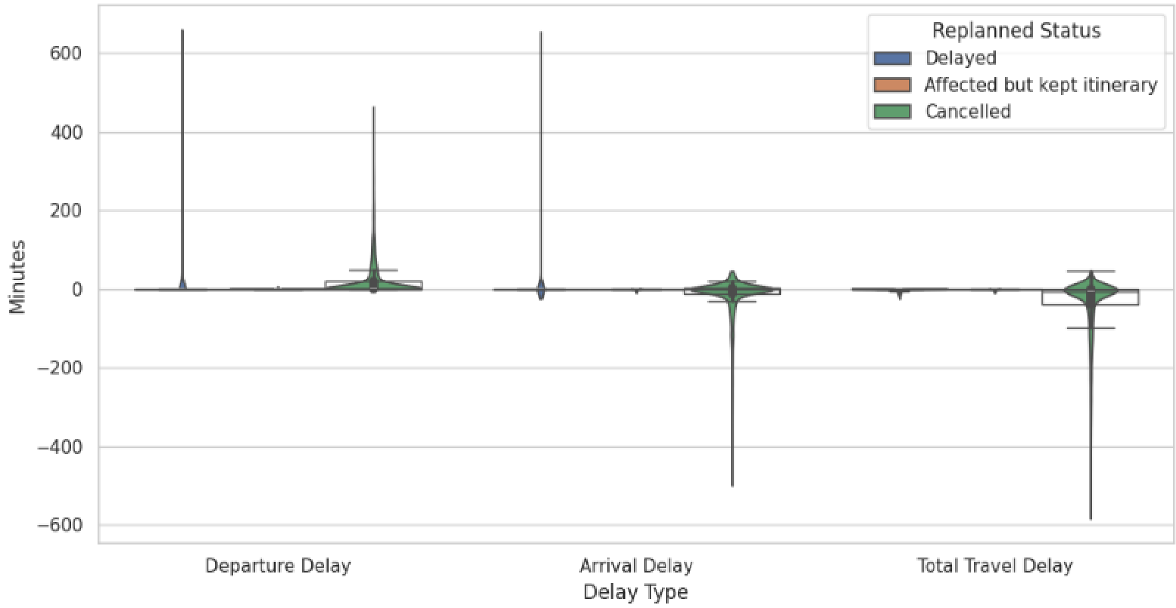
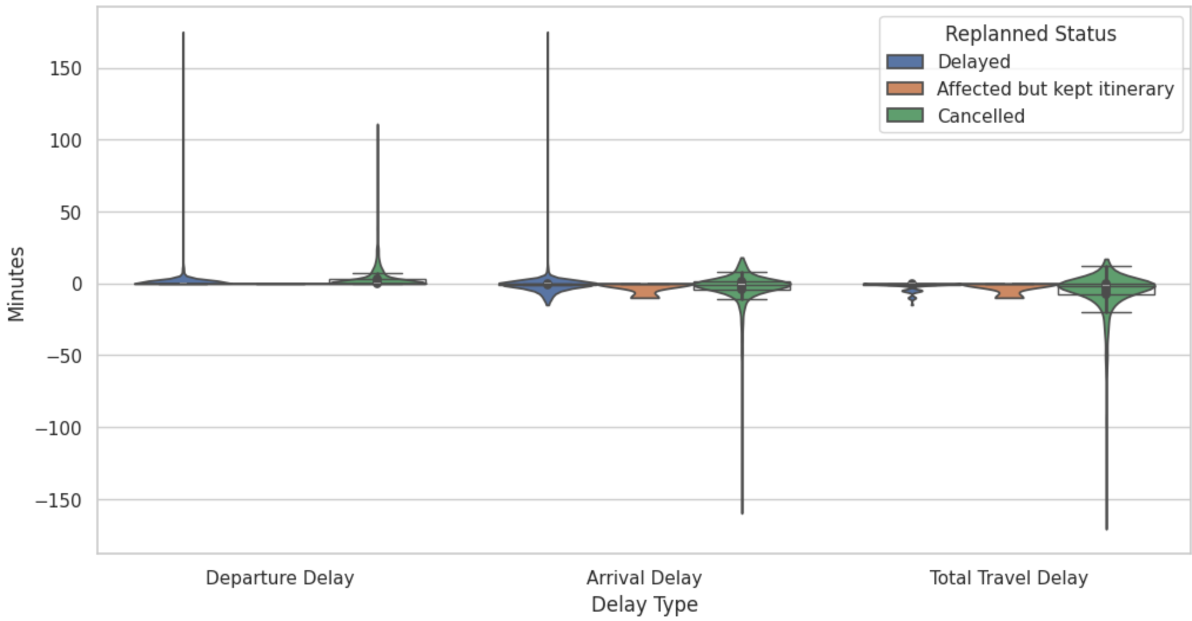


a) dm20



b) dm21

Figure C31: Distribution of the departure and arrival delays, and travel time deviation for cs10.pp00.nd00.so00.00.dp310 for pa04 and dm20 and dm21.

Figure C31 presents the distribution of delays for departure, arrival and total travel time for the baseline (dm20) and optimised (dm21) cases. The optimised case seems to obtain lower arrival delays and travel time deviations.

As presented, the significant amount of affected passengers due to the replanning of the rail services, which are treated as cancellations and the addition of new services produce a high amount of rebookings with very small delays. This section has shown how SOL399/SOL1 is able to evaluate a network optimised by SOL401/SOL3, contributing to the achievement of EXE03-CRT-0399-ERP-050.18 and, therefore, the validation objective EXE03-OBJ-0399-TRL2-ERP-050.

Further work should improve the compatibility of assumptions between the network considered by SOL401/SOL3 in its optimisation and the underlying network evaluated in SOL399/SOL1.

Conclusions on Experiment 1

The activities conducted in the experiment satisfy the criteria EXE02-CRT-0399-ERP-050.1. It has been shown how SOL399/SOL1 can evaluate scenarios with different type of disruptions: rail links and airport closures, ATFM regulations, such as industrial actions, and reduced capacity. Different replanning of passengers alternatives have been considered by SOL399/SOL1. The replanning of operations by SOL401/SOL3 have been assessed by SOL399/SOL1. The different scenarios have been compared by calculating passenger-centric mobility PIs.

C3.2.1.2 Experiment 2

As discussed, the tactical evaluation of (re)planned network has been extensively presented in Section B.3.2.1.3. Moreover, the tactical evaluation of a network, including the introduction of a mechanism to manage multimodality, is presented in C.3.2.1 (Experiment 3). Not executing tactically the replanned networks can be seen as a limitation to evaluate the robustness of the replanned network, however, this would be more related with the benefits of SOL401/SOL3 rather than to show the capabilities of SOL399/SOL1. For all these reasons, this no execution of tactical network is not considered a limitation for the validation of SOL399/SOL1.

C.3.2.2 OBJ-0399-TRL2-ERP-060 Results

Objective: A mechanism to tactically support multimodality, fast-track processing for multimodal passengers at airports, is evaluated by the Tactical Evaluator.

Validation:

C3.2.2.1 Experiment 3

In this experiment, a fast-track to process passengers at the airport pre-departure is used as a tactical disruption management mechanism.

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 *Passenger Handler* requests the *Airport Terminal* the time required to perform the kerb-to-gate. In the nominal situation, i.e. without the fast-track mechanism, the *Airport Terminal* will return the value independently of the passenger's situation. When the fast-track mechanism is in place, the *Passenger Handler* includes information about the passenger's status in the request message, i.e. if the passenger is delayed or not. The *Airport Terminal* then provides either the nominal kerb-to-gate time or a faster time (according to the coefficient). This speed-up coefficient value is consistent with the results presented in [7].

For this experiment, scenario cs10.pp20.nd02.so10.01 with 30 minute ground mobility delay has been run. Fig. C32 shows the number of missed connections for a 30-minute disruption with a varying fast-track 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-

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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, 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 who 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 [8] and [21]. As can be seen from the results, the mechanism can reduce the number of missed connections and thus improve the robustness of itineraries which was compromised after applying SOL400/SOL2.

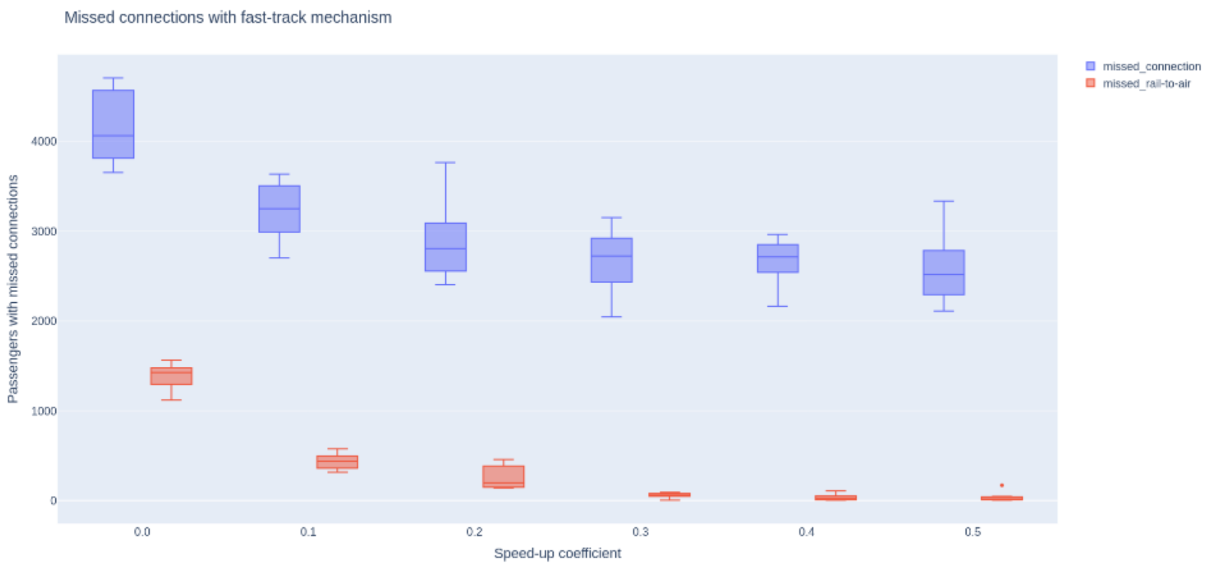

Figure C32: Passengers with missed connections with fast-track mechanism

Conclusions on Experiment 3

The activities conducted in the experiment satisfy the criteria EXE02-CRT-0399-ERP-060.1 as a fast-track to process passengers at the airport pre-departure has been used as a tactical disruption management mechanism for scenario cs10.pp20.nd02.so10.01 with 30 minute ground mobility delay. The scenario with and without the mechanism have been compared in terms of passengers with missed connections to assess the benefit of the mechanism.

C.3.3 Unexpected behaviours/results

No major unexpected results were encountered. The largest consideration was the need to reconsider the replanned rail services from SOL401/SOL3 as cancellation and addition of new services. This was to avoid the re-usage of the rail service identification but with different stop sequences, as that would have led to erroneous results. The approach followed avoided this, but meant that a large number of passengers needed to be reaccommodated when their original service was still running but just delayed. Future work should be done to avoid having to do this by, for example, renaming the passenger itineraries in the new replanned rail operations instead.

C.3.4 Confidence in results of validation exercise #03

C.3.4.1 Level of significance/limitations of validation exercise results

Results presented use cs10 (intra-Spain mobility), which presents the same limitations as the ones highlighted in B.3.4.1.; these, however, do not hinder the validation of the capabilities of SOL399/SOL1 to assess the impact of replanned operations on the passenger itineraries.

Besides the validation of SOL399/SOL1 to assess replanned networks produced by SOL401/SOL3, some further work could be done to ensure the full compatibility of the assumptions modelled within SOL401/SOL3. That would allow a deeper analysis of the benefits of SOL401/SOL3. In its current form, we have been able to validate SOL399/SOL1 to assess the outcome of SOL401/SOL3, but the benefits of the solution are left to the ERR of SOL401/SOL3, see [26].

The re-evaluation of the replanned network by the Tactical Multimodal Evaluator would allow us to assess the robustness of the replanning and could provide a better insight into the benefits of the replanning with respect to the baseline of doing nothing. This, however, could be partially limited due to the non-modelling of rail-rail disruptions within the Tactical Multimodal Evaluator, which focuses on the air-air and multimodal connections and relies on already modified rail inputs.

Finally, an overall improved baseline of the operations disrupted if no disruption management is used could be considered as in the current version it is assumed that the impact of the disruption in terms of replanning of the network is available (or provided by SOL401/SOL3).

C.3.4.2 Quality of validation exercises results

We consider that there are no issues regarding the quality and accuracy of the results.

The quality of the replanning relies on the planned network; therefore, some of the limitations observed in B.3.4.2 could also apply here. For example, some of the model input parameters when building the planned network could be reviewed. The results found in this exercise show the importance of the access/egress areas of airports when considering alternative routes. This could be reviewed in the future, and the model could penalise changes of departing and arrival nodes if they require significant ground access/egress change (in distance and/or time) with respect to the originally planned itinerary, even if feasible.

With the maximum flexibility to reaccommodate passengers evaluated, passengers depart from their origin much earlier than initially planned to reach their destination. A parametric analysis by limiting this maximum earlier departure time could provide interesting insight into the required look-ahead notification to passengers to reroute their itineraries. This is not a limitation on the quality of the results but a highlight of possible future analysis that could be done with the current model.

These aspects are not significant to, once again, show how SOL399/SOL1 is able to assess a replanned network under different levels of flexibility to reaccommodate impacted passengers.

As previously mentioned, when evaluating the recurrent output of SOL401/SOL3, the replanning of rail operations can lead to a significantly high number of accommodated passengers who might be delayed instead. This, however, should not impact in a significant way the results in terms of passenger-centric metrics (delays, number of stranded passengers, etc.).

C.3.4.3 Significance of validation exercises results

Operational significance has already been discussed in section C.3.4.1. (Level of significance/limitations of validation exercise results).

C.4 Conclusions

C.4.1 Conclusions on concept clarification

With this validation exercise, SOL399/SOL1 has proven to fulfil the research objectives proposed in the ERP (EXE03-OBJ-0399-TRL2-ERP-050 and EXE03-OBJ-0399-TRL2-ERP-060).

This exercise validated the Strategic Multimodal Evaluator when assessing a replanned multimodal mobility network subject to different types of disruptions and flexibility to reaccommodate passengers and management actions (such as the replanning of operations by SOL401/SOL3). Moreover, it has shown how the Tactical Multimodal Evaluator is able to assess mechanisms to support multimodality, evaluating their benefits when applied on a given (re)planned network.

The experiments showed that the proposed framework is capable of a performance assessment of replanned networks and mechanisms to support multimodality.

C.4.2 Conclusions on technical feasibility

SOL399/SOL1 fulfils all the functional requirements outlined in the FRD for the assessment of replanned networks.

C.4.3 Conclusions on performance assessments

As discussed in the ECO-EVAL, the Performance Assessment Solution (SOL399/SOL1) is able to assess replanned networks from a passenger-centric perspective and, in particular, replanned networks considering disruptions and optimised by disruption management Solutions (such as SOL401/SOL3). This has been demonstrated through the use of the Strategic Multimodal Evaluator capabilities to assess a range of disruptions under different replanning of passengers assumptions, and considering also the replanned network by SOL401/SOL3.

Moreover, this exercise has validated the capabilities of SOL399/SOL1 to assess the performance of multimodal mechanisms to support these types of connections with the Tactical Multimodal Evaluator.

The exercise shows how SOL399/SOL1 can provide estimations of the indicators defined in the multimodal performance framework in particular those that are passenger-centric and passenger-experience related.

It is worth reminding the reader that results show the importance of disaggregating the indicators on specific cases to fully understand the impact of the replanned operations, particularly looking at

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specific origin-destination 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 sub-operational environments (e.g. islands, hubs) can (or not) support the disrupted passengers.

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 this exercise, these factors have been grouped in representative alternatives (pa01 to pa05), but as previously discussed further potential considerations could be analysed.

C.5 Recommendations

Future work could address shortcomings previously mentioned:

- The replanned rail services from SOL401/SOL3 could be processed so that the affected passengers can be identified as delayed instead of replanned,
- The Tactical Multimodal Evaluator should include rail-rail connections in the simulation.

As described in C.3.4.2., further work could be done to produce improved inputs for the model.