

DES HE SESAR solution 401 exploratory research report

Deliverable ID:	D6.2
Project acronym:	MultiModX
Grant:	101114815
Call:	HORIZON-SESAR-2022-DES-ER-01
Topic:	HORIZON-SESAR-2022-DES-ER-01-WA2-6
Consortium coordinator:	BHL
Edition date:	05 November 2025
Edition:	02.00
Status:	Official
Classification:	PU

Abstract

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, the conclusion of each validation exercise, and the maturity of the Solution, along with some final recommendations.

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Document history

Edition	Date	Status	Organisation author	Justification
01.00	10.06.2025	Submitted	BHL	New document for review by the SJU
02.00	05.11.2025	Submitted	BHL	Revised document incorporating feedback from the Maturity Gate

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MultiModX

INTEGRATED PASSENGER-CENTRIC PLANNING OF MULTIMODAL
NETWORKS

MultiModX

This document is part of a project that has received funding from the SESAR 3 Joint Undertaking under grant agreement No [Click or tap here to enter Grant No.] under European Union's Horizon Europe research and innovation programme.



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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.

2 Introduction

2.1 Purpose of the document

The Exploratory Research Report (ERR) is the document that consolidates the results obtained by the MultiModX project once the validation activities, experiments, etc, regarding SOL0399/SOL1 have been completed. 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.

The Exploratory Research Report (ERR) is the document that consolidates the results obtained by the MultiModX project once the validation activities, experiments, etc, regarding SOL401 have been completed. This document is the final version of the report, which includes all the results of the validation activities.

The purpose of the document is to summarise the validation results, conclusions and recommendations for SOL401. This solution proposes a disruption management approach to design tactical adjusted schedules, along with train rerouting, flight diversions, and service replacements for air and rail to offer more and better options for multimodal passengers under disruptions.

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 policy-making. These may include SESAR JU, SESAR IR Projects, SESAR 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

The disruption management is founded in part on the advanced architecture for optimal and automatic railway traffic management set by the EU FP7 project [ON-TIME](#) and enhanced in successive projects such as [SORTEDMOBILITY](#). Those are complemented by the disruption management algorithms developed by the SESAR project TRANSIT and the advanced disruption management mechanisms developed in previous research projects such as CASSIOPEIA II and Domino. The existing disruption management solutions will be extended into a more comprehensive solution able to deal with multimodal passenger-centred disruption management at a network level, with the purpose of optimally adjusting air and rail services to minimise disruption effects on passengers, while taking into account the resources needed by airlines and railway undertakings and the infrastructure capacity. This will benefit from the insight into the traffic management solutions developed in the ON-TIME and SORTEDMOBILITY projects.

The approaches for optimal passenger-centric railway network traffic management, such as railway network vulnerability models [1], and the integrated passenger-centric multimodal rescheduling algorithms from the ERA-NET [SORTEDMOBILITY](#) [2] project like MASP [3], which currently integrate rail and bus services, will be extended towards integrating airline operations. Furthermore, approaches to

simulate disruption management of the main stakeholders of the ATM environment, explored in the Modus project, will be extended to integrate railway operations.

Apart from the projects cited above, there is very little literature on passenger-centric multimodal disruption management in transport networks with different levels of centralization.

The potential of collaborative decision-making on multimodal disruption management is discussed in ([4]). ([5]) shows the potential of collaborative decision-making and provides recommendations for the multimodal case. Some research covers multimodal real-time disruption management on the local scale, i.e. contingency plans for airport-bound urban transport systems at particular airports ([6], [7]). Other researchers cover multimodal real-time disruption management in national transportation networks by combining air services with flexible ground replacement services, explicitly regarding passengers ([8], [9]). Focusing on operations only, [10] manage national network disruptions in real-time, using existing rail services as replacements. It is noticeable, that the approaches above consider only a limited set of counter measures (i.e. rescheduling, cancellation and vehicle rotation adjustments), but do not incorporate the disruption responsive rescheduling of existing scheduled ground services such as railways. Only [11] introduce a tactical multimodal network approach which adjusts all covered modes in a national network and considers the passenger perspective, using a limited set of countermeasures for each (i.e. rescheduling, cancellation, flight swaps and train short-turning) in a fully centralized manner.

The reviewed literature reveals that recent research does not fully cover the topic of SOL401 as they either focus on disruption management within spatially limited areas (i.e. local or national), unimodal service adjustments, limited sets of disruption measures, have an operational focus or provide only fully centralized approaches for network disruption management. Further, the majority of approaches tackle real-time disruption management problems, whilst only a few cover the tactical perspective, i.e. dealing with disruptions happening shortly in advance within the day of operations, lasting up to several hours only.

The development of SOL401 fills in those gaps by considering multimodal disruption management measures such as schedule, speed and trajectory adjustments in the entire network, which allows for rescheduling, cancelling, rerouting and short-turn services. Optimizing the aforementioned measures in a passenger-centric fashion for international transportation networks whilst considering different levels of centralization, SOL401 will contribute to general research in the field of multimodal passenger-centric network disruption management.

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 and B.

2.5 Glossary of terms

Term	Definition	Source of the definition
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AIR-REPORT	A report from an aircraft in flight prepared in conformity with requirements for position, and operational and/or meteorological reporting.	ICAO Annex 3

Table 1: glossary of terms

2.6 List of acronyms

Term	Definition
ATM	Air traffic management
DES	Digital European Sky
ERP	Exploratory research plan
ERR	Exploratory research report
FRD	Functional requirements document
GA	Grant agreement
GDPR	General data protection regulation
HE	Horizon Europe
ID	Identifier
KPA	Key performance area
KPI	Key performance indicator
OSD	Operational service and environment description
SESAR	Single European sky ATM research
SESAR 3 JU	SESAR 3 Joint Undertaking
TRL	Technology readiness level

Table 2: list of acronyms

3 Context of the exploratory research report

3.1 MultiModX / SESAR solution 401: a summary

The Disruption Management Solution (SOL401) adjusts coordinated multimodal schedules for air and rail with passenger focus for a given set of disruptions. Taking into account the infrastructure, the service features and the passenger properties, an optimization model is applied to identify the optimal disruption management measures and correspondingly adjust original input timetables (s. Figure 1). The model is based on a multimodal network with three layers: infrastructure, services and passengers (s. Figure 2). Based on disruptions of the infrastructure, services are adjusted (i.e. rerouted, canceled, short-turned and retimed), replacement services are defined, and passengers are rerouted in the multimodal network or completely cancelled (i. e. cut-off). A disruption occurs a few hours in advance, typically within the day of operations or during the planning of the operations on D-1. The objective function contains different parameters and can be modified to obtain different results.

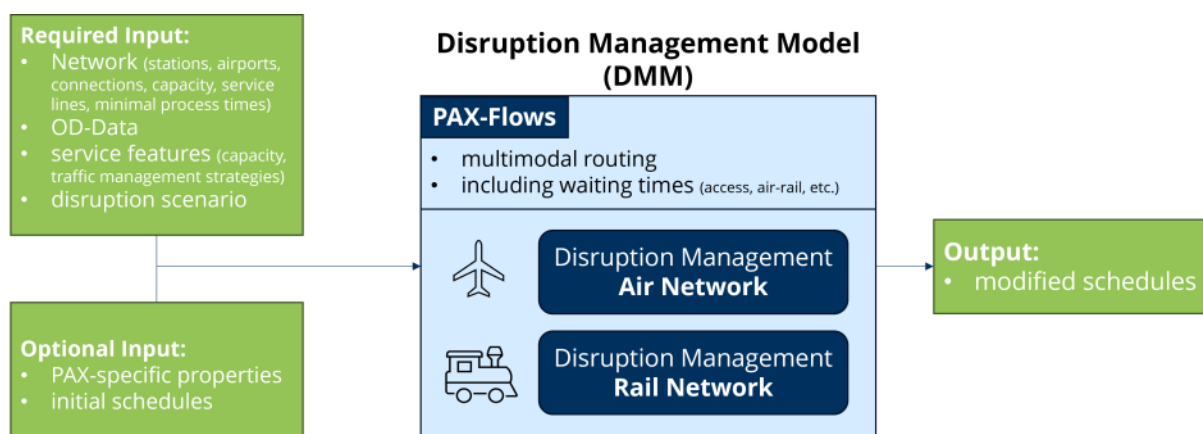


Figure 1: Overview of the DMM structure

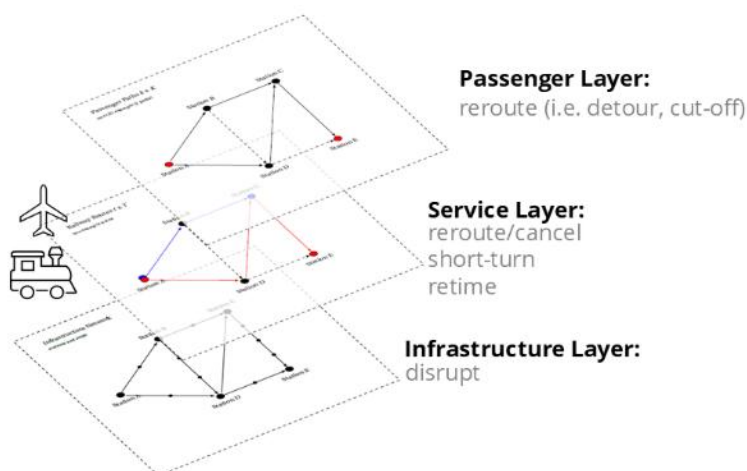


Figure 2: Network layers of the DMM

3.2 Summary of the exploratory research plan

3.2.1 Exploratory research plan purpose

The overall aim of the ERP is to **determine the research questions, objectives, and validation process of the Disruption Management Solution (SOL401)**, to design **tactical adjusted** schedules, along with train rerouting, flight diversions, and rail service replacements for air and rail to offer more and better options for multimodal passengers under disruptions. This SESAR Solution is expected to reach TRL-2.

SOL401 will be validated by means of two validation exercises:

- Validation exercise 1 will focus on executing SOL401 in different operational settings defined based on the sub-operational environments and their characteristics as defined in the associated OSED [\[12\]](#).
- Validation exercise 2 will focus on validating the relevance of the approach of SOL401 by collecting feedback from relevant stakeholders and the Industry Board (IB) members.

As defined in the OSED [\[12\]](#) the following characteristics should be considered when defining the sub-operational environments:

- Overall multimodal operational aspects considerations: mid-long distance mobility with multimodal governance in place.
- European regional archetypes: ensuring that all different regions (defined at NUTS 2 level) are covered.
- Multimodal policy packages: to describe different evolutions of the mobility ecosystem where multimodality is incentivised (e.g. with CO₂ taxes) or enforced (by means of flight bans imposition).
- Infrastructure characteristics: focusing on connecting nodes and the scarcity of infrastructure in the regions.
- Network disruptions: which represent disruptions which require (or could benefit) from the replanning of operations. This should consider disruptions in the air and/or rail network.
- Level of centralisation: provides 2 levels of centralisation between air and rail operators: centralised and decentralised.

Considering these previous characteristics, the validation of SOL401 focuses on intra-Spain mobility. This considers passenger demand flows between the 49 biggest cities in Spain (all cities of more than 100 000 inhabitants and all islands which have an airport). This will be used for the validation exercises, and the representativeness of the results for general mobility is described in the relevant sections below.

SOL401 is a disruption manager that builds on the existing literature, and it is capable of optimising a complete multimodal network (rather than just a pair train station+airport). Thus, the exact scope of the case studies is to optimise an (inter)national network. The results of this optimisation will be assessed on the entire network but also region-wise (at a NUTS2 level), according to the different European regional archetypes developed in the project and on the different infrastructure

characteristics, as well as different disruption packages as defined in the OSED [12]. Note that Spain contains the three European regional archetypes identified by MultiModX (see D3.1 [14] and Section 5.1.1).

Different scenarios built over the previously defined scopes will be considered when defining the experiments developed for the validation of the Solution.

Scenarios are based on three different multimodal policy packages and the disruption package, as described in the operational characteristics in SOL401 OSED [12].

During the project we further collected travel and demand data from a busy day in 2019. Since travel is predicted to increase, but the overall network (train stations, airports) is not predicted to change substantially, we assume that this data is representative of a nominal day in 2030. We will test how SOL401 improves the multimodal situation data of the network.

In this context, the scenarios (reference and solution) include disruptions, a combination of multimodal policies and a timeline. The scenarios that will be tested in the experiments are based on:

- REF1 (as in the ECO-EVAL). This scenario refers the reference policy package with no particular policies. We take the data from 2019 and a defined disruption from the disruption package.
- REF1+SOL401. This is the situation after the application of SOL401.
- REF3 (as in the ECO-EVAL). This scenario refers to the policy pack “multimodality enforced”. We take the data from 2019 and apply several policies related to multimodality, particularly a short haul flight ban and a tax on CO₂.
- REF3+SOL401. This is the situation after the application of SOL401.

Note that each of these experiments uses the same disruption type, derived from the disruption package, to ensure a meaningful comparison on results. The disruption type is selected based on the inputs from the Validation exercise #2 and consists of a capacity reduction at the airport of Madrid (LEMD).

The specific scenarios are formally defined in the following.

General information about scenario definition can be found in table 3.

Category	Sub-Category	Definition
cs (Case Study)	cs10: Intra-Spain Mobility	This case study is the main case study of MultiModX. We study the air and rail mobility of the Spanish network but excluding international flights. Although this scenario will not be analysed in the ERR we include it here for completeness.
	cs11: Intra-Spain+International flights	This case study is an extension of the previous one that includes international flights. The results of the ERR are based on this case study.

pp (Policy Package)	pp00: Baseline 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	It is the same as pp10 with an additional flight ban on flights shorter than 3h (where a rail alternative under 3h exists).
nd (Network demand)	nd10: Nominal demand	This demand represents the nominal demand of 1380 origin-destination pairs with an overall number of 300.807 (potential) PAX
	nd20: Reduced demand	This is the same as nd10 but reduced by 10 %, representing the demand decrease due to reduced services (e. g. a potential flight ban).
	nd30: Homogeneous demand	This is a homogeneous demand, using the same origin-destination pairs but with equal demands of ca. 295 PAX per pair, representing an alternative demand structure. (Note that the supply, i.e. flights and train services, remains unchanged. This creates a different relation between demand and supply, i.e. the supply does not necessarily correspond well to the given new demand, providing a more challenging setup for the disrupted scenarios. This discrepancy is addressed further in the results section.)
	dm000: Baseline	No disruption management.

dm (Disruption Management)	dm100: decentralized disruption management	Decentralized disruption management w.r.t. the corresponding alliances. Due to missing real-life data, the alliances have been formed by sorting all airlines and railway undertakings into several distinct representative groups.
	dm200: centralized disruption management	Centralized disruption management, also including replacement services.

Table 3: MultiModX scenarios and nomenclature.

For the analysis of SOL401 we selected a subset of the scenarios, presented in table 4.

Scenario	Comment
cs11.pp00.nd10.dm000	This is a baseline scenario for this validation exercise with the nominal demand and without policies.
cs11.pp00.nd10.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management and with the nominal demand.
cs11.pp00.nd10.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management with the nominal demand. It corresponds to a Solution Scenario.
cs11.pp20.nd20.dm000	This is a baseline scenario for this validation exercise with the reduced demand and with policies.
cs11.pp20.nd20.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management and with the reduced demand. It corresponds to a Solution Scenario.
cs11.pp20.nd20.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management and with the reduced demand. It corresponds to a Solution Scenario.
cs11.pp00.nd30.dm000	This is a baseline scenario for this validation exercise with homogeneous demand and without policies.
cs11.pp00.nd30.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management and with homogeneous demand. It corresponds to a Solution Scenario.

cs11.pp00.nd30.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management and with homogeneous demand. It corresponds to a Solution Scenario.
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Table 4: Selected scenarios for the evaluation of SOL401.

The **overall assumptions** that guide the research activities are the following:

- The two scopes (intra-Spain and intra-Spain+International) provide an interesting variety in terms of regional specificities and situations of multimodal transport and the implication of disruptions in such networks (national and international case study);
- The set of defined passenger archetypes is representative of the entirety of travellers;
- The required data (demand for each passenger archetype, travel times, infrastructure capacity, actual traffic state of the network, location of the passengers and vehicles, disruption information, etc.) is available in the regions under study;
- A multimodal performance scheme and multimodal governance are in place, allowing cooperation for the disruption management between modes of transport (shared data, possibility to modify or replace the existing timetables, information, incentive...).
- The different regional archetypes represent a real combination of air and rail characteristics within a region or a transport corridor, and thus, the variety of multimodal conditions within the EU
- Only long-distance means of transport, including air and rail, are considered within the disruption management, with urban public transport considered only when necessary to connect an airport and a rail station in a city and to estimate the available infrastructure capacity for long-distance services
- The positions, actual departure and arrival times and loads of all vehicles as well as the actual number of passengers including their itinerary and current location are known.
- Passengers who planned their journey do not change their planned destination, nor do they choose to cancel their trip themselves.
- Passengers are routed along the shortest/fastest available paths within the network
- The original timetable is feasible and does not exceed capacities or violate other operational constraints
- Information about a disruption is completely known, including type, start and end times, and location.
- Services are adapted/managed only if they are directly affected by a disruption
- Vehicle rotations and crew schedules are not considered during the disruption management
- The liabilities for managing the disruptions, e.g. passenger compensation, are not explicitly allocated to the different stakeholders.

The specific assumptions for the Disruption Management Solution are further described in Section 4 of the ERP.

3.2.2 Summary of validation objectives and success criteria

This section lists, for each of the research questions, the validation objectives and their related success criteria required for this exploratory plan.

- **RQ-0401-ERP-010 - Which modal constraints/decisions need to be considered in multimodal disruption management?**
 - **Objective (OBJ-0401-ERP-010):** Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.
 - KPA/KPI: this RQ takes a subset of (multimodal) KPAs and PIs proposed in SOL399 and is listed in Table 3.2.2.
 - **Success criteria (CRT-0401-ERP-010.1):** Produce a detailed description of decision/actions for multimodal disruption management.
 - **Success criteria (CRT-0401-ERP-010.2):** The disruption management strategies and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10) in validation exercise #2.
 - **Success criteria (CRT-0401-ERP-010.3):** Disruption types are judged as relevant for the stakeholders in validation exercise #2 (the ones with highest scores will be taken for experiments).
 - **Objective (OBJ-0401-ERP-020):** Define a reasonable planning horizon for disruption management.
 - **Success criteria (CRT-0401-ERP-020.1):** A majority of stakeholders considers that the planning horizon representative and relevant.
- **RQ-0401-ERP-020 - How can multimodal disruption management improve passenger-centric performance in multimodal transport networks?**
 - **Objectives (OBJ-0401-ERP-030):** Compute an adjusted multimodal schedule including adjusted flight schedules and rail timetables.
 - KPAs/KPIs: (same as for the previous objective)
 - **Success criteria (CRT-0401-ERP-030.1):** Calculate the KPIs for (non-centralised or centralised) multimodal adjusted schedules for at least three different demand scenarios
 - **Objective (OBJ-0401-ERP-040):** Generate adjusted air and rail schedules that provide better multimodality to passengers.
 - KPAs/KPIs: (same as for the previous objective)

- **Success criteria (CR-0401-ERP-040.1):** For all experiments in validation exercise #1, the selected KPIs after the application of SOL401 should be better than without its application. Calculate the KPIs for centralised and non-centralised multimodal adjusted schedules compare them to the KPI values of disrupted schedules without SOL401 (i.e. estimate passenger flows without adjusting schedules), demonstrating its ability to enhance overall passenger-centric performance by at least 10%, and an additional passenger-centric performance of centralised SOL401 with respect to non-centralised version shall be observed.

KPA	PI
Efficiency	arrival delay (services)
	total journey time (PAX)
	stranded PAX
???	departure delay
	no. of cancellations
	no. of diversions
Flexibility/Resilience	replanned resilience
	replanned passengers

Table 5. KPI/PIs for assessing SOL401.

3.2.3 Validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A1	Case studies coverage	It is assumed that the three case studies provide an interesting variety in terms of regional specificities and situations of multimodal transport (national case study and international corridor with an	Regional archetypes have been studied and the case studies cover a national and an international case.	Medium

		integrated HSR station in an airport).		
A2	Regional archetypes	It is assumed that results derived from the Spanish (national), German (national) and the Spanish-German (international) regional archetypes can be translated and upscaled to a EU level using different regional archetypes as examples	The different regional archetypes represent a real combination of air and rail characteristics within a region or a transport corridor, and thus, the variety of multimodal conditions within the EU	Low
A3	Passenger archetypes coverage	It is assumed that the set of passenger archetypes considered are representative for the entirety of travelers.	Extensive research has been conducted to ensure that those passenger archetypes represent the variety of travelers.	Medium
A4	Data availability	It is assumed that the required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, etc.) are available in the regions under study.	Data are required to execute the solution but modelling assumptions could be established if needed.	Medium
A5	Existence of multimodal governance	It is assumed that a multimodal performance scheme and multimodal governance is in place, allowing cooperation between modes of	The interest of the project lies in studying the impact of a multimodal and	High

		transport (shared data, information, incentive...).	collaborative framework.	
A6	Long distance	Only long-distance means of transport, including air and rail, are considered within the disruption management, with urban public transport considered only when necessary to connect an airport and a rail station in a city and to estimate the available infrastructure capacity for long-distance services	Passengers typically consider intercity and high-speed train services when traveling long distances. And urban and regional services may be used only for transferring between airport and station.	Low
A7	Coordination between air and rail	The schedule coordination occurs between rail and air, leaving aside other long-distance ground transportation means as long-distance buses.	The scope and focus of the project is on air and rail collaboration. For future projects it would be interesting to include road transport.	Medium
A8	Traffic state	The positions, actual departure and arrival times and loads of all vehicles as well as the actual number of passengers including their itinerary and current location are known.	The actual traffic state of the system is required to adequately adjust the operations with regards to the disruption.	Medium
A9	Passenger choice	Passengers who planned their journey do not change their planned destination, nor do they	Recent research shows that destination	Low

		choose to cancel their trip themselves.	choice is not a short-term behavioral aspect. As passengers can be expected to already travel along their planned itineraries when disruptions occur and due the short-term (i. e. tactical) temporal scope of our approach, destination choice is not considered.	
A10	Passenger routing	Passengers are routed along the shortest/fastest available paths within the network	Recent research shows that passengers short-term routing decisions depend on the duration of available routing alternatives.	Medium
A11	Original schedule	The original timetable is feasible and does not exceed capacities or violate other operational constraints	Initial timetables originate from SOL2 or actual operations and will thus be feasible.	Low
A12	Disruption info	Information about a disruption is completely known, including type,	Disruption management decisions	Medium

		start and end times, and location.	require knowledge of the disruption. As our Solution is a tactical approach, it can rely on historical set-ups, where the complete information is available.	
A13	Disruption impact	Services are adapted only if they are directly affected by a disruption	Real-life disruption management measures are usually applied for directly affected services only.	Small
A14	Vehicle and crew	Vehicle rotations and crew schedules are not considered during the disruption management	Due to the tactical scope of our approach and regarding the policy oriented perspective of our project in combination with the steps of operational planning in industry; vehicle rotations and crew schedules are expected to be scheduled at a subsequent planning stage.	Medium

A15	Liabilities	The liabilities for managing the disruptions, e.g. passenger compensation, are not explicitly allocated to the different stakeholders.	As our solution considers the presence of liabilities and the presence of multimodal governance, the liability allocation is expected to have a limited impact on the disruption management outcome.	Low
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Table 6: validation assumptions overview

3.2.4 Validation exercises list

Identifier	SOL401-Validation-Exercise-1 TVAL.01.1-MultiModX-0401-TRL2
Title	Simulations of SOL401
Description	The exercise will consist of: - replanning a network considering disruptions with and without the use of Disruption Management Solution (SOL401) - ensuring the feasibility of the newly-generated adjusted schedules (maximising covered/transported demand, minimized total travel times); - assessing the benefits of Disruption Management Solution (SOL401), both centralised and decentralised versions, by comparing the passenger-centric indicators (and the tactical ones if available).
KPA/TA addressed	- Efficiency - Resilience

Addressed expected performance contribution(s)	Improvement of the defined KPIs/PIs
Maturity level	TRL2
Use cases	Replan network in case of disruption
Validation technique	PIs and KPIs calculation and comparison
Validation platform	Software
Validation location	N/A
Start date	24/03/2025
End date	28/04/2025
Validation coordinator	TUD
Status	Completed
Dependencies	Upstream: T3.1. Data collected in T3.1 is available.
Identifier	SOL401-Validation-Exercise-2
Title	Stakeholder survey validation
Description	The exercise will consist of: - presenting the various results and KPIs obtained through the application of the Solution in the different experiments to a minimum of 20 relevant stakeholders; - gathering feedback from said stakeholders to evaluate the pertinence of the Solution and its results.
KPA/TA addressed	- Efficiency - Resilience

Addressed expected performance contribution(s)	Validation of the project assumptions and the optimisation techniques
Maturity level	TRL2
Use cases	N/A
Validation technique	Feedback gathering from the stakeholders. Basic statistical analysis of the answers to the survey.
Validation platform	Presentation, Mentimeter software.
Validation location	Rome
Start date	M16 (according to the GA), realised on 12/11/2024
End date	M16 (according to the GA), realised on 12/11/2024
Validation coordinator	TUD
Status	Completed
Dependencies	N/A

Table 7: Validation exercise #2 summary

3.3 Deviations

3.3.1 Deviations with respect to the S3JU project handbook

There are no deviations from the S3JU project handbook.

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

In agreement with SJU the second case study of the Spain-Germany-Corridor has not been assessed.

The validation originally assumed using intra-Spain case. However, due to the limited amount of multimodal connections within the nominal domestic Spanish network, and due to the expected importance of disruption management for domestic and international travel, we decided to include as many services as possible into our experiments to illustrate the capabilities and assess the impact of disruptions management. We hence applied our solution on the Spanish network, also incorporating

inter-European travel (cs11). Thereby, we are able to determine the impact not only from a national Spanish perspective, but also allow insights on the benefits for European and other long-distance travellers.

The original research objectives have been slightly modified. Originally, validation objective OBJ-0401-ERP-020 was to “compare the KPIs for multimodal disruption management.” and its associated success criteria CRT-0401-ERP-020.1 “a majority of stakeholders considers that the defined KPIs/PIs are representative and relevant”. However, we realised that this objective and validation criteria were not well defined.

It became clear that the objective and criteria were not sufficiently well-defined to support effective evaluation. In particular, the planned validation through stakeholder feedback was not feasible, as no industry board meeting was scheduled after the experiments, and the complete experimental results were not available in time for the final board meeting.

Additionally, as the project progressed, the **time horizon** of disruption management emerged as a key consideration. This aspect had not been part of the original objective but proved to be highly relevant and was subsequently addressed in discussions with the industry board. This is why we have decided to modify that research objective and success criterion by:

- OBJ-0401-ERP-020: Define a reasonable planning horizon for disruption management.
 - CRT-0401-ERP-020.1: A majority of stakeholders considers that the planning horizon representative and relevant.

The validation activities remain unchanged.

4 Validation results

4.1 Summary of MultiModX / SESAR Solution 401 validation results

MultiModX / SESAR solution 401 validation objective ID	MultiModX / SESAR solution 401 validation objective title	MultiModX / SESAR solution 401 success criterion ID	MultiModX / SESAR solution 401 success criterion	MultiModX / SESAR solution 401 validation results	MultiModX / SESAR solution 401 validation objective status
OBJ-0401-ERP-010	Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.	CRT-0401-ERP-010.1	Produce a detailed description of decision/actions for multimodal disruption management.	Detailed description was produced.	OK
		CRT-0401-ERP-010.2	The disruption management strategies and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10) in validation exercise #2.	Answers: all measures (i.e. retiming, rerouting/diverting, cancellation and short-turning) got ranked with a score higher than 5/10.	OK

		CRT-0401-ERP-010.3	Disruption types are judged as relevant for the stakeholders in validation exercise #2 (the ones with highest scores will be taken for experiments).	Answers: capacity reductions on railway corridors/airports, airspace capacity reduction/closure and multiple simultaneous disruptions got ranked with a score higher than 5/10.	OK
OBJ-0401-ERP-020	Define a reasonable planning horizon for disruption management.	CRT-0401-ERP-020.1	A majority of stakeholders considers that the planning horizon representative and relevant.	Answers: 1 day ahead	OK
OBJ-0401-ERP-030	Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.	CRT-0401-ERP-030.1	Calculate the KPIs for (non-centralised or centralised) multimodal adjusted schedules for at least three different demand scenarios	The KPIs for non-centralised and centralised multimodal disruption management for three demand scenarios have been calculated.	OK

OBJ-0401-ERP-040	Generate adjusted air and rail schedules that provide better multimodality to passengers.	CRT-0401-ERP-040.1	For all experiments in validation exercise #1, the selected KPIs after the application of SOL401 should be better than without its application. Calculate the KPIs for centralised and non-centralised multimodal adjusted schedules compare them to the KPI values of disrupted schedules without SOL401 (i.e. estimate passenger flows without adjusting schedules), demonstrating its ability to enhance overall passenger-centric performance by at least 10%, and an additional passenger-centric performance of centralised SOL401 with respect to non-centralised version shall be observed.	For every experimental instance, KPIs/PIs were computed and compared. Decentralized and centralized disruption management showed clear improvements for passenger-centric performance. The centralized disruption management showed performance improvements up to and even beyond 10 %.	OK
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Table 8: summary of validation exercises results

4.2 Detailed analysis of MultiModX / SESAR solution 401 validation results per validation objective

Important note: To increase readability, most of the discussion in the following sections will be qualitative and highly aggregated. For the full quantitative results, we recommend reading the appendices A and B. In this appendix, each validation exercise is thoroughly analysed for every demand scenario and w.r.t. the benchmark (i.e. without disruption management), decentralised and centralised disruption management.

4.2.1 OBJ-0401-TRL2-ERP-010 results

Objective: Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.

Validation EX1: Produce a detailed description of decision/mechanisms/actions for multimodal disruption management.

Validation EX2: The disruption management strategies and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10) in validation exercise #2.

Validation EX2: Disruption types are judged as relevant for the stakeholders in validation exercise #2.

A detailed description of the disruption management decisions (i. e. rerouting, retiming, diverting, cancelling and scheduling replacement services) and the corresponding mechanisms (i. e. disruption measure pricing, disruption measure computation, passenger path pricing, passenger path computation, disruption management and passenger assignment) has been derived during the project (s. MMX SOL401 FRD, Sec. 3).

The disruption measures i.e. retiming, rerouting, diverting, cancellation and short-turning were validated in the second IB meeting via the question “*For operators, how relevant are the following measures?*”, which resulted in interest scores above 5/10 for every single measure.

The relevant disruption types were validated in the second IB meeting via the question “Which types of disruptions would be the most interesting to evaluate?”, where the following ones got scores above 5/10:

- capacity reduction of airports/railway corridors
- airspace capacity reduction/closure
- multiple simultaneous disruptions in the network

All relevant disruption measures and types were successfully incorporated into the disruption manager of SOL401. The experimental set-ups have been chosen accordingly. Thus, the status of this validation objective is OK.

4.2.2 OBJ-0401-TRL2-ERP-020 results

Objective: Define a reasonable planning horizon for disruption management.

Validation: A majority of stakeholders considers that the planning horizon representative and relevant.

The results of second IB meeting suggested that contingency planning with the tactical planning horizon for multiple hours or even days ahead is of practical interest. The results thus prove the chosen modeling approach and model selection to be relevant and reasonable. For the experiments, we chose 1 day ahead of operations. Thus, the status of this validation objective is OK.

4.2.3 OBJ-0401-TRL2-ERP-030 results

Objective: Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.

Validation: Calculate the KPIs for (non-centralised or centralised) multimodal adjusted schedules for at least three different demand scenarios.

Three demand scenarios with different nominal schedules, representing several defined scenarios, have been conducted to show the performance of SOL401. There, the Disruption Manager provided the tactical adjusted schedules for all air and rail services in the network. The corresponding KPIs have been computed. Thus, the status of this validation objective is OK.

4.2.4 OBJ-0401-TRL2-ERP-040 results

Objective: Generate adjusted air and rail schedules that provide better multimodality to passengers.

Validation: For all experiments in validation exercise #1, the selected KPIs after the application of SOL401 should be better than without its application. Calculate the KPIs for centralised and non-centralised multimodal adjusted schedules compare them to the KPI values of disrupted schedules without SOL401 (i.e. estimate passenger flows without adjusting schedules), demonstrating its ability to enhance overall passenger-centric performance by at least 10%, and an additional passenger-centric performance of centralised SOL401 with respect to non-centralised version shall be observed.

The KPIs and PIs for centralised (dm100) and decentralised disruption management (dm200) have been calculated for the defined experimental instances, considering the demand levels with and without multimodal policies, and a homogeneous one. They have been compared with a benchmark, where no schedule was adjusted using SOL401 (dm000). The numbers in the Tables X and X+1 represent difference between the considered dm100/dm200, i.e. SOL401 variant, and dm000. The results show distinct changes for the decentralised and centralised disruption management, where the centralised disruption management consistently performed better than its decentralised counterpart.

The **decentralised disruption management** showed improvements for the number of stranded passengers (up to 6 %), for the service delays (more than 30 %). For the experiment cs11.pp00.nd20.dm100, the decentralised disruption management caused rather stable numbers of stranded passengers (+ 2 %), which allowed to significantly reduce delay of the remaining travellers and thus reveals the trade off between different objectives of delay and number of transported PAX. Differently, the results for the journey times displayed inconsistent behaviour. Aggregated journey times are strongly related to: 1. the number of travelling PAX, i. e. the more PAX travel, the higher are the overall journey times in the system; and 2) the overall distance of the corresponding travelling OD pairs and thus also increase with increasing distances - particularly when considering international connections. Due to the resulting strong relation with travelling (and hence also stranded) passengers and delays, the journey times improved only in one case, whilst for two experiments, the journey times

increased significantly. For those experiments with travel times increases, other PIs improved such as the reduction of delays or the reduction of stranded passengers. Consequently, the higher journey times are the price for the reconnection of the vulnerable, international connections.

Also, particularly the last scenario cs11.pp00.nd30.dm100 shows the impact of differing demand structures. The scenario considers significant discrepancies between the nominal supply (flight and train services) and the demand (passengers), and thus would require high efforts of the network to adapt. Therefore, in order to reconnect only a small share of OD-pairs and reduce the corresponding number of stranded PAX (obtained 1% improvement), SOL401 results in significant increases of delays and travel times. (Note that SOL401, one of the main objectives, aims to transport as many passengers as possible.) The results thus clearly show the importance of well-designed undisrupted networks, whereas a mismatch of nominal supply and demand requires high adaptation efforts during (disrupted) operations. Resultingly, the numbers of stranded PAX reduced slightly whilst journey times and delays increased significantly.

For the number of cancellations and the number of diversions over all experiments, no significant changes were found. The replanned resilience showed decrease in similarity w.r.t. original plan (up to 2 %), whilst the number of replanned passengers clearly increased (up to 8 %). This relation clearly indicates the higher flexibility due to multimodality, i.e. more passengers are replanned and transported by making minor changes to the multimodal adjusted schedule.

scenario	arrival delay	avg. journey time	stranded PAX	departure delay	no. of cancellations	no. of diversions	replanned resilience	replanned passengers
cs11.pp00.nd10.dm100	- 35 %	- 2 %	- 6 %	- 33 %	0 %	6	- 2 %	+ 8 %
cs11.pp00.nd20.dm100	- 46 %	+ 16 %	+ 2 %	- 43 %	0 %	1	0 %	+ 1 %
cs11.pp00.nd30.dm100	+ 53 %	+ 260 %	- 1 %	+ 41 %	0 %	3	- 1 %	+ 4 %

Table 9. Results for decentralised disruption management

For **centralised disruption management** nearly all KPIs and PIs improved significantly, showing even greater benefits. Most importantly, the passenger travel times decreased by more than 10 % (up to 13 % in total and up to 20 % for avg. travel times) in the best case. However, due to the strong connection with the number of transported passengers, the journey times increased for the other cases where PAX increased. The number of stranded passengers decreased for the first two cases by about 15 %. However, the last case only showed a minor decrease. Also the service delays reduced by almost 50 % for cumulative and average numbers in most cases. The resilience also showed promising changes, as the number of replanned passengers increased for all cases. whilst the service similarity decreased by at most 20 %.

Particularly the last scenario cs11.pp00.nd30.dm200 shows clearly different results, which come from the impact of differing demand structures. Similarly as for decentralised case dm100, the resulting discrepancies between the nominal supply and the demand require high efforts of the disruption management to adapt the network, which results in significant adjustments, here including also major use of the available replacement services, to reconnect OD-pairs and reduce the corresponding number of stranded PAX. Due to the increasing numbers of PAX and their corresponding travel distances the journey times increase, as often longer journeys are affected by disconnections firstly (and hence require higher efforts to be restored). Still, taking into account centralised nature of SOL401, the resulting number of passengers is reduced by 2%, and arrival/departure delays are at the similar level as benchmark, providing overall better performance than dm100. Similarly as for dm100, the results thus clearly show the importance of well-designed undisrupted networks, whereas a mismatch of supply and demand requires high efforts during (disrupted) operations.

Due to the scheduled replacement services in dm200, up to 64 in total over the experiments, even the disrupted network could provide significant service improvements by providing additional connections and departures, thus leading to higher journey times, lower numbers of stranded PAX and increasing numbers of replanned PAX.

scenario	arrival delay	avg. journey time	stranded PAX	departure delay	no. of cancellations	no. of diversions	replanned resilience	replanned passengers
cs11.pp00.nd10.dm200	- 53 %	- 19,6 %	- 17 %	- 50 %	0 %	3	- 1 %	+ 10 %
cs11.pp00.nd20.dm200	- 41 %	+ 55 %	- 15 %	- 37 %	0 %	1	0 %	+ 21 %
cs11.pp00.nd30.dm200	- 1 %	+ 376 %	- 2 %	- 1 %	+24 %	2	- 20 %	+ 207 %

Table 10: Results for centralised disruption management

Finally, the disruption management of SOL401 clearly enhances the passenger centric performance by 10 %. Depending on the degree of centralization, different levels of improvement are revealed. There, the centralized disruption management shows clear superiority in almost every aspect. Thereby, it suggests that the benefits of multimodality can be leveraged best by managing disruptions in a centralized and coordinated manner. Consequently, the status of this validation objective is OK.

4.3 Confidence in validation results

4.3.1 Limitations of validation results

For validation exercise EX1, the main limitations are related to the data and the PIs used. 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. This is mitigated by the use of policy packages that *force* multimodality, e.g. with the ban of short-haul flights, with the consideration of longer distance trips such as to-from the Canary Islands from all the peninsula regions in Spain and with the application of centralised and decentralised disruption management, which allowed multimodal passenger rerouting with differing degrees of freedom. Furthermore, the Disruption Manager could consider assigning passengers to transfers which might not be used in reality due to their lacking attractiveness, i.e. leading to too long journey times. Thus, the number of replanned passengers might be slightly overestimated. However, due to the clarity of the results/improvements of up to 20 %, even an (unexpectedly high) error range of 50 % would allow to meet the objectives. We hence consider the impact of this limitation rather low.

The validation results are expected to be robust despite being based on a single case study (cs11), as the experimental design was carefully constructed to encompass a variety of conditions, which also could easily be represented by separate case studies. By incorporating both, timetable modifications (due to the simulated flight ban policy) and demand changes (through the homogeneous-demand scenario), the experiments effectively capture key characteristics of general multimodal transport networks. This approach ensures that the analysis extends beyond a simple replication of the Spanish case and provides meaningful insights into broader network behaviors, which should be applicable in the heterogeneous European context. As a result, we expect the findings - particularly regarding the performance and benefits of different disruption management strategies - to remain consistent across similar setups, indicating a low sensitivity with respect to the specific case study used and reinforcing the general applicability of the results. We hence consider the impact of this limitation low.

4.3.1.1 Quality of validation results

Validation exercise EX1 is composed of mathematical optimization, where Human Factor (HF) is practically absent. Therefore we consider that there are no issues regarding the quality and accuracy of these results.

Validation exercise EX2 was realised during the development of the code and was hence limited by the fact that SOL401 was not fully mature. The quality of the results is also influenced by the number of stakeholders attending the meeting.

4.3.1.2 Significance of validation results

The results of validation exercise EX1 are in general significant, as they have been computed using deterministic models and show clear distinctions between the benchmark and the SOL401 results. Operational significance is somehow limited by the assumptions of the project (discussed in section 4.3.1). However, we consider that the optimization constraints are sufficiently realistic to offer a complete vision of the potential of SOL401 and the corresponding multimodal disruption management.

The results regarding validation exercise EX2 are statistically significant. Operational significance is not applicable for this exercise.

5 Conclusions and recommendations

5.1 Conclusions

5.1.1 Conclusions on MultiModX / SESAR solution 401 maturity

All the validation criteria have been met, showcasing the effort put into the maturity of the Solution.

Additionally, given its complexity and performance, SOL401 represents a significant improvement from [SORTEDMOBILITY](#), TRANSIT, CASSIOPEIA II and Domino. Compared to the mentioned disruption management tools, the reach of SOL401 is much larger, as it can be used in a much wider network, allows for multimodal disruption management and takes into account industry constraints in much greater detail.

SOL401 has also been validated by industry experts in validation exercise EX2. The combination of all these factors, along with the Maturity Self-Assessment, grant SOL401 the TRL2 level.

5.1.2 Conclusions on concept clarification

SOL401 is a tool that can allow airlines and rail companies to manage network disruptions in a coordinated manner at a country-wide level. From the validation exercises, we can extract the following conclusion regarding concept clarification:

- Service specific dwell times/turnaround times for replacement services should be introduced to capture the possible replacement options more accurately.
- Timetable supplements are globally parameterized. However, supplements might not be homogeneously allocated in real networks. Hence arc-specific supplements might capture the timetabling constraints more accurately.
- Waiting times for passenger itineraries should be included to better consider unattractive transfers and hence improve the passenger assignment and the corresponding disruption measures.

SOL401 is a disruption management tool, and hence it does not affect the SESAR architecture. The operational feasibility of SOL401 depends on the SESAR capability of Single ticketing along with the remaining assumptions of the project regarding airline and rail coordination and cooperation. Technically, SOL401 has proven to be effective at adjusting air and rail schedules under disruptions.

5.1.3 Conclusions on technical aspects

Validation exercise EX2 helped in the design of the functional requirements of SOL401. In particular, it helped define the following functional requirements.

- SOL401 Disruption Management Solution shall adjust multimodal schedules for air and rail with a focus on the passenger for a day of operations taking into account a given set of disruptions (REQ-SOL401-OP-DMM01.001);
- SOL401 shall respect the capacity and operation constraints of railway and airline systems (REQ-SOL401-FR-DMM02.002);
- SOL401 shall allow for combining multiple objectives to cover different scenarios (i.e. with/without airline alliances) while generating the disruption management solution (REQ-SOL401-FR-DMM02.003);
- SOL401 shall consider existing and allow new service connections in the adjusted service network (REQ-SOL401-FR-DMM03.003);
- SOL401 shall allow passenger rejection in the passenger assignment. (REQ-SOL401-FR-DMM03.004);

Validation exercise EX1 confirmed that the solution implemented these functional requirements correctly. SOL401 fulfils all the functional requirements outlined in the FRD.

5.1.4 Conclusions on performance assessments

As discussed in the ECO-EVAL, given its multimodal status SOL401 does not fundamentally change the current SESAR KPAs, which are traditionally only centred around ATM. For this reason, part of the objective of the project is to develop a multimodal performance framework centred on multimodality. More information about MultiModX performance framework can be found [here](#).

We present here a summary of the performance results per performance area developed within the project:

- Efficiency. SOL401 is able to balance the avg. arrival and departure delays per service, the total journey time and arrival delays for passengers, the numbers of stranded passengers. Also, reducing the numbers of cancellations for some cases. And, diversions are applied sparingly - only when they generate significant benefits to network operations. Thus, SOL401 has a medium - high impact on this KPA.
- Flexibility. SOL401 is capable of managing and improving the replanned resilience and passengers by appropriate disruption management decisions which leads to higher connectivity and increases passenger transport during disruptions. Thus, SOL401 has a high impact on this KPA.

5.2 Recommendations

5.2.1 Recommendations for next R&I phase

The maturity achieved by the current solution presents a solid foundation for advancing to the next Technology Readiness Level (TRL). To ensure continued progress, the forthcoming Research and

Innovation (R&I) phase will concentrate on incorporating critical operational elements and facilitating seamless integration within the SESAR framework.

Research avenues to be explored for next TRL-levels:

- **Comprehensive Data Integration.** This involves accessing and combining **real-world datasets** from both the air and rail domains, including airline schedules, rail timetables, passenger flow data, and disruption records. Using these datasets, new **case studies and simulations** should be developed to validate the model under realistic operational conditions. Particular focus should be put to the definition and validation of interfaces with real-world datasets. Additionally, data harmonization across stakeholders (airlines, rail operators, infrastructure managers, and network managers) will be required to ensure consistency in data formats, temporal resolution, and operational definitions.
- **Investigate and calibrate passenger preferences during disruptions:** A critical area towards higher TRL is the calibration of models with the passenger preferences during disruption scenarios. Currently, there is limited empirical data on how passengers make decisions when faced with options such as being stranded versus accepting a detour, or their tolerance for delays and schedule changes. These behavioral factors play a significant role in the effectiveness and acceptance of disruption management (DM) strategies, yet they are not adequately captured in existing models. Without this insight, it is challenging to design DM approaches that are truly passenger-centric. Further research—through surveys, behavioral experiments, and/or analysis of real-world disruption cases—is needed to better understand these preferences. This would enable the development of more responsive and adaptive DM strategies, improving both operational outcomes and passenger satisfaction.
- **Algorithm validation in controlled environment.** Future R&I phases should also focus on testing and refining the disruption management algorithms within a controlled lab-based simulation environment to ensure stability, accuracy, and scalability. Those simulation-based demonstrations can explicitly showcase the benefits for passengers, operators, and traffic managers in controlled simulated environment. Parallel to this, systematic tuning of model parameters – including the calibration of specific weights defined within the model – will be essential to optimize performance and enhance the realism of simulated operational outcomes.
- **Ensure integration within the Air Traffic Management (ATM) landscape.** Another key avenue towards higher TRL is to define how SOL401 fits within the broader Air Traffic Management (ATM) ecosystem in terms of systems, roles, and operational procedures. There are various alternatives in which SOL401 could be used as a base to enhance some of the ATM capabilities to include passenger requirements and rail multimodal alternatives in the decision-making process when dealing with capacity-demand imbalances. For instance, SOL401 could extend some of the Network Manager's capabilities. In particular, the model of SOL401 could be applied as a pre-processing step for assigning slots in case of ATFM regulations to minimize the impact on passenger itineraries. SOL401 could also be integrated as part of the optimization process performed when identifying which flights should be diverted (or cancelled) in case of crisis, for example, in the event of mass diversions. SOL401 can, therefore, work as part of the optimization of the management of supply but also as a what-if evaluator to support the decision-making process of relevant stakeholders. In this role as support tool,

some evolution of SOL401 could be integrated as a service within the INM for example extending the information available in current platforms such as the Airport Corner. Overall, this will require a review of the current Network Manager architecture and an identification of which elements should be replaced and connected with these capabilities emanating from SOL401. The capabilities of SOL401 would also allow for the capture of the full economic impact of disruptions on airline operations and the corresponding disruption management strategies.

- **Stakeholder Engagement.** As SOL401 evolves, it is essential to establish clear integration pathways that align with existing ATM frameworks and regulatory structures. Engaging proactively with ATM stakeholders – such as air navigation service providers, airports, and airlines – will help identify the procedural or technological adaptations required to ensure compatibility and operational coherence when introducing SOL401. This collaborative approach will also support mutual understanding of system interfaces and information flows, helping to position SOL401 as a complementary and interoperable component within the vision for integrated, multimodal air and ground mobility. This is particularly relevant to ensure the acceptability of any change to the system by the end users, particularly when it can impact access to resources and the assignment of slots/delays.
- **Define the required changes to NM's regulatory framework.** Future R&I phases should address the evolving role of the Network Manager (NM) in managing multimodal disruption information, including data on timetables and operational disturbances across transport modes. To enable effective processing and response, potential adjustments to the NM's regulatory framework should be explored alongside required updates to existing NM systems to ensure full integration of SOL401 within the current software environment. Active involvement of the NM in the future industrialisation phase will be essential to align system enhancements with practical operational needs and ensure smooth adoption.
- **Interface design.** Future research phases should aim to define clear interfaces that enable seamless integration of the solution with existing traffic management systems, such as the enhanced tactical flow management system (ETFMS) for air transport to obtain up-to-date traffic information, and the Traffic Management Systems (TMS) for rail. In parallel, engaging operators and infrastructure managers to collect feedback will be crucial to ensure the solution's practical applicability and alignment with operational workflows across modes.
- **Proof-of-concept demonstrations in operational environments that reflect real-world multimodal transport scenarios.** A vital next step for advancing the maturity of the solution involves testing and validating its performance under realistic operational conditions. Future research should focus on deploying the model within live or high-fidelity multimodal transport environments, where complex interdependencies between air, rail, and ground systems exist and the corresponding data is available. Such validation would enable the assessment of the solution's robustness, scalability, and responsiveness in actual disruption contexts. It would also provide empirical insights into data exchange, interoperability, and decision-making processes across transport modes. The findings from these operational trials would form a critical foundation for refining the model and ensuring its suitability for large-scale deployment. Future validation activities should thus employ real-world datasets – such as airline schedules, rail timetables, and passenger flow data – to develop new case studies that reflect actual operational conditions. Incorporating a broader range of disruption scenarios,

including excessive delays and the closure of airports or stations, will enable more comprehensive testing of system robustness and adaptability under realistic and challenging circumstances.

5.2.2 Recommendations for future R&I activities

For future R&I activities the following topics have been discovered:

- **Incorporate dynamic disruption set-ups:** To tackle disruptions of the everyday life, their location, effects and duration are crucial. Currently, the locations and the effects on the capacity are captured by SOL401, assuming a consistent set-up throughout the day. Thus, including varying disruptions during the course of the day and the corresponding transition phases between different disrupted and undisrupted network states can increase SOL401's accuracy and thus enables it further for real-life application.
- **Multimodal contingency planning:** The SOL401 results also stress the relevance of contingency planning during the tactical planning phase, within the unimodal networks of air and rail in general, but also particularly for their multimodal combination. Thus, future R&I activities should focus on tactical contingency planning for the different modes, but also particularly for multimodal operations. Resultingly, future activities should work towards establishing SOL401 to support the management of catastrophic events
- **Enhancing computational performance for real-time support:** To support more near real-time operations, future R&I activities should focus on enhancing coordination strategies, data sharing, and dynamic plan updating between air and rail operators. In such time-critical contexts, the rescheduling horizon becomes shorter and more fluid, increasing the need for improved computational efficiency. Advancing the solver and algorithm performance of SOL401 will be essential to enable faster calculation and execution times, strengthening its applicability in dynamic environments. Beyond these improvements, exploring the extension of SOL401 toward genuine real-time disruption management will be vital – evaluating its responsiveness, scalability, and interoperability in live multimodal environments whilst regarding for the varying operational lead times to put the correspondingly adjusted schedules into operations.
- **Integrate passenger departure time distributions:** A promising avenue towards future activities is the integration of passenger departure time distribution into the disruption management model. Currently, this aspect is not represented, which may limit the accuracy of rescheduling and replacement service planning. Departure time preferences and distributions can significantly influence the feasibility and effectiveness of rebooking strategies, particularly in time-sensitive disruption scenarios. Without this data, the model may overlook critical constraints or opportunities, potentially leading to different operational outcomes. Incorporating this dimension would allow for a more realistic simulation of passenger behavior, improve the timing and allocation of replacement services, and enhance the overall responsiveness of disruption management strategies.
- **Incorporate revenue management and ticket pricing perspectives:** A valuable avenue would be the integration of ticket pricing effects into disruption management, which are currently not considered. While the model assumes that ticket prices remain fixed during disruptions, in reality, pricing can be influenced by traffic management decisions—such as rerouting,

cancellations, or the deployment of replacement services. Although fixed pricing may be a reasonable assumption for short-term demand during a disruption, it overlooks the potential for pricing to influence future demand, which in turn shapes the long-term demand landscape. This dynamic interaction between pricing, passenger behavior, and operational decisions is particularly relevant for strategic disruption management (DM). Incorporating pricing mechanisms would enable a more holistic evaluation of DM strategies, accounting for both immediate operational impacts and long-term market responses. This would support more informed decision-making around cost-benefit trade-offs and passenger satisfaction.

- **Evaluating the Cost and Strategic Role of Operational Resources in Disruption Management:** Disruption management (DM) heavily relies on the availability and strategic use of operational resources – including infrastructure capacity, timetable buffers, crew schedules, vehicle rotations, and spare assets. These resources are essential for mitigating the impact of disruptions, but their maintenance and provision come at a significant cost. This has a direct influence on the overall expenses of both service and infrastructure providers. Despite their importance, the interplay between disruption management and long-term strategic decisions – such as infrastructure design, vehicle procurement, and crew hiring – remains underexplored. Future research should focus on quantifying the cost-benefit relationship of these resources within DM strategies and exploring how strategic planning decisions can enhance operational resilience. This also involves active engagement with the corresponding stakeholders such as airlines or airports. This would support more cost-effective and robust disruption management frameworks, aligning short-term operational flexibility with long-term investment planning.
- **Optimisation with other modes of transportation.** Airports are typically not only connected by trains. Consequently, also disruptions on other modes might impact the air-rail transportation system (e. g. a traffic jam prevents crew from arriving in time). Implementing a tool capable of considering air, bus (or other conventional transportation modes) and rail would be an interesting avenue to explore in future projects. Also, it could be further developed toward door-to-door disruption management.
- **Integrate with airport operations.** Future research should also work on integrating multimodal disruption management models with detailed airport operations, including gate assignment, ground handling, and taxiing. This integration would enable a more holistic response to disruptions by aligning airside constraints with multimodal passenger and service flows, ensuring seamless coordination across the entire transport chain.

6 References

6.1 Applicable documents

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

[SESAR solution pack](#)

- [1] SESAR DES Solution Definitions Green-GEAR V1.0, 3rd June 2024.
- [2] SESAR Operation Concept Document OCD 2023, 02.00.00, 14th July 2023.
- [3] SESAR DES & DSD Solutions slides 2023 (1_0).pptx

[Content integration](#)

- [4] Content Integration – Executive Overview, Edition 00.01, 16th February 2023.
- [5] DES Common Assumptions, Edition 00.02.01, 29th June 2023.
- [6] DES Performance Framework, Edition 00.01.04, 29th June 2023.
- [7] DES Performance Framework – U-space Companion Document, Edition 00.01.02, 3rd April 2023.

[Content development](#)

- [8] SESAR 3 Joint Undertaking – Communication Guidelines 2022-2027, Edition 0.03, 23rd November 2022.

[System and service development](#)

[Performance management](#)

- [9] Performance Assessment and Gap Analysis Report (PAGAR) 2019 – updated version, Edition 00.01.00, 20th May 2021.
- [10] SESAR Solution Cost Benefit Analysis (CBA) Quick Start Guide (1_0).docx
- [11] SESAR ECO-EVAL Quick Start Guide (1_0).docx
- [12] Performance Assessment and Gap Analysis Report (2019), Edition 00.01.02, 13th December 2019.

[Validation](#)

- [13] DES HE requirements and validation /demonstration guidelines, Edition 3.00, 15th September 2023.

[14] DES SESAR Maturity Criteria and sub-Criteria_01_01 (1_1).xls

System engineering

Safety

[15] DES expanded safety reference material (E-SRM), Edition 1.2, 17th November 2023.

[16] Guideline to Applying the Extended Safety Reference Material (E-SRM), Edition 1.1, 17th November 2023.

Human performance

[17] SESAR DES Human Performance Assessment Process TRL0-TRL8, Edition 00.03.01, November 2022.

Environment assessment

[18] SESAR Environment Assessment Process, Edition 05.00.00, 23rd July 2024.

Security

Programme management

[19] Green-GEAR Grant Agreement No. 101114789, version 1, signed 11th May 2023.

[20] SESAR 3 JU Project Handbook – Programme Execution Framework, Ed. 01.00, 11th April 2022.

[21] Common Taxonomy Description (1_0).pdf, Edition 1.0, 7th February 2023.

[22] Horizon Europe ethics guidelines – essentials_1 (1_0).pptx

[23] Project Reviews 2024_guidance for IR1 & ER1 (1_0).pptx

6.2 Reference documents

[24] «SESAR 3 ER 1 Green-GEAR – D2.2 – Updated data management plan», ed. 02.00, 30th Aug 2024.

Appendix A Validation exercise #01 report

A.1 Summary of the validation exercise #01 plan

A.1.1 Validation exercise description and scope

The first validation exercise consists of validating the multimodal disruption manager SOL401. It relies on running SOL401 Disruption Management Solution, both centralised and decentralised and validating the used methods and algorithms by comparing PIs and KPIs as defined in SOL401 ERP, Section 4.3.

The main goals are to:

- Show that SOL401 can generate feasible multimodal adjusted schedules for realistic multimodal networks
- Ensure SOL401 can handle given disruptions.
- Demonstrate the ability to produce schedules of better quality taking into account passenger-centric perspective.
- Estimate the benefits of disruption management solutions by focusing on passenger-centric indicators.

The case studies and scenarios defined in Section 3.1 will be used to test the disruption manager. The main validation techniques will be calculation and analysis of KPIs/PIs.

In this context, 3 experiments are performed:

- **Experiment 1 - “without policies (REF1)”**

In this experiment, we apply SOL401 to adjust the air and rail schedules at the Spanish air and rail network for the overall demand level and “without policies”. We then compute and compare the corresponding PIs/KPIs.

- **Experiment 2 - “with policies (REF3 - multimodality enforced)”**

In this experiment, we apply SOL401 to adjust the air and rail schedules at the Spanish air and rail network for the reduced demand level and “with policies - multimodality enforced”, i.e. reduced level of services with no short-haul flights. We then compute and compare the corresponding PIs/KPIs.

- **Experiment 3 - “homogeneous demand”**

In this experiment, we apply SOL401 to adjust the air and rail schedules at the Spanish air and rail network for an overall homogeneous demand level. We then compute and compare the corresponding PIs/KPIs.

The first experiment reflects a realistic setup in terms of demand and supply relations, while the latter two represent more challenging scenarios characterized by a limited number of short-haul services and an imbalance between demand and supply - specifically, a homogeneous demand expected to be

served by the originally planned services. Therefore, the latter two cases place significantly greater stress on SOL401, requiring more extensive adjustments to air and rail services, as well as to passenger flows.

For all experiments, the decentralized and centralized disruption management are compared against a benchmark solution, where no disruption management is performed.

With this validation exercise, the main use case of SOL401 as defined in the OSED “*Replan network in case of disruption*” is addressed.

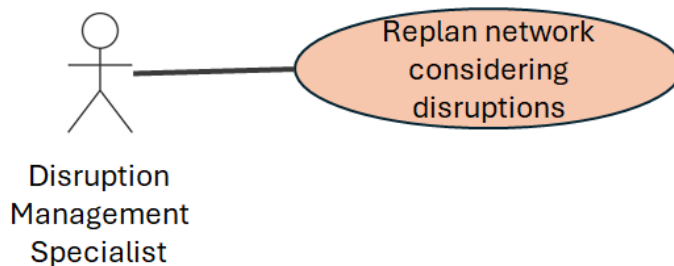


Figure A.1: Use case of SOL401

The validation objectives addressed by this exercise are

- EX01-OBJ-0401-ERP-010. Establish mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.
- EX01-OBJ-0401-ERP-030. Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.
- EX01-OBJ-0401-ERP-040. Test decentralised vs centralised SOL401 by solving multiple experiment instances and comparing KPIs

The platform used for this validation exercise is SOL401 disruption manager.

The adjusted schedules realised in the experiments consider many constraints to ensure that results are realistic and well posed. The constraints that are considered in SOL401 are

- Operational constraints, such as:
 - Running times. Times between stations have to be maintained in order to be realistic.
 - Dwell times. Different dwell times according to station size are considered.
 - Headway times. This ensures minimum separation between trains or planes.
 - Infrastructure capacity. Maximum airport/airspace/railway corridor capacity is considered in the model.
 - Early departure prevention. The original timetable needs to be respected. Hence, no departures ahead of the schedule are allowed (if a schedule is available).

- Passenger assignment constraints
 - Minimal connection times. These minimal connection times ensure that transfer can be made (and passengers do not lose their connections).
 - Seat capacity. This constraint ensures that trains and planes are not overbooked.

A.1.2 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 exercises	Exercise validation objective	Exercise success criteria
EX01-OBJ-0401-ERP-010	EX01-CRT-0401-ERP-010.1	Fully covered	Establish mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.	Produce a detailed description of decision/mechanisms/actions for multimodal disruption management
EX01-OBJ-0401-ERP-030	EX01-CRT-0401-ERP-030.1	Fully covered	Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.	Generate feasible schedules for both decentralised and centralised SOL401.

EX01-OBJ-0401-ERP-040	EX01-CRT-0401-ERP-040.1	Fully covered	Test decentralised vs centralised SOL401 by solving multiple experiment instances and comparing KPIs	Calculate the KPIs/PIs for centralised and decentralised multimodal adjusted schedules for at least three different demand scenarios and compare them to the KPI/PI values of schedules without using SOL401, demonstrating its ability to enhance the overall passenger-centric performance by at least 10%.
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Table A.1: validation exercise success criteria. In *italic* validation criteria that have been modified from the original ERP.

A.1.3 Summary of validation exercise #01 validation scenarios

The scenarios considered in MultiModX are a combination of geographical scope, policy packages, network definition and the application (or not) of SOL401. The disruption type is selected based on the inputs from the Validation exercise #2 and consists of a capacity reduction at the airport of Madrid (LEMD). In particular, the LEMD capacity is reduced to 10 flights/hour, representing a significant disruption at the airport (the nominal capacity is around 35-40 flights/hour).

For the analysis of SOL401 we selected a subset of the scenarios, presented in table 4 of the SOL401 ERR.

Scenario	Comment
cs11.pp00.nd10.dm0000	This is a baseline scenario for this validation exercise with the nominal demand and without policies.
cs11.pp00.nd10.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management. It corresponds to a Solution Scenario.
cs11.pp00.nd10.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management. It corresponds to a Solution Scenario.
cs11.pp20.nd20.dm0000	This is a baseline scenario for this validation exercise with the reduced demand and with policies.
cs11.pp20.nd20.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management. It corresponds to a Solution Scenario.
cs11.pp20.nd20.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management. It corresponds to a Solution Scenario.

cs11.pp00.nd30.dm0000	This is a baseline scenario for this validation exercise with homogeneous demand and without policies.
cs11.pp00.nd30.dm100	This scenario corresponds to the application of SOL401 with decentralized disruption management. It corresponds to a Solution Scenario.
cs11.pp00.nd30.dm200	This scenario corresponds to the application of SOL401 with centralized disruption management. It corresponds to a Solution Scenario.

Table A.2: Selected scenarios for the evaluation of SOL401

A.1.4 Summary of validation exercise #01 validation assumptions

No extra assumptions are necessary for this exercise.

A.2 Deviation from the planned activities

No deviation from the planned activities.

A.3 Validation exercise #01 results

A.3.1 Summary 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
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OBJ-0401-ERP-010	Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.	EX01-CRT-0401-ERP-010.1	Produce a detailed description of decision/mechanisms/actions for multimodal disruption management	N/A	Detailed description was produced.	OK
OBJ-0401-ERP-030	Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.	EX01-CRT-0401-ERP-030.1	Generate feasible schedules for both decentralised and centralised SOL401.	N/A	Feasible schedules were provided for every SOL401 instance.	OK

OBJ-0401-ERP-040	Generate air and rail coordinated schedules that improve overall network connectivity .	EX01-CRT-0401-ERP-040.1	Calculate the KPIs/PIs for centralised and decentralised multimodal adjusted schedules for at least three different demand scenarios and compare them to the KPI/PI values of schedules without using SOL401, demonstrating its ability to enhance the overall passenger-centric performance by at least 10%	N/A	For every experimental instance, KPIs/PIs were computed and compared. Decentralized and centralized disruption management showed clear improvements for passenger-centric performance. The centralized disruption management showed performance improvements up to and even beyond 10%	OK
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Table A.3: validation exercise #01 results

A.3.2 Analysis of validation exercise #01 results per validation objective

A.3.2.1. OBJ-0401-ERP-010 Results

Objective: Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.

Validation: Produce a detailed description of decision/mechanisms/actions for multimodal disruption management

A detailed description of the disruption management decisions (i.e. rerouting, retiming, diverting, cancelling and scheduling replacement services) and the corresponding mechanisms (i.e. disruption measure pricing, disruption measure computation, passenger path pricing, passenger path

computation, disruption management and passenger assignment) has been derived during the project (see MMX SOL-401 FRD, Sec. 3). The status of this validation objective is OK.

A.3.2.2. OBJ-0401-ERP-030 Results

Objective: Compute an adjusted multimodal schedule including adjusted flight schedules, rail timetable and passengers' itineraries.

Validation: Generate feasible schedules for both decentralised and centralised SOL401.

Several experiments have been conducted to show the performance of SOL401. There, the disruption manager provided the tactical adjusted schedules for all air and rail services in the network. Fig. XX1 provides an adjusted timetable for air services for scenario cs11.pp00.nd10.dm100.

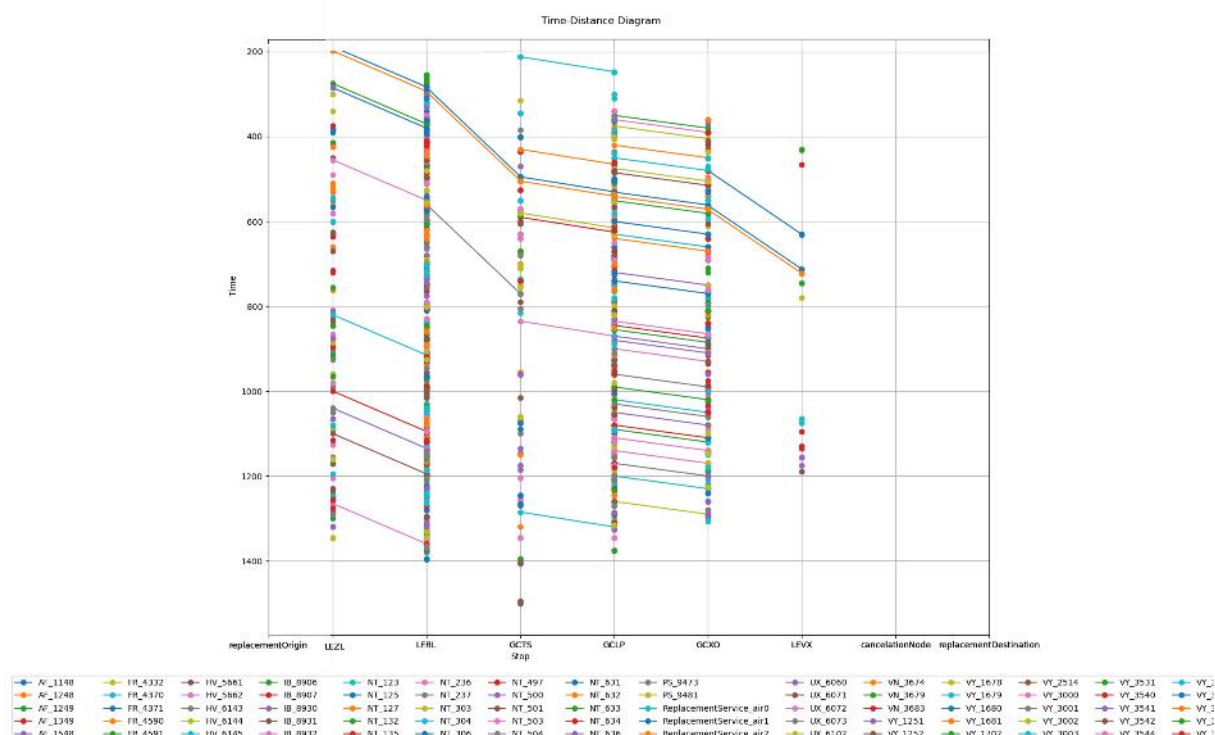


Figure A.2: Adjusted timetable for a feasible flight plan along the route of two replacement flight services from LEZL to LEVX

Fig. A.2 shows an illustrative timetable for multiple airports in a time-distance diagram. Arrivals and Departures at those airports are marked by circles, scheduled connections are indicated by the time-distance lines. It can be seen that minimal separation times between the services are respected and no conflicting connections exist. Further, the rotations of two successively schedules replacement services become visible, which sequentially serve the selected airports.

All provided schedules have been analysed for their feasibility. Every schedule was proven to be feasible. Thus, the status of this validation objective is OK.

A.3.2.3. OBJ-0401-ERP-040 Results

Objective: Generate air and rail coordinated schedules that improve overall network connectivity.

Validation: Calculate the KPIs/PIs for centralised and decentralised multimodal adjusted schedules for at least three different demand scenarios and compare them to the KPI/PI values of schedules without using SOL401, demonstrating its ability to enhance the overall passenger-centric performance by at least 10%.

KPA	PI	Variants	analysed?	comments	results
Efficiency	arrival delay (services)	sum	✓		improved
		avg. p. flight	✓		improved
	total journey time (PAX)	sum	✓	enhance the overall passenger-centric performance by at least 10% for EX01-CRT-0401-ERP-040.1	improved
		avg. p. PAX	✓	enhance the overall passenger-centric performance by at least 10% for EX01-CRT-0401-ERP-040.1	improved
	stranded PAX	sum	✓	enhance the overall passenger-centric performance by at least 10% for EX01-CRT-0401-ERP-040.1	improved
DES performance framework	departure delay	sum	✓		improved
		avg. p. flight	✓		improved

	no. of cancellations	total	✓		constant
	no. of diversions	total	✓		increased
Resilience	replanned resilience	avg. route dissimilarity	✓		increased
		no. of additional replacement departures (over all stations and replacement services, i.e. each replacement service may visit multiple airports/stations)	✓		improved
	replanned passengers	sum	✓	enhance the overall passenger-centric performance by at least 10% for EX01-CRT-0401-ERP-040.1	increased

Table A.4: overview of the KPI/PIs used in SOL401

A.4 Experimental Settings

- number of OD-pairs: 1380
- total passenger demand: 300.807 PAX
- number of flights: 1703
- number of trains: 1256
- disruption setup: capacity reduction in Madrid (LEMD) to at most 10 flights/hour
- decentralized disruption management within three randomly assigned alliances

disruption management sub-category	number of alliances	no. of maximal possible replacement services
dm00	3	0

dm01	3	0
dm02	1	8 (3 flight, 5 train)

Table A.5: Summary of the SOL401 parameters

A.5 Results per KPA and PI

This section introduces the results of the experiments. It compares the PI for every KPA for experiments w.r.t. the two levels of centralization (i.e. centralized and decentralized as defined in OSED of SOL401) and a benchmark experiment. The results are calculated for three different demand levels: (1) nominal, (2) reduced and (3) homogeneous demand (i.e. 295 PAX per OD pair, same total demand).

A.5.1 Efficiency

A.5.1.1. Arrival delay (services)

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	sum of arrival delays (services)	avg. arrival delay (services)
cs11.pp00.nd10.dm000	166.337 min	7.85 min
cs11.pp00.nd10.dm100	107.581 min	5.08 min
cs11.pp00.nd10.dm200	77.692 min	3.67 min

Table A.6: Arrival delay for scenarios cs11.pp00.nd10

The results reveal a significant reduction in arrival delays as a result of implementing disruption management (DM), with the extent of improvement strongly influenced by the level of coordination. Specifically, decentralized DM leads to a 36% decrease in arrival delays, while centralized DM achieves an even greater reduction of 54%.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	sum of arrival delays (services)	avg. arrival delay (services)
cs11.pp20.nd20.dm000	150.834 min	7.14 min
cs11.pp20.nd20.dm100	81.596 min	3.86 min
cs11.pp20.nd20.dm200	88.711 min	4.20 min

Table A.7: Arrival delay for scenarios cs11.pp20.nd20

Arrival delays decrease notably even when the number of operating services remains constant and passenger volumes increase. Under these conditions, decentralized DM achieves a 46% reduction in delays, while centralized DM results in a 42% decrease. This indicates that both forms of DM are effective in mitigating delays despite rising passenger loads, with decentralized coordination showing a slight advantage in this scenario, at the cost of lower amounts of transported PAX.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	sum of arrival delays (services)	avg. arrival delay (services)
cs11.pp00.nd30.dm000	99.894	4.71
cs11.pp00.nd30.dm100	152.893 min	7.22 min
cs11.pp00.nd30.dm200	98.558 min	4.65 min

Table A.8: Arrival delay for scenarios cs11.pp00.nd30

The arrival delays increase clearly by the introduced decentralised DM. However, for this allows to reduce the amount of stranded PAX and limiting the operational effort. The centralised DM makes use of the more flexible PAX routing and hence allows significantly more cancellations, which reduce the delay substantially.

A.5.1.2. Total journey time (PAX)

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	sum of total journey time	avg. total journey time
cs11.pp00.nd10.dm000	20.003.108 min	95.17 min
cs11.pp00.nd10.dm100	20.075.230 min	93.11 min
cs11.pp00.nd10.dm200	17.361.289 min	76.91 min

Table A.9: Total journey time for scenarios cs11.pp00.nd10

The evaluation of cumulative travel times reveals nuanced effects of the different DM strategies. In the case of the decentralized DM approach, the total travel time increases slightly. This is primarily attributed to the higher number of passengers being accommodated (see section 3.1.3), which, in turn, leads to a minor reduction in the average journey time by approximately 2.2%. This suggests that while more passengers are served, the system maintains a relatively stable efficiency in terms of individual travel durations.

In contrast, the centralized DM solution demonstrates a significant improvement in overall travel efficiency. Despite an increase in the number of transported passengers, the cumulative travel time decreases by 13.2%. This improvement is largely due to enhanced coordination between air and rail services, which enables more effective rerouting and scheduling. Consequently, the average journey time is reduced substantially by 19.2%, highlighting the effectiveness of centralized control in mitigating the impact of disruptions.

Figure A.3 illustrates the travel time increases per passenger across the different experimental scenarios, providing a detailed view of how each strategy affects specific travel routes.

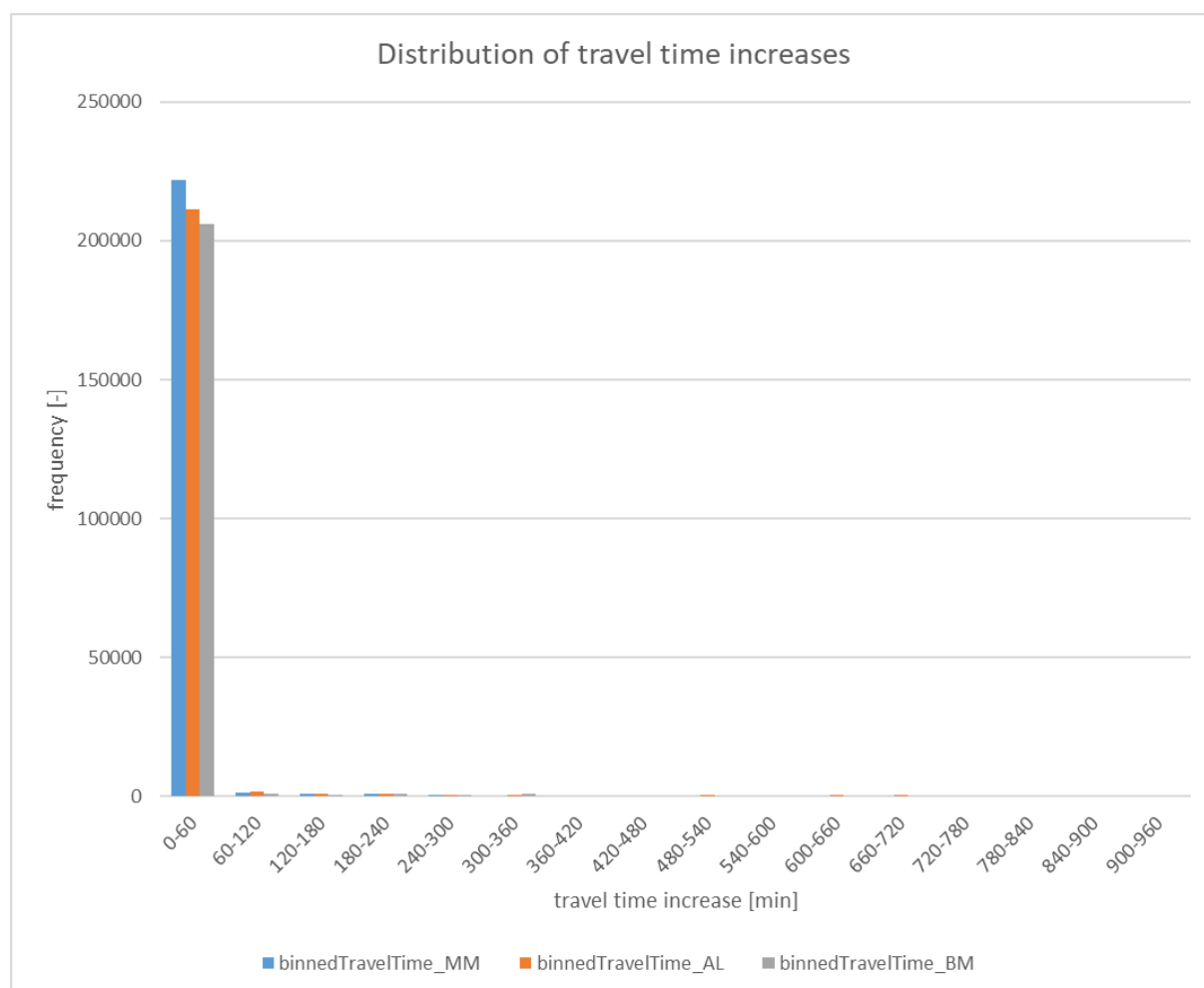


Figure A.3: Travel time increase distribution over all three experiments without policies (MM: centralised DM - dm200, AL: decentralised DM - dm100, BM: benchmark dm00)

The analysis reveals that the majority of passengers experience only minor increases in travel time, typically up to 60 minutes. Specifically, centralised DM (dm200) shows better performance than decentralised (dm100) and benchmark (dm00) (no SOL401). This trend is consistent across all evaluated scenarios, indicating that most disruptions are managed with relatively limited impact on individual travel durations.

For passengers experiencing more substantial travel time increases, the distribution patterns appear similar across all three experimental setups. However, the DM solutions—both centralized and decentralized—exhibit slightly higher frequencies in these higher travel time brackets compared to the benchmark scenario.

The benchmark solution consistently shows lower absolute numbers of affected passengers, which reflects its overall reduced capability to transport passengers during disruptions. This limitation underscores the trade-off between minimizing travel time increases and maximizing the number of passengers served by providing travel alternatives.

Notably, the decentralized DM solution introduces additional travel time increases of up to 720 minutes, although such extreme cases occur at a generally low frequency. This suggests that while the decentralized approach may lead to longer detours for some individuals, it also provides greater flexibility in accommodating disrupted passengers.

Overall, the results indicate that disruption management strategies—particularly those involving centralized decision-making—enable a broader range of travel alternatives. These alternatives allow more passengers to complete their journeys, albeit sometimes at the cost of extended travel times.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	sum of total journey time	avg. total journey time
cs11.pp20.nd20.dm000	22.197.903 min	106.35 min
cs11.pp20.nd20.dm100	25.574.696 min	123.83 min
cs11.pp20.nd20.dm200	36.745.804 min	164.89 min

Table A.10: Total journey time for scenario cs11.pp20.nd20

Travel times increase significantly under DM due to rising passenger volumes transported and due to the long distances of international travel. Specifically, decentralized DM leads to a 15% increase, while centralized DM results in a more pronounced 66% rise. Additionally, the average journey time per passenger increases as DM tends to preserve long-distance itineraries, contributing to the persistence of extended travel patterns in the European context.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	sum of total journey time	avg. total journey time
cs11.pp00.nd30.dm000	22.539.151 min	132.01
cs11.pp00.nd30.dm100	81.419.478 min	474.89 min

cs11.pp00.nd30.dm200	85.993.646 min	495.70 min
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Table A.11: Total journey time for scenario cs11.pp00.nd30

Due to a mismatch between demand and supply, a significant number of changes in the disrupted network is required which led to more transported passengers. Travel times increase significantly under DM, primarily due to rising passenger numbers and the growing use of detours enabled by DM strategies. This also leads to a rise in average journey time per passenger, as more detours are introduced to maintain service continuity. Also, DM allows to reconnect the vulnerable international connections, which induce high journey times into this PI. These findings suggest that longer travel times are a trade-off for reducing the number of stranded (international) passengers, highlighting a key tension between efficiency and accessibility in DM implementation. They further show that, for the centralised DM in particular, the adaptability of the network (resulting from DM) to changed demand structures can leverage significant shares of (potentially previously unserved) demands.

A.5.1.3. Stranded passengers

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	no. of stranded PAX
cs11.pp00.nd10.dm000	90.624
cs11.pp00.nd10.dm100	85.202
cs11.pp00.nd10.dm200	75.080

Table A.12: Stranded passengers for scenarios cs11.pp00.nd10

The number of stranded passengers decreases by 17.2% from 90.624 to 75.080 out of 300.807 passengers with travel intention. Thus, the number of transported passengers increases accordingly.

Pax Flow Difference Plot "defaultClass"

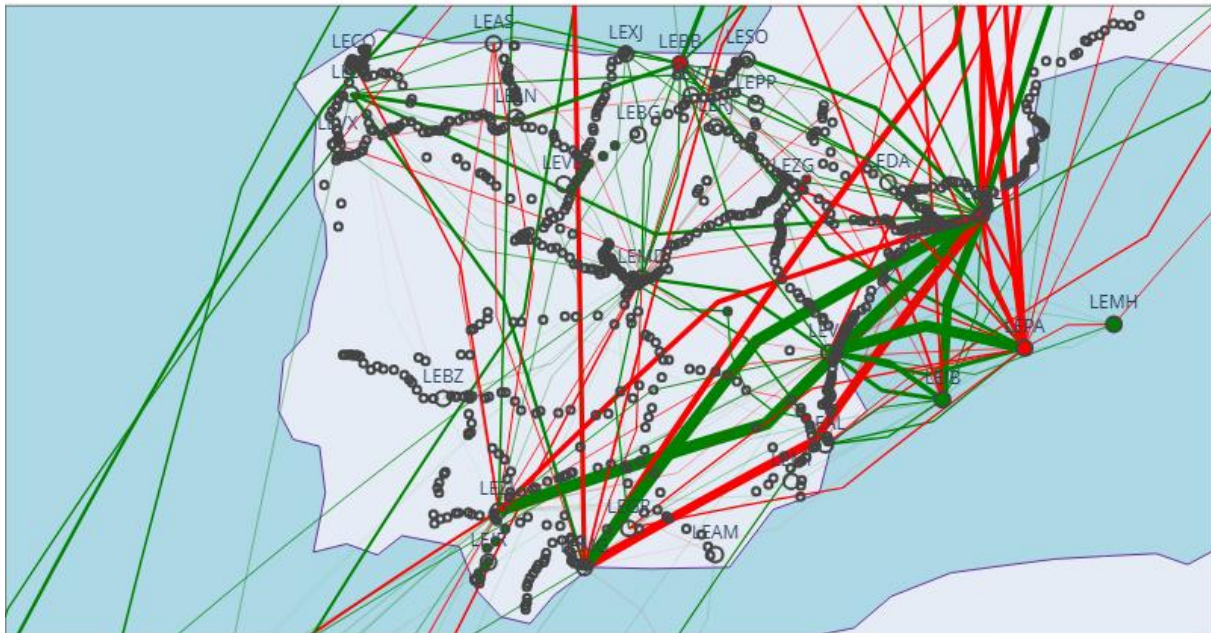


Figure A.4: PAX-flow comparison of decentralized DM solution with benchmark solution (green: increasing PAX-numbers, red: decreasing PAX-numbers)

Fig. A.4 shows passenger flow comparison of decentralized DM solution with benchmark solution. The analysis reveals a mixed impact of the decentralized DM across the network. While certain regions benefit from improved connectivity and increased passenger throughput, other areas—particularly those involving international flights—experience flow degradations. These degradations are primarily attributed to flight diversions and the resulting need for additional transfers, which disrupt direct international connections.

Despite these regional disparities, the overall system performance remains comparable to the benchmark scenario, indicating that the implemented strategies maintain a balanced trade-off between local improvements and broader network challenges.

A notable trend is the increase in domestic passenger flows, especially on routes from Barcelona to Seville and Málaga.

Conversely, international flows show a decline, caused by flight diversions and the correspondingly induced transfers.

A detailed map of the Iberian Peninsula (Spain and Portugal) overlaid with a complex network of green and red lines. The lines represent connections between numerous nodes, many of which are labeled with three-letter codes (e.g., LECO, LEAS, LEXJ, LEBB, LESO, LEPN, LEBG, LEPF, LEVZ, LEVA, LEZG, LEDP, LEMH). The network is particularly dense in the central and eastern parts of the peninsula, with many lines radiating from a central hub area. The background shows the geographical outline of the peninsula and surrounding waters.

Fig. A.5 shows passenger flow comparison of centralized DM solution with benchmark solution. The centralized DM strategy demonstrates a clear advantage over the benchmark solution in its ability to maintain and even enhance passenger service levels during disruptions. This is particularly evident in the increased passenger flows observed on key domestic corridors.

However, this improvement comes at the cost of reduced direct international connectivity. The need to reroute or divert international flights results in a greater reliance on transfer connections, thereby decreasing the volume of direct international flows. This trade-off highlights the centralized system's prioritization of overall passenger throughput and network resilience, even if it requires more complex travel paths for certain segments.

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Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	no. of stranded PAX
cs11.pp20.nd20.dm000	92.077
cs11.pp20.nd20.dm100	94.271
cs11.pp20.nd20.dm200	77.956

Table A.13: Stranded passengers for scenarios cs11.pp20.nd20

The number of stranded passengers decreases by up to 19% with the implementation of centralized DM, indicating a clear benefit in maintaining passenger continuity. However, the effectiveness of DM varies with its structure: decentralized DM offers rather stable, slightly degrading results w.r.t. stranded passengers. Consequently, this allowed to significantly reduce delay of the remaining travellers and thus reveals the trade off between different objectives of delay and number of transported PAX. Furthermore, this is to some extent resulting from the increasing number of diversions, which are needed to accommodate the originally removed short flights (in the particular scenario nd20) and to reduce operational costs (i.e. service trip times). This overall came at the expense of the additionally stranded passengers (2%), which mostly belong to small OD pairs travelling long distances (e.g. international travellers).

Differently, centralized DM combines operational efficiency and passenger benefit, given the higher level of flexibility to replan passengers in the network, and thus, it offers a 19% lower number of stranded PAX at 8% lower operational expenses comparing the benchmark solution.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	no. of stranded PAX
cs11.pp00.nd30.dm000	130.067
cs11.pp00.nd30.dm100	129.360
cs11.pp00.nd30.dm200	127.329

Table A.14: Stranded passengers for scenarios cs11.pp00.nd30

When comparing benchmark operations with decentralized DM, there is no significant difference in the number of stranded passengers, however a continuous decrease emerges. Thereby, centralized DM leads to reductions of up to 2%, demonstrating its greater effectiveness in minimizing passenger disruptions.

A.5.1.4. Departure delay

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	sum of departure delays (services)	avg. departure delay (services)
cs11.pp00.nd10.dm000	192.875 min	9.10 min
cs11.pp00.nd10.dm100	129.335 min	6.10 min
cs11.pp00.nd10.dm200	95.631 min	4.51 min

Table A.15: Departure delay for scenarios cs11.pp00.nd10

The delay decreases with constant number of operating nominal services.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	sum of departure delays (services)	avg. departure delay (services)
cs11.pp20.nd20.dm000	177.853 min	8.41 min
cs11.pp20.nd20.dm100	102.042 min	4.83 min
cs11.pp20.nd20.dm200	113.236 min	5.36 min

Table A.16: Departure delay for scenarios cs11.pp20.nd20

The delay decreases by 43% for decentralized DM and 37% for centralized DM at a constant service number but with increasing numbers of passengers.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	sum of departure delays (services)	avg. departure delay (services)
cs11.pp20.nd30.dm000	130.044 min	6.14 min
cs11.pp20.nd30.dm100	182.796 min	8.63 min
cs11.pp20.nd30.dm200	129.945 min	6.13 min

Table A.17: Departure delay for scenarios cs11.pp00.nd30

Departure delays increase under decentralized DM, primarily due to the need to accommodate competing routes for different airline alliances. In contrast, centralized DM demonstrates relatively better performance by reducing such redundancies (i.e. by cancelling more services) and decreasing the delay up to the level of the benchmark solution.

A.5.1.5. No. of cancellations

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	no. of cancellations
cs11.pp00.nd10.dm000	391
cs11.pp00.nd10.dm100	391
cs11.pp00.nd10.dm200	391

Table A.18: No. of cancellations for scenarios cs11.pp00.nd10

The number of cancellations remains stable over all scenarios and shows, that cancellations are largely dominated by the disruption, rather than the DM strategy. It furthermore indicates that cancellation is the least attractive DM measure and only applied if avoidance is not possible.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	no. of cancellations
cs11.pp20.nd20.dm000	315
cs11.pp20.nd20.dm100	315
cs11.pp20.nd20.dm200	315

Table A.19: No. of cancellations for scenarios cs11.pp20.nd20

For the assessed scenarios the number of cancellation remains stable, but is clearly lower than REF1 due to the lower nominal number of flights (due to the flight-ban policy). However, the same reasoning as for the results of scenarios cs11.pp20.nd20 applies.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	no. of cancellations
cs11.pp00.nd30.dm000	315

cs11.pp00.nd30.dm100	314
cs11.pp00.nd30.dm200	390

Table A.20: No. of cancellations for scenarios cs11.pp00.nd30

The results are rather stable for those scenarios and the decentralised DM. However, the number of cancellations has slightly decreased for the scenarios with decentralised DM. Due to the possibility of diversion and the significantly different demand structure, those measures are applied to still provide PAX benefits, which also manifests in the correspondingly reduced numbers of stranded PAX. However, due to the increasing PAX rerouting capabilities for the centralised DM, the number of cancellations increases significantly (up to the level of cs11.pp0.nd10) which leads to reducing the delays for the services substantially whilst still serving more PAX.

A.5.1.6. No. of diversions

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	no. of diversions
cs11.pp00.nd10.dm000	0
cs11.pp00.nd10.dm100	6
cs11.pp00.nd10.dm200	3

Table A.21: No. of diversions for scenarios cs11.pp00.nd10

Under the decentralized DM, the number of diversions increases. This is aimed at minimizing the impact on passengers (PAX) by enabling quicker, more localized responses to disruptions.

However, for centralized DM, the number of diversions decreases due to the greater flexibility in passenger routing and the higher availability of alternative connections. This improved adaptability leads to more efficient disruption handling, i.e. with lower operational efforts, and a better overall passenger experience. (For the further impact of diversions on the network, see Section 4.2.1.).

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	no. of diversions
cs11.pp20.nd20.dm000	0
cs11.pp20.nd20.dm100	1

cs11.pp20.nd20.dm200	1
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Table A.22: No. of diversions for scenarios cs11.pp20.nd20

The scenarios analyzed show a low number of diversions, primarily due to a reduced number of flights operating under these scenarios (flight-ban). This naturally limits the scale of potential diversions. Additionally, a significant portion of passengers had already shifted to rail transport, further decreasing the number of air passengers affected by disruptions. As a result, both the volume of flights and the number of impacted passengers were lower, contributing to the overall reduction in diversions.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	no. of diversions
cs11.pp00.nd30.dm000	0
cs11.pp00.nd30.dm100	3
cs11.pp00.nd30.dm200	2

Table A.23: No. of diversions for scenarios cs11.pp00.nd30

In this scenario, a slightly higher number of diversions was observed. This outcome is primarily attributed to a significantly different demand structure, which led to notable changes in mode choice and routing behaviour. A large number of passengers required rebooking or rerouting, resulting in a higher volume of replanned passenger journeys and, consequently, a modest need for diversions.

A.5.2 Flexibility

A.5.2.1. Replanned resilience

To measure the replanned resilience, we use the indicator of avg. route dissimilarity, which measures the similarity among the nominal routes and the replanned ones of all services w.r.t. operation time. Since the similarity is a share of disjoint route elements of two routes on their overall route elements, it can take values from 1 (completely different) to 0 (identical). Values in between give the share of dissimilarity in percent.

$$d_{\{r_1, r_0\}} = \frac{|E_{r_1} \setminus E_{r_0}|}{|E_{r_1} \cup E_{r_0}|}$$

Additionally, replacement departures represent the total across all stations and replacement services, as each replacement air or rail service may serve multiple airports or stations.

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	avg. route dissimilarity	no. of additional replacement departures
cs11.pp00.nd10.dm000	0,1322	0
cs11.pp00.nd10.dm100	0,1346	0
cs11.pp00.nd10.dm200	0,1329	10

Table A.24: Replanned resilience for scenarios cs11.pp00.nd10

The benchmark solution shows a dissimilarity of ca. 13,22% due to the cancellations of 391 services and the resulting unavailable services. The dissimilarity increases for the DM solutions, since the increasing number of diversions results in new, additional travel opportunities, which result in a more different service network comparing the nominal case. Since the number of diversions decreases for the centralized DM, the dissimilarity value decreases as well. However, the centralized DM solution provides 10 additional departures, hence providing a less network changes (i.e. higher similarity) with increasing travel options (i.e. departures). Finally, despite their major disruptions, the adjusted network seems to be rather similar, providing overall low values.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	avg. route dissimilarity	no. of additional replacement departures
cs11.pp20.nd20.dm000	0,1102	0
cs11.pp20.nd20.dm100	0,1106	0
cs11.pp20.nd20.dm200	0,1106	21

Table A.25: Replanned resilience for scenarios cs11.pp20.nd20

In the decentralized DM scenario, a slight increase in route dissimilarity was observed. This is primarily due to the higher number of diversions, which led to more varied routes. In contrast, the centralized DM scenario showed a comparable level of route dissimilarity, but with a higher number of replacement departures. Hence, the replacement services might compensate for a higher dissimilarity, resulting in similar levels for centralised and decentralised DM.

Table A.25 summarizes the number of additional flight legs over the two DM solutions which are as a result of multistops allowed for diverted flights and replacement flights (Note: diversions are discussed in Section 4.1.6). It clearly shows the significantly higher efforts of the decentralized DM to cope with

disruptions whilst still serving lower PAX numbers. The numbers of additional legs are gradually higher than the number of diversions and replacement services.

scenario	no. of additional flight legs
cs11.pp20.nd20.dm100	70
cs11.pp20.nd20.dm200	38

Table A.26: Numbers of additional flight legs for scenarios cs11.pp20.nd20

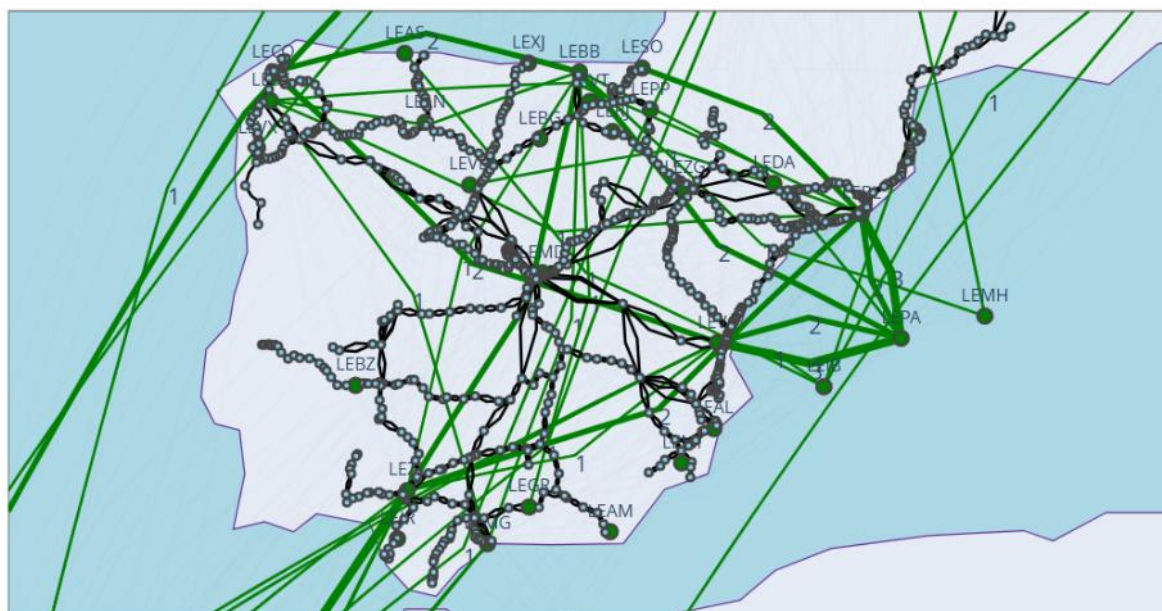


Figure A.6: Service comparison between benchmark and decentralized DM (green: increasing number of flights, red: decreasing number of flights, numbers indication increasing/decreasing number of services)

Figure A.6 illustrates a substantial increase in the number of additional flight legs compared to the benchmark scenario (in total 70 additional flight legs from diversions). This surge in flight activity reflects the operational decisions made under the decentralized DM strategy, which emphasizes local autonomy and flexible rerouting.

A significant portion of these additional flights are diversions, with major redirections observed toward key domestic hubs such as Barcelona and Valencia, as well as toward airports in the northern regions of the Iberian Peninsula. These locations appear to serve as strategic alternatives for absorbing displaced air traffic during disruptions.

Moreover, the data also indicate a number of diversions extending beyond the peninsula, suggesting that the decentralized strategy leverages a broader spatial scope to maintain service continuity. While this approach increases operational complexity, it also enhances the system's adaptability by utilizing

a wider range of available infrastructure, which is only limited due to the decentralized decision making.

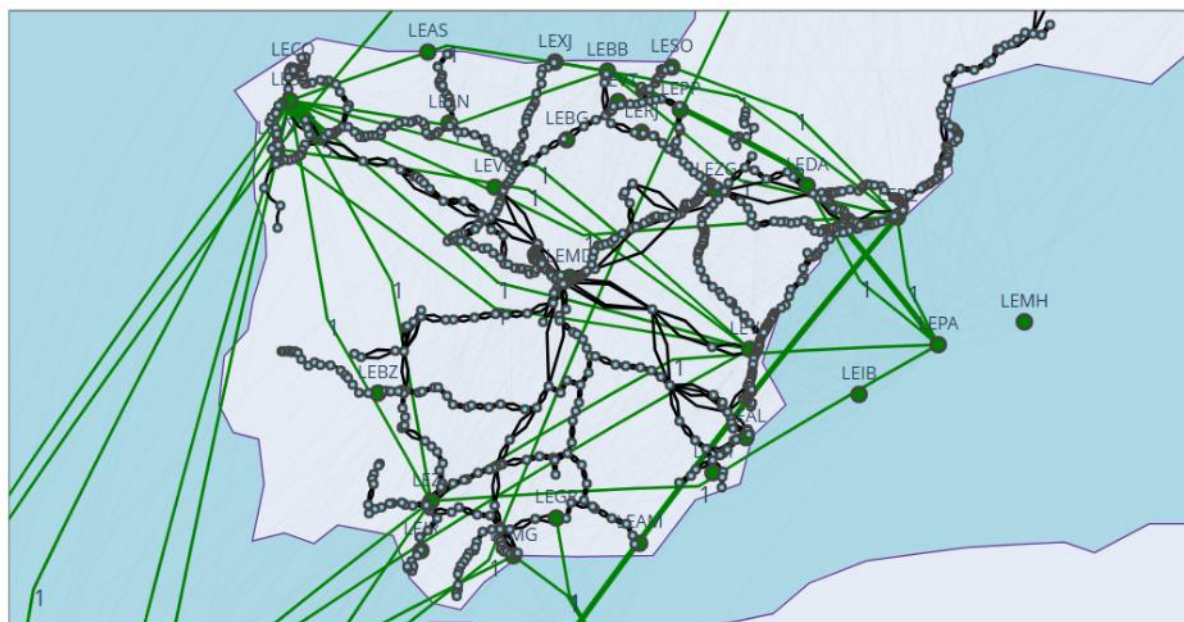


Figure A.7: Service comparison between benchmark and centralized DM (green: increasing number of flights, red: decreasing number of flights, numbers indication increasing/decreasing number of services)

Figure A.7 clearly highlights the presence of additional services resulting from flight diversions and the implementation of replacement connections, totally increasing the number of additional flight legs by 38. These services are distributed relatively homogeneously across the network, indicating a broad and balanced use of available infrastructure to mitigate disruption impacts – due to the centralized manner of DM.

A slight concentration of diverted flights is observed toward Santiago, suggesting its strategic role as a key destination or transit point during disruption scenarios. This pattern underscores the airport's capacity and geographic suitability for absorbing rerouted traffic, particularly due to the available railway capacities, which allow to connect Coruna without requiring additional services.

In addition, several diversions extend beyond the borders of the Iberian Peninsula, reflecting the decentralized disruption management strategy's flexibility in utilizing international alternatives to maintain service continuity.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	avg. route dissimilarity	no. of additional replacement departures
cs11.pp00.nd30.dm000	0,1104	0

cs11.pp00.nd30.dm100	0,1111	0
cs11.pp00.nd30.dm200	0,1323	64

Table A.27: Replanned resilience for scenarios cs11.pp00.nd30

A similar overall picture emerges for those scenarios. However, different DM decisions lead to different dissimilarity values for centralised and decentralised DM and different numbers of departures for the centralised DM. Furthermore, the centralised DM provides a significantly higher dissimilarity due to the increasing number of cancellations. In turn, it also provides a high number of additional departures as it uses all options of scheduling replacement services.

A.5.2.2. Replanned passengers

Results for scenarios cs11.pp00.nd10 (Without policies (REF1) and nominal demand)

scenario	no. of replanned PAX
cs11.pp00.nd10.dm000	4230
cs11.pp00.nd10.dm100	4549
cs11.pp00.nd10.dm200	4652

Table A.28: Replanned passengers for scenarios cs11.pp00.nd10

In the centralized DM scenario, the number of replanned passengers increased by 10%. This rise highlights the growing flexibility of passenger travel behaviour, enabled by a broader range of available travel options. For decentralised DM, the number increases by 8% as well, showing the potential of this approach as well. Both increases suggest that DM supports more dynamic rebooking and routing, allowing passengers to adapt more easily to disruptions.

Results for scenarios cs11.pp20.nd20 (With policies (REF3 - multimodality enforced) and reduced demand)

scenario	no. of replanned PAX
cs11.pp20.nd20.dm000	4926
cs11.pp20.nd20.dm100	4947
cs11.pp20.nd20.dm200	5948

Table A.29: Replanned passengers for scenarios cs11.pp20.nd20

In the decentralized DM scenario, the number of replanned passengers increases, driven by the greater diversity of available travel options. This reflects the system's ability to offer more flexible and localized responses to disruptions due to the DM. The centralized DM scenario shows an even higher increase in replanned passengers, supported by a broader range of coordinated alternatives. This highlights the enhanced capacity of centralized coordination to manage disruptions through more comprehensive rebooking and rerouting strategies.

Results for scenarios cs11.pp00.nd30 (Without policies (REF1) and homogeneous demand)

scenario	no. of replanned PAX
cs11.pp00.nd30.dm000	11.469
cs11.pp00.nd30.dm100	11.940
cs11.pp00.nd30.dm200	23.718

Table A.30: Replanned passengers for scenarios cs11.pp00.nd30

The number of replanned passengers increases with the implementation of DM, reflecting greater system adaptability in response to disruptions, which was required in order to have less stranded passengers. This effect is especially pronounced under centralized DM, which results in a significantly higher number of replanned passengers. These findings suggest that while centralized coordination enhances flexibility and continuity, it also introduces more complex reallocation processes within the network.

Discussion

Since all the indicators have been measured and compared, the comparison revealed improvements beyond the required 10%. Thus, the validation objective status is OK. Additionally, we present here a brief analysis of the results.

The experiments examined the impact of DM and its coordination levels on various performance indicators across different demand scenarios—nominal, reduced, and homogeneous. Here, the latter two have been significantly challenging due to limited services, and imbalanced supply-demand relation, requiring significant managing interventions of SOL401.

Delays were generally reduced under nominal demand through increased coordination, highlighting the effectiveness of DM in optimizing operations. However, under reduced demand, while DM initially reduced delay levels, the resulting centralization led to a slight increase in delays due to higher passenger volumes. In the homogeneous demand scenario, DM in some scenarios increased delays, primarily driven by the rise in transported passengers and the required waiting for transfers.

Travel times followed a similar pattern: they decreased under nominal demand with centralised DM, but increased in both reduced and homogeneous demand scenarios due to elevated passenger volumes.

Stranded passengers consistently decreased across all demand levels with the implementation of DM and higher coordination, indicating improved passenger handling and system responsiveness.

Cancellations remained largely unaffected by DM or demand variations, suggesting a stable baseline which rather relates to the disruption scenarios.

Diversions increased with DM, particularly under nominal demand with decentralized strategies, likely due to stricter transfer policies, i.e. transfers possible only within the given alliances. In contrast, the level of centralization had negligible effects on diversions under reduced and homogeneous demand.

Resilience, measured through service dissimilarity, declined with DM, especially in decentralized systems, due to the lack of compensatory replacement services.

Finally, the number of **replanned passengers** rose with both the implementation and centralization of DM, reflecting increased system adaptability at the cost of operational complexity.

Overall, while DM can enhance efficiency and reduce disruption impacts under certain conditions, their effectiveness is highly dependent on the demand structure and the degree of centralization. Centralized DM outperformed decentralized DM for almost every scenario and demand level, illustrating the significance of centralization when dealing with disruptions.

A.5.3 Unexpected behaviours/results

There were no problems while running validation exercise #1 but there were some unexpected results:

- The results showed an increase in the number of stranded passengers for one of the challenging scenarios, reflecting the general trade-off in DM. The DM system is designed to balance operational efforts with passenger benefits, aiming to reduce overall operational costs—such as those associated with diversions—while maintaining service continuity. In some cases, this balance results in lower operational expenses at the cost of leaving some more passengers stranded. This outcome underscores the importance of carefully setting key parameters within the DM model to reflect real-world priorities. It also illustrates that the developed approach is capable to capture the inherent trade-off between airline costs (e.g. operations, compensation) and passenger outcomes (e.g. delays, itinerary reliability).
- Some results – particularly for the homogeneous demand scenarios – indicate a significant increase in travel times, which primarily driven by a higher number of replanned passengers and a reduction in stranded passengers. This trend is further supported by an overall rise in delays, reflecting the system's effort to maintain connectivity through rebooking rather than making cancellations. These changes also point to the induced new travel demand, enabled by adapted multimodal services that offer connections previously unavailable. While this can enhance network reach, it also suggests that the nominal network configuration may not be optimally aligned with actual demand patterns (this has been exemplified by our latter two scenarios). This misalignment is likely influenced by the homogeneous demand structure and the centralized nature of the Spanish transport network, which may limit flexibility and responsiveness in disruption scenarios.

A.5.4 Confidence in results of validation exercise #01

A.5.4.1. Level of significance/limitations of validation exercise results

The current results are based on the evaluation of a single disruption case study. At the same time, the scenarios (particularly respecting demand and supply) were defined to provide more diverse as well as more challenging environment to SOL401. (\footnote: Assessing on the same/similar demand-supply patterns is expected to yield similar results.) This approach was chosen to ensure comparability of results, as it allowed for a controlled environment with a limited and consistent set of input parameters. While this may influence the specific quantitative outcomes, it is unlikely to alter the fundamental insights into the behaviour and effectiveness of the different DM approaches. To further strengthen the robustness and generalizability of the findings, the next priority will be to assess additional disruption scenarios. This will help validate the observed resulting patterns and support more comprehensive strategic recommendations.

The results rely on estimated values for operational expenses and passenger behaviour, set to the best of our current knowledge. These assumptions were necessary to enable consistent analysis across different scenarios. However, it is important to note that adjusting these parameters to reflect real-world data could lead to different trade-off decisions, particularly in balancing passenger benefits (e.g. reduced delays, improved connectivity) against operational costs (e.g. diversions, compensation, resource deployment). In reality, different operators may assume different sets of parameters, which could be considered in the modelling. Future work should focus on calibrating these inputs with empirical data to enhance the accuracy and strategic relevance of the experimental results.

Due to the lack of available data, airline alliances within the experiments have been artificially defined. These assumptions were necessary to enable the simulation of decentralized DM strategies. Alliances play a critical role in the effectiveness of decentralized DM, as they directly influence the ability to share resources and reroute passengers. Different alliance structures can lead to varying performance outcomes, with a general trend toward higher expectation of improved performance in scenarios with fewer, larger alliances (ultimately leading to one overall alliance i.e. centralised DM). While these variations may affect the performance gap between decentralized and centralized DM approaches, they are not expected to alter the overall ranking of the strategies in terms of the revealed properties. The number of available replacement services in the model has been set to the best of our current knowledge, based on general industry practices and operational constraints. In reality, the availability of such services depends on several factors, including cost considerations, airline resource availability, and strategic priorities. These variables can significantly influence the effectiveness of disruption management strategies. An increase in available replacement services tends to enhance the performance of centralized disruption management, as it allows for more coordinated and efficient passenger rerouting. There is also potential to improve decentralized DM performance by also considering replacement services there, but this would require detailed, real-world data, which is currently not available.

A.5.4.2. Quality of validation exercises results

Since the exercise is composed of mathematical optimization, there is almost no Human Factor (HF) involved in the validation exercise. Hence, we consider that there are no issues regarding the quality and accuracy of the results.

A.5.4.3. Significance of validation exercises results

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

A.6 Conclusions

A.6.1 Conclusions on concept clarification

With this validation exercise, SOL401 has proven to fulfil all the research objectives proposed in the ERP by providing centralised and decentralised disruption management decisions to provide feasible adjusted schedules for a disrupted air-rail network.

A.6.2 Conclusions on technical feasibility

SOL401 fulfils all the functional requirements outlined in the FRD.

A.6.3 Conclusions on performance assessments

As discussed in the ECO-EVAL, given its multimodal status SOL401 does not fundamentally change the current SESAR KPAs, which are traditionally only centred around ATM. For this reason, part of the objective of the project was to develop a multimodal performance framework centred in multimodality.

We present here a summary of the performance results per performance area developed within the project:

- Efficiency. SOL401 is able to balance the avg. arrival and departure delays per service, the total journey time and arrival delays for passengers, the numbers of stranded passengers. Also, reducing the numbers of cancellations for some cases. And, diversions are applied sparingly - only when they generate significant benefits to network operations. Thus, SOL401 has a medium - high impact on this KPA.
- Flexibility. SOL401 is capable of managing and improving the replanned resilience and passengers by appropriate disruption management decisions which leads to higher connectivity and increases passenger transport during disruptions. Thus, SOL401 has a high impact on this KPA.

A.7 Recommendations

The recommendations we can extract from this validation exercise are the following:

- Conflicting PIs (e.g. travel time vs. passenger numbers, passenger benefit vs. operational cost) should be carefully designed and assessed, in order to keep in mind the holistic picture. Consequently, considering operational cost as a PI would also explicitly capture the corresponding trade-off. This can be adapted for upcoming experiments with the SOL401 disruption manager.
- The results rely on estimated values for some input parameters (e.g. operational expenses, passenger behaviour) and were set to the best of our current knowledge. Calibrating these inputs with empirical data could enhance the accuracy and strategic relevance of the experimental results.
- The results could be verified and deepened by applying the computed, adjusted schedules of SOL401 with SOL1 tactical evaluator. This was performed during the project.

Appendix B Validation exercise #02 report

B.1 Summary of the validation exercise #02 plan

As in the ERP SESAR Solution 401.

B.1.1 Validation exercise description and scope

The second validation exercise consists of presenting the results to a board of around 20 relevant stakeholders to evaluate and validate the project assumptions and the optimisation techniques.

The validation exercise aims to verify the validation objectives that ensure the delivery of the key project results. The overall goal is to demonstrate that a relevant Disruption Management Solution has been developed in the project.

The key validation objectives are the validation from the stakeholders both of the relevance of the Solution and the quality of its results. Concretely, the validation objectives that are assessed by this exercise are

- EX02-OBJ-0401-ERP-010. Provide a set of decisions, and relevant system constraints for multimodality which improve the passenger-centric performance of the system.
- EX02-OBJ-0401-ERP-010. Provide a set of disruptions relevant for evaluating multimodal disruption management.
- EX02-OBJ-0401-ERP-020. Define a reasonable planning horizon for disruption management.

The validation technique is through a presentation and feedback gathering of the Industry Board, composed of around 20 relevant stakeholders from various backgrounds. The exact gathering method and validation platform used was mentimeter.

B.1.2 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 validation objective	Exercise success criteria

EX02-OBJ-0401-ERP-010	EX02-CRT-0400-ERP-010.2	Fully covered	Provide a set of decisions, and relevant system constraints for multimodality which improve the passenger-centric performance of the system.	The adjustment decisions and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).
	EX02-CRT-0401-ERP-010.3	Fully covered	Provide a set of disruptions relevant for evaluating multimodal disruption management.	The disruption types are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to
EX02-OBJ-0401-ERP-020	EX02-CRT-0401-ERP-020.1	Fully covered	Define a reasonable planning horizon for disruption management.	A majority of stakeholders considers that the planning horizon is representative and relevant.

Table B.1: Validation exercise success criteria. In *italic* validation criteria that have been modified from the original ERP.

B.1.3 Summary of validation exercise #02 validation scenarios

Since this exercise consisted in presenting SOL401 to the relevant stakeholders, the reference scenarios and validation scenarios do not apply here.

B.1.4 Summary of validation exercise #02 validation assumptions

No extra assumptions are available beyond those specified in 3.2.3. Validation assumptions.

B.2 Deviation from the planned activities

The original research objectives have been slightly modified. Originally, validation objective OBJ-0401-ERP-020 was to “compare the KPIs for multimodal disruption management.” and its associated success criteria CRT-0401-ERP-020.1 “a majority of stakeholders considers that the defined KPIs/PIs are representative and relevant”. However, we realised that this objective and validation criteria were not well defined.

It became clear that the objective and criteria were not sufficiently well-defined to support effective evaluation. In particular, the planned validation through stakeholder feedback was not feasible, as no industry board meeting was scheduled after the experiments, and the complete experimental results were not available in time for the final board meeting.

Additionally, as the project progressed, the **time horizon** of disruption management emerged as a key consideration. This aspect had not been part of the original objective but proved to be highly relevant and was subsequently addressed in discussions with the industry board. This is why we have decided to modify that research objective and success criterion by:

- OBJ-0401-ERP-020: Define a reasonable planning horizon for disruption management.
 - CRT-0401-ERP-020.1: A majority of stakeholders considers that the planning horizon is representative and relevant.

The validation activities remain unchanged.

B.3 Validation exercise #02 results

B.3.1 Summary of validation exercise #02 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
OBJ-0401-ERP-010	Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.	EX02-CRT-0400-ERP-010.2	The adjustment decisions and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).	N/A	Answers: all measures (i.e. retiming, rerouting/diverting, cancellation and short-turning) received a score higher than 5/10.	OK
		EX02-CRT-0401-ERP-010.3	The disruption types are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10)		Answers: capacity reductions on railway corridors/airports, airspace capacity reduction/closure and multiple simultaneous disruptions got ranked with a score higher than 5/10.	OK

OBJ-0401-ERP-020	Define a reasonable planning horizon for disruption management .	EX02-CRT-0401-ERP-020.1	A majority of stakeholders considers that the planning horizon is representative and relevant.	N/A	Answers: 1 day ahead	OK
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Table B.2: validation exercise #02 results

B.3.2 Analysis of validation exercise #02 results per validation objective

B.3.2.1. OBJ-0401-ERP-010 Results

Objective: Provide a set of mechanisms and relevant system constraints for multimodality which improve the passenger-centric performance of the system.

Validation:

- The adjustment decisions and constraints are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).
- The disruption types are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10)

During the second Industry Board (IB) meeting, the proposed disruption management measures and the considered disruption types were presented, and several questions were raised to assess whether this section was representative of and relevant for reality. This process aimed to support the overall objective to improve the passenger-centric performance of the system under disruptions.

Figures B.1 and B.2 show the results of the corresponding questions. Fifteen experts in rail, aviation, and transportation answered the question.

Q3.4: For operators, how relevant are the following measures?

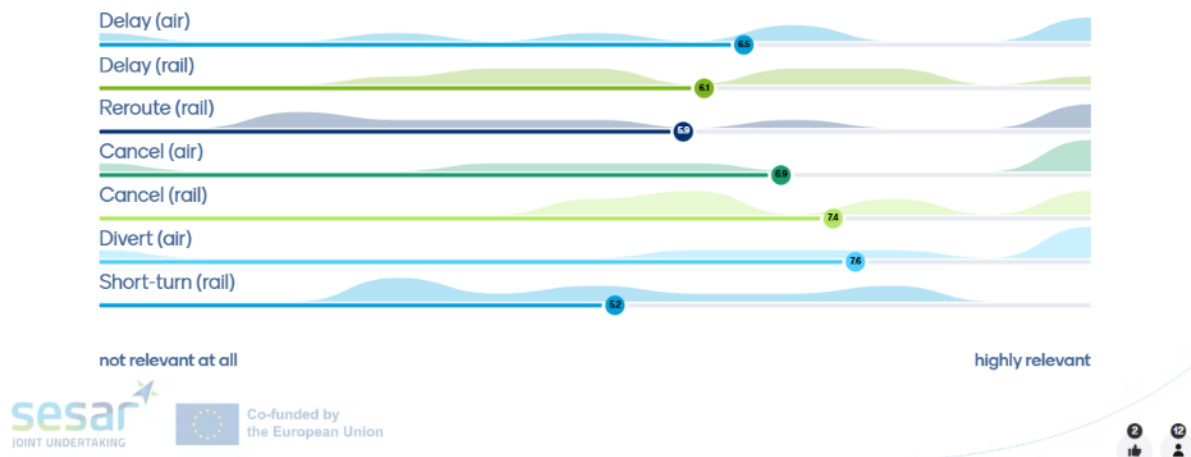


Figure B.1: IB voting results of disruption management measure relevance

Fig. B.1 presents a comparative assessment of the perceived relevance of various disruption management measures for air and rail transport operators. The measures are evaluated on a Likert scale from "not relevant at all" to "highly relevant," with visual indicators marking the perceived importance.

The measures evaluated include:

- **Air:** Delay, Cancel, Divert
- **Rail:** Delay, Reroute, Cancel, Short-turn

No measure got ranked irrelevant nor highly relevant. Instead, all measures got ranked moderately relevant with a slightly higher importance for diversions and cancellations on the air side and cancellations on the rail side. Delaying air and rail services got ranked similarly to rail rerouting, whilst short-turning rails got the least relative importance. However, all measures got ranked rather similar. The answers thus suggest that the currently considered measures and corresponding adjustment decisions are relevant.

Q3.5: Which types of disruptions would be the most interesting to evaluate?

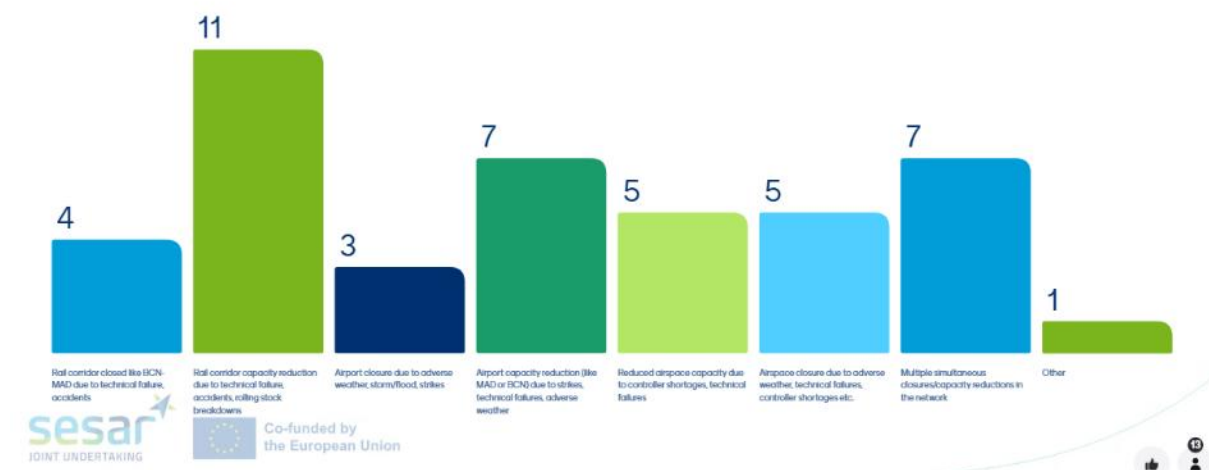


Figure B.2: IB voting results of disruption types interest

Fig. B.2 presents the number of responses indicating interest in various disruption types. The answers reflect preferences among the participants for evaluating specific types of disruptions in the air and rail transport systems.

- **capacity reductions** on railway corridors got ranked **most** interesting
- **capacity reductions** at airports and **multiple, simultaneous network disruptions** got ranked **second most** interesting
- airspace **capacity reduction and closures** got ranked **moderately** interesting
- rail corridor and airport **closures** got ranked the **least** interesting
- “Other” category received minimal attention, indicating that predefined disruption types largely cover the respondents' interests.

This distribution suggests a strong focus on capacity reducing disruptions, especially on rail corridors and airports and the corresponding network effects, as key scenarios for further evaluation. Those results suggest that the currently modelled disruptions and the chosen experimental settings were of practical relevance and of interest. Given the focus of SESAR JU on air transport, we selected airport capacity reduction for the experiments.

As both, the disruption types and the corresponding disruption measures, were considered relevant and interesting by the industry board, this objective can be considered fulfilled.

B.3.2.2. OBJ-0401-ERP-020 Results

Objective: Define a reasonable planning horizon for disruption management.

Validation criterion: A majority of stakeholders considers that the planning horizon is representative and relevant.

To this end, during the second IB meeting, experts were asked to assess the relevance of the considered planning horizon w.r.t. disruption management. Voting for multiple options was allowed.

Figures 3 and 4 show the respective results.

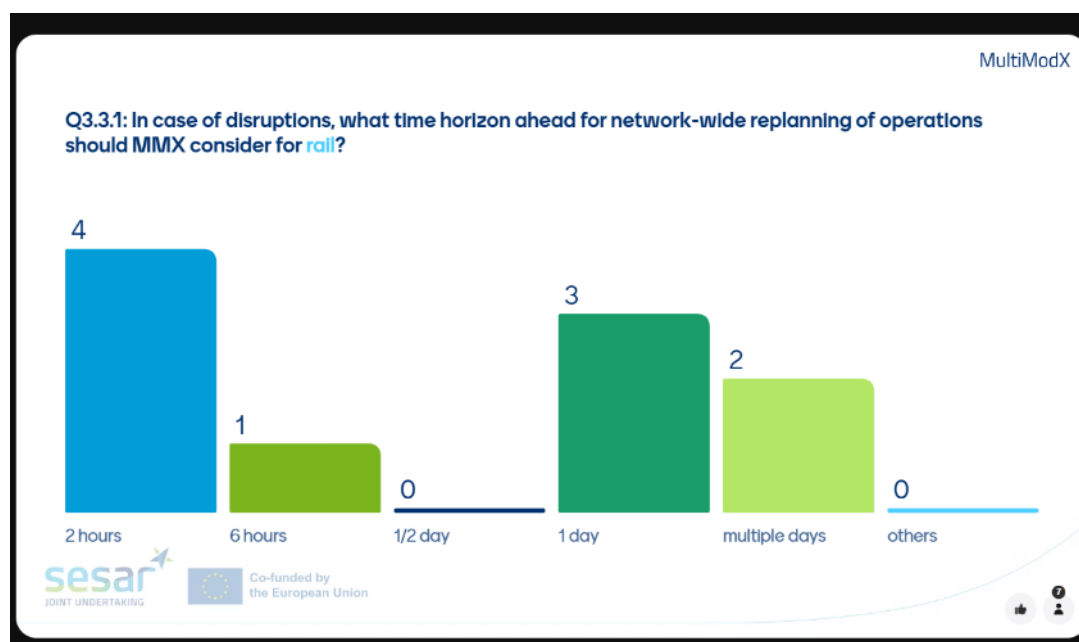


Figure B.3: IB voting results for the rail planning horizon

The survey results for the first question, regarding the preferred time horizon for network-wide replanning of **rail operations** in case of disruptions, indicate a majority preference for a 2-hour window, with 4 respondents selecting this option. This was followed by 3 votes for a 1-day horizon, 2 for multiple days, and 1 for 6-hours. No respondents selected the "others" or half-a-day category.

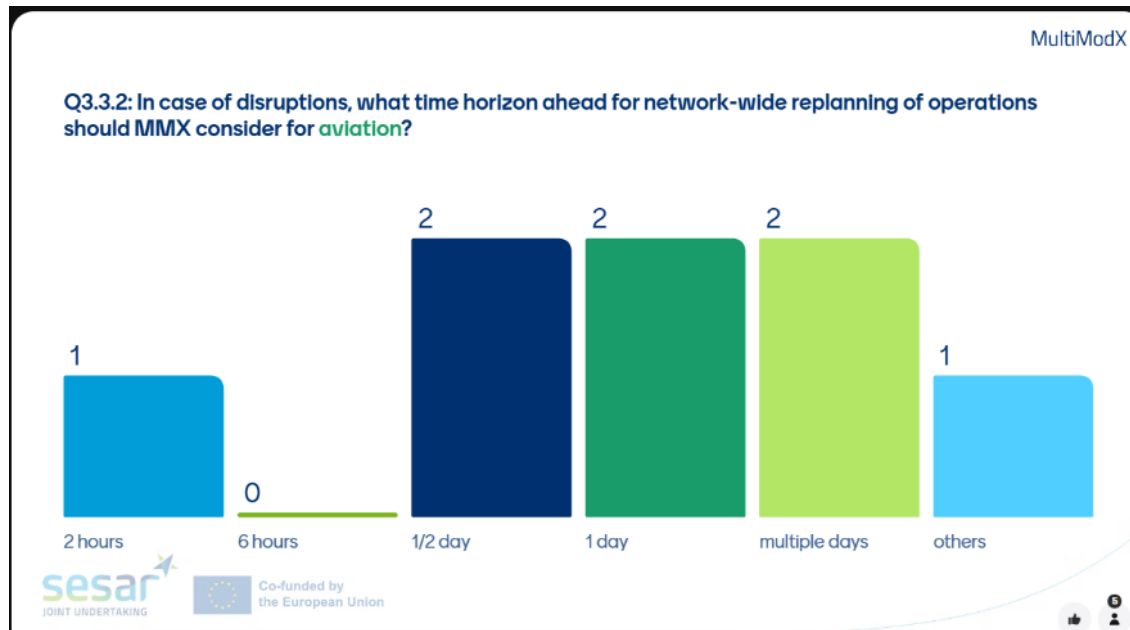


Figure B.4: IB voting results for the air planning horizon

The survey results for the second question, which asked about the preferred time horizon for network-wide replanning of **aviation operations** during disruptions, show a relatively even distribution among longer planning horizons from half-a-day up to multiple days. One respondent preferred a 2-hour horizon, while no one selected 6 hours. The "others" category was mentioned once. We selected a planning horizon of 1 day ahead of operations.

The IB answers suggest that contingency planning with the tactical planning horizon for multiple hours or even days ahead is of practical interest. The results thus prove the chosen modeling approach and model selection w.r.t. the planning horizon to be relevant and reasonable for practice. We thus consider this objective fulfilled.

B.3.3 Unexpected behaviours/results

There were no unexpected behaviours or results.

B.3.4 Confidence in results of validation exercise #02

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

Assumptions made in sections 3.2.3 and A.1.4 may have an impact on the representativeness of the validation results.

The group of experts that participated in the second IB meeting was composed of experts from a wide range of fields, both from the aviation and the rail industry. There were enough participants and enough diversity among their profiles to consider this sample representative. Thus, we believe that the level of significance of this validation exercise is high, and that the results of this survey can be extrapolated to the wider aviation and rail industry community.

Due to the fact that this exercise was realised in parallel with code development, only very preliminary results of SOL401 could be shown in the presentation. Despite the fact that SOL401 was adequately

introduced, this constituted a limitation of the results. Only the assumptions underlying SOL401 are validated in this exercise. The outputs of SOL401 are validated in validation exercise 1 instead.

B.3.4.2. Quality of validation exercises results

This validation exercise was realised during the development of the code. Hence, it does not validate the results of the application of SOL401, rather the assumptions on which the Disruption Management Solution (SOL401) is based. The quality of the results is influenced by the number of stakeholders (a greater sample is always better).

B.3.4.3. Significance of validation exercises results

The results of this exercise are statistically significant. Operational significance does not apply here.

B.4 Conclusions

B.4.1 Conclusions on concept clarification

This validation exercise confirmed the concept of the Disruption Management Solution (SOL401). The questions asked were relevant on how to address the problem of disruption management of two modes of transport intrinsically very different and with very different constraints.

B.4.2 Conclusions on technical feasibility

This validation exercise confirmed the functional requirements indicated in the Functional Requirements Document (FRD). In particular, SOL401

- replans operations in a network considering disruptions (REQ-SOL401-OP-DMM01.001);
- applies disruption management strategies to adapt the services to the current disruption scenario (REQ-SOL401-FR-DMM02.001);

The result of this validation exercise has been key to the design and implementation of these functional requirements of SOL401.

B.4.3 Conclusions on performance assessments

The MultiModX Key Performance areas evaluated during this exercise are

- Efficiency
- Resilience

By validating the disruption measures and the considered planning horizon, we are ensuring that the results of the disruption manager are realistic and comply with the industry constraints. They have an impact on the efficiency and resilience KPA, since the planning horizon and the measures determine how much the services can be adjusted under disruptions. As a result, the disruption management measures and the planning horizon impact the service delays and the corresponding changes of the overall supplied connections and frequencies. The results thus stress the relevance of contingency planning during the tactical planning phase, within the unimodal networks of air and rail in general, but also particularly for their multimodal combination.

B.5 Recommendations

Due to the limited reach of this particular validation exercise, the recommendations regarding SOL401 are assessed in chapter 5 of the main deliverable and in chapter A.5.