DES HE SESAR solution 0400 exploratory research report

Deliverable ID:	**D5.2**
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:	**30 October 2025**
Template 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.

Authoring & approval

Author(s) of the document

Name / Organisation name	Position / Title	Date
Lucía Menéndez-Pidal/Nommon	**Consortium member**	27.10.2025
Ricardo Herranz/Nommon	**Consortium member**	27.10.2025
David Mocholí/ Nommon	**Consortium member**	27.10.2025
Bing Liu/TU Dresden	**Consortium member**	27.10.2025
Nikola Besinovic/TU Dresden	**Consortium member**	27.10.2025
Christopher Szymula/TU Dresden	**Consortium member**	27.10.2025

Reviewed by

Organisation name		Date
Eric Tchouamou Njoya/BHL	**Project coordinator**	28.10.2025
Luis Delgado / UoW	**Consortium member**	28.10.2025
Michal Weiszer / UoW	**Consortium member**	28.10.2025

Approved for submission to the SESAR 3 JU by

Organisation name		Date
Eric Tchouamou Njoya/BHL	**Project coordinator**	28.10.2025

Rejected by

Organisation name	Date

Document history

Edition	Date	Status	Organisation author	Justification
01.00	03.06.2025	Release	MultiModX Consortium	New document for review by the SJU
02.00	30.10.2025	Release	MultiModX Consortium	Document amended for Maturity Gate

Copyright statement

Disclaimer

The opinions expressed herein reflect the author's view only. Under no circumstances shall the SESAR 3 Joint Undertaking be responsible for any use that may be made of the information contained herein.

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.

Table of contents

EUROPEAN PARTNERSHIP

Co-funded by the European Union

List of figures

List of tables

EUROPEAN PARTNERSHIP

Co-funded by the European Union

1 Executive summary

The Schedule Design Solution (SOL400/SOL2) aims to design passenger-centric coordinated multimodal schedules for air and rail. The passenger-centric aspect comes from the passenger flows calculated using SOL399/SOL1, taking into account the sensitivities of passengers with regard to several travel aspects (mode (air, rail, multimodal), travel time, price and CO2 emissions) when selecting a specific path, and mode(s), to reach their desired destination. The flows of each path determine the demand to be satisfied by the schedules. The schedules are designed to accommodate the passenger flows as well as possible and, therefore, prioritise coordinating the connections with higher demand.

Using the available data, the Schedule Design Solution generates coordinated air and rail schedules.

SOL400/SOL2 is capable of implementing optimised schedules with the constraints of moving existing services only up to the industries' acceptable thresholds (about 20 minutes in accordance with the Industry Board's feedback). Relaxing these constraints for broader changes will be explored in the experiments.

The objectives when creating the schedules are amongst or a combination of the following:

- minimise waiting times or total travel times for passengers;
- maximise the number of people travelling;
- minimise the deviations from the original schedules.

by accommodating passenger flows as defined from SOL399/SOL1

The document outlines the results of two validation exercises, one focusing on internal validation through simulations and the other on external stakeholder validation. Additionally, it specifies how SOL400/SOL2 progresses from TRL1 to TRL2 level.

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 SOL400/SOL2 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 SOL400/SOL2. This solution proposes a Schedule Designer capable of optimising a country-wise network of trains and flights, taking into account passenger preferences and industry constraints.

2.2 Intended readership

The readers of this document would typically include a range of stakeholders involved in the rail and aviation industry, transportation planning, and policymaking. These may include SESAR JU, SESAR IR 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 schedule design solution builds upon previous projects from aviation and rail. The approach for timetable synchronisation developed within the SESAR H2020 ER TRANSIT [24] project will be extended into a more comprehensive solution to be able to deal with multimodal passenger-centred schedule design at a network level, with the purpose of optimally coordinating air and rail services to minimise the overall passenger journey times and impacts of everyday stochastic disruptions, while taking into account the resources needed by airlines and railway undertakings and the infrastructure capacity. This will benefit from the insights into the airline schedule and strategic passenger flow and schedule generator developed in the SESAR H2020 ER Modus [25] project.

The approaches for optimal railway timetabling from EU FP7 project ON-TIME [26], such as micro-macro models [27], and the integrated passenger-centric multimodal scheduling algorithms from the ERA-NET SORTEDMOBILITY [28] project, like MASP [29], which currently integrate rail and bus services, will be extended towards integrating airline operations.

The synchronisation of air and railway timetables has been drawing growing attention recently. Most of the studies focused on the synchronisation at transfer hubs with one airport and one train station. The authors of [30] studied a feeder railway timetabling problem at one transfer hub, in which the flight timetable is given, and the feeder railway timetable is optimised to maximise the number of synchronisations and the coverage of synchronised flights and minimise passenger transfer penalties. In [31], a joint design model was proposed that adjusts the given flight and train timetables to increase passenger accessibility at a transfer hub and minimise the time shift of initial timetables. In [32], the authors proposed a demand-driven train timetabling method to minimise passenger waiting time, in which the number of waiting passengers is calculated by the cumulative arrival and service passenger curves. In [33], the authors integrated the rescheduling model of air-rail timetable and passenger flow forecasting to capture the interaction of timetable and passenger flow distribution. In [34], a time-space network-based formulation was proposed for the synchronisation problem of train, aircraft, shuttle, and passenger flows.

Very few research studied the air-rail timetable synchronisation problem at a network level. The adjustment of the service timetable at one station not only affects the passengers transferring at the station but also has an impact on other passengers taking the service and other services on the network sharing the same infrastructure. In [35], an optimisation model for air-rail timetable synchronisation to minimise passenger transfer discomfort and schedule deviation was studied. Some network characteristics are considered in the model, including the network effect of adjusting the departure time at one station and some operational constraints at stations and airports. The proposed model assumes the transfer demand of each connection is fixed. However, new connections are possible in the synchronised timetable, and passengers may re-choose their itinerary.

The development of SOL400/SOL2 partly fills in this gap by taking into account demand and building a passenger-centric approach to scheduling by optimising both the air and rail network to account not only for waiting time but also for capacity whilst also minimising timetable deviation.

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
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
Case study	Geographical context in which the Solution will be applied, i.e., trains and flights considered	Own elaboration
Demand served	Demand that can be allocated to specific itineraries	Own elaboration
Experiment	A succession of steps within a validation exercise that are analysed together	Own elaboration
Itinerary	succession of services that passenger take	Own elaboration
OD pair	Origin and Destination pair. Refers to the start and end points of each passenger's journey. The number of O-Ds also indicates the size and complexity of a network.	ATPCO Glossary

Scenario	A specific socio-economical context in which the Solution will be applied within a case study	Own elaboration
Service	specific train or plane	own elaboration
Use case	A potential situation in which a system receives an external request (such as user input) and responds to it.	Wikipedia (use case definition)
Validation exercise	Set of experiments done in order to validate the utility of a Solution	ERP document
Waiting time	Time spent between a service and another that do not account for other processing times. This time is composed of minimal a buffer time (necessary to not miss a connection) and additional time that can be minimised by optimisation. waiting time are also referred as buffer times.	Own elaboration

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
HF	Human factor
ID	Identifier
KPA	Key performance area
KPI	Key performance indicator
OD	Origin Destination
OSED	Operational service and environment description
PI	Performance Indicator
SESAR	Single European sky ATM research
SESAR 3 JU	SESAR 3 Joint Undertaking
TRL	Technology readiness level

Table 2: list of acronyms

EUROPEAN PARTNERSHIP
Co-funded by the European Union

3 Context of the exploratory research report

3.1 MultiModX / SESAR solution 400: a summary

SOL400/SOL2 takes the supply (i.e. rail timetable and flight schedules) and demand (i.e. itineraries) characteristics from SOL399/SOL1 to improve the transfer experience of passengers in the air-rail integrated system by simultaneously coordinating the services and assigning passengers to services. The output is the coordinated rail timetables and flight schedules, which can be fed into the strategic evaluator of SOL399/SOL1 to:

- Calculate the MultiModX PIs at the strategic level
- Assign the passengers to the coordinated services

SOL400/SOL2 first identifies the demand and services of interest (i.e. transfer demand and corresponding services). Time-based (i.e. timetable shift) strategies are then applied to generate a coordinated schedule of trains and flights. SOL400/SOL2 also identifies the better itineraries in the coordinated schedule and assigns passengers to shift their itineraries.

Multiple objectives are considered in the optimisation model (i.e. unserved demand, transfer time and timetable deviation. Some operational constraints (e.g. running time, dwell time, headway, airport capacity) and passenger assignment constraints (e.g. minimal connection time and seat capacity) are imposed in the model to guarantee the feasibility of the solution.

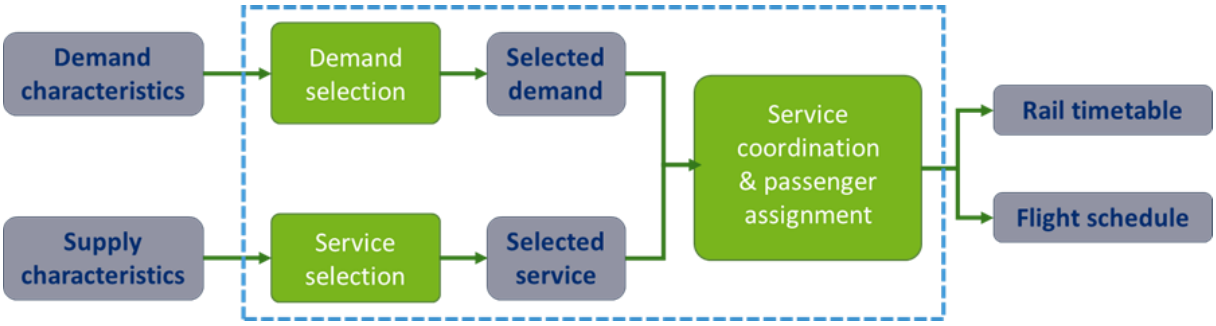

Figure 1: Overview of SOL400/SOL2

3.2 Summary of the exploratory research plan

3.2.1 Exploratory research plan purpose

The overall purpose of the ERP is to **determine the research questions, objectives, and validation process of the Schedule Design Solution** (SOL400/SOL2), for the integrated planning and coordinated design of air and rail schedules according to expected demand behaviour, optimising the waiting times at transfer nodes in order to offer more and better options for multimodal passengers. This SESAR Solution is expected to reach TRL-2.

SOL400/SOL2 has been validated by means of two validation exercises:

EUROPEAN PARTNERSHIP
Co-funded by the European Union

- Validation exercise 1 focuses on executing SOL400/SOL2 in different operational settings defined based on the sub-operational environments and their characteristics as defined in the associated OSED [36].
- Validation exercise 2 focuses on validating the relevance of the approach and results obtained with SOL400/SOL2 by collecting feedback from relevant stakeholders and the Industry Board (IB) members.

The following explanations hold mainly for validation exercise 1, but they are presented here for completeness.

As defined in the OSED [36], the following characteristics are 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 NUTS2 level) are covered.
- Multimodal policy packages: to describe different evolutions of the mobility ecosystem where multimodality is incentivised (e.g. with CO_2 taxes) or enforced (by means of flight ban imposition).
- Infrastructure characteristics: focusing on connecting nodes and the scarcity of infrastructure in the regions.

Considering these previous characteristics, the validation of SOL400/SOL2 focuses on 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.

Since SOL400/SOL2 is a schedule designer that builds on the existing literature, it is capable of optimising a complete multimodal network (rather than just a pair of train stations and airports). Thus, the exact scope of the case studies is to optimise a country-wide network. The results of this optimisation are 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 defined in the OSED [36]. Note that Spain contains the three European regional archetypes identified by MultiModX (see D3.1 [37] and Section 5.1.1). In addition to these regions ad-hoc analysis of different infrastructures will also be provided to further understand where SOL400/SOL2 provides additional benefits and performance trade-offs.

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, as described in the operational characteristics in SOL2 OSED [36]. In this context, the scenarios (reference and solution) include a combination of multimodal policies and a timeline. Scenarios are also based considering network definition, which changes itinerary generation. General information about the 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. The results of the ERR are based on this case study
	cs11: Intra-Spain+International flights	This case study is an extension of the previous one that includes international flights. Although this scenario will not be analysed in the ERR we include it here for completeness.
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 CO2 tax for air itineraries is implemented (0.15 EUR / Kg CO2).
	pp20: Multimodality enforced	It is the same as pp10 with an additional flight ban (where a rail alternative under 3h exists).
nd (Network definition)	nd00: Baseline	max connections in connected itineraries: 2
	nd01: Focus on connecting passengers	max connections in connected itineraries: 2 Connections with mixed operators (air) allowed The focus in passenger assignment is on connecting passengers
	nd02: Focus on total passengers	max connections in connected itineraries: 2 Connections with mixed operators allowed The focus in passenger assignment is on total passengers
so (Schedule Optimisation)	so00.00: Baseline	No schedule optimisation
	so01.01	Timeshift strategies in SOL400/SOL2 Maximum timetable deviation of 20 minutes per service.
	so01.X, where X greater or equal to 02	This corresponds to X successive applications of SOL400/SOL2 jointly with SOL399/SOL1

Table 3: MultiModX scenarios and nomenclature. We note that since disruptions are not considered for SOL400/SOL2 analysis, we exclude it from this table

For the analysis of SOL400/SOL2 we selected a subset of the scenarios, presented in Table 4.

Scenario	Comment
cs10.pp00.nd02.so00.00	This is the baseline scenario for this validation exercise.
cs10.pp00.nd02.so10.01	This scenario corresponds to the Spanish air and rail network after one application of SOL400/SOL2. It corresponds to a Solution Scenario.
cs10.pp00.nd02.so10.02	This scenario corresponds to a second application of SOL400/SOL2 in the Spanish air and rail network. It corresponds to a Solution Scenario.
cs10.pp20.nd02.so00.00	This is the second baseline scenario for this validation exercise.
cs10.pp20.nd02.so10.01	This scenario corresponds to a second application of SOL400/SOL2 in the Spanish air and rail network. It corresponds to a Solution Scenario.

Table 4: Selected scenarios for the evaluation of SOL400/SOL2

We have focused on the network definition nd02. This network definition allows itineraries with mixed operators (for example, we are allowing people to take two planes from different airlines), and when assigning passengers to seats, maximising the total passengers is prioritised. We decided for these characteristics to try to maximise the effects of SOL400/SOL2. The scenario pp20 (enforced policy package) is prioritised over pp10 (incentivised policy package) as it is expected that more multimodality and opportunity for optimisation of the network will be present when flight bans are in place.

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

- The scope (Spanish air and rail network) provides an interesting variety in terms of regional specificities and situations of multimodal transport (national case study and international corridor);
- The set of defined passenger archetypes is representative of the entirety of European travellers;
- The required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, etc.) is available in the regions under study;
- A multimodal performance scheme and multimodal governance model allow cooperation **for the schedule coordination** between modes of transport (shared data, possibility to modify or replace the existing timetables, information, incentive, etc.);
- 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.

The specific assumptions for the Schedule Design Solution are further described in Section 4.

As described, to show that SOL400/SOL2 is able to deliver an optimised air and rail network, the results obtained with the intra-Spanish scope are sufficient, albeit with some limitations, as discussed in Section 5.1.6. The scenarios related to this scope are considered "Fundamental". We are aware that the number of multimodal trips in this geographical context could be limited; this is why extending the scope to include international trips is considered, as future work. Note, however, how intra-Spain trips include trips to the Canary Islands, which are further away from the mainland and for which multimodality could already be suitable. For this reason, to increase potential multimodal journeys, pp20 has also been implemented. As previously indicated, experiments with this extended scope will

Co-funded by the European Union

be prioritised but completed after the fundamental ones are finished and, therefore, probably reported outside the validation activities considered here.

Besides the execution of SOL400/SOL2 in validation exercise 1, external validation has been conducted by presenting to relevant stakeholders and the Industry Board (IB) the approach and results of SOL400/SOL2 (validation exercise 2).

3.2.2 Summary of validation objectives and success criteria

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

3.2.3 Validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A1	Case studies coverage	It is assumed that the Spanish air and rail network is sufficient to show how SOL400/SOL2 operates	Regional archetypes have been studied, and they are all represented in Spain.	Medium
A2	Regional archetypes	It is assumed that results derived from the Spanish (national), regional archetypes can be translated and upscaled to an EU level using different regional archetypes as examples	The different regional archetypes represent a real combination of air and rail characteristics within a region, 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 of the entirety of travellers.	Extensive research has been conducted to ensure that those passenger archetypes represent the total variety of travellers.	Medium
A4	Data availability	It is assumed that the required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, 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 are in place, allowing cooperation between modes of transport (shared data, information, incentive…).	The interest of the project lies in studying the impact of a multimodal and collaborative framework.	High
A6	Fixed demand per OD pair	It is assumed that the demand for each OD pair is fixed, meaning that the choice of passengers to travel is independent of the schedules (there will be no more or less demand) and their destination will not change as a result of the schedule optimisation.	It is considered sufficiently precise to have demand flows per OD pair and archetype for each scenario (including the impact of policies). The reaction of demand to the supply is considered to have a potential small impact only.	Medium
A7	Coordination between air and rail	The schedule coordination occurs between rail and air, leaving aside other long-distance ground transportation means such 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	Fixed prices	It is assumed that the prices of the different paths are fixed as an input of the solution and will not be updated within the solution.	The reaction of the price to the demand through an economic model is considered out of the scope and interest of the project. Price variations may come from the policies defined in the scenarios.	Low
A9	Considered times	It is assumed that the data collected (from busy days in 2019 for air and 2023 for rail) will represent a nominal day in 2030.	It is assumed that the maturation of the solution from TRL 1 to TRL 2 can be sufficiently performed by using historical data.	Medium

Table 5: validation assumptions overview

3.2.4 Validation exercises list

Identifier	**TVAL.01.1-MultiModX-0400-TRL2**
Title	Modelling of SOL400/SOL2 in an entire network
Description	The exercise will consist of: executing simulations using SOL400/SOL2 for various experiments (variations of Scenario); ensuring the feasibility of the newly generated coordinated schedules (maximising covered/transported demand); comparing the results of the newly generated coordinated schedules with the non-coordinated schedules to observe the impact of coordinating schedules on the defined PIs and KPIs.
KPA/TA addressed	Efficiency Interoperability Flexibility Cost effectiveness Capacity Environment
Addressed expected performance contribution(s)	Improvement of the defined KPIs
Maturity level	TRL2
Use cases	Use case: Schedule generation, as defined in the OSED
Validation technique	PIs and KPIs calculation and comparison
Validation platform	Software and SOL1 multimodal strategic evaluator and performance framework
Validation location	N/A
Start date	01/04/2025
End date	28/04/2025
Validation coordinator	Nommon
Status	Pending
Dependencies	Upstream T3.1 data

Table 6: Validation exercise #1 summary

EUROPEAN PARTNERSHIP
Co-funded by the European Union

Identifier	**TVAL.02.1-MultiModX-0400-TRL2**
Title	Stakeholder survey validation
Description	The exercise will consist of the realisation of a stakeholder survey in order to assess the adequacy of SOL400/SOL2
KPA/TA addressed	Efficiency Capacity
Addressed expected performance contribution(s)	Validation of the project assumptions and the optimisation techniques
Maturity level	TRL2
Use cases	N/A
Validation technique	basic statistical analysis of the answers to the survey
Validation platform	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	Nommon
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)

The original research objectives have been slightly modified. Originally, validation objective OBJ-0400-ERP-060 was to “generate air and rail coordinated schedules that minimise timetable deviation“ and its associated success criteria EX01-CRT-0400-ERP-060.1 “for all experiments, the timetable deviation after the application of SOL400/SOL2 should be better than before its application“. However, we realised that this objective and validation criteria were not well defined.

SOL400/SOL2 is a schedule optimiser, meaning it takes original schedules and modifies them. Hence, timetable deviation only makes sense **after** the optimisation process, and not before, as was suggested

EUROPEAN PARTNERSHIP
Co-funded by the European Union

in the original validation criterion. This objective is part of the research question RQ-0400-ERP-030 "**How can optimised air and rail schedules be designed to ensure an efficient and realistic use of the available resources?"** The main objective of this question is to guide our research to construct a tool capable of progressing to higher TRL and being able to be used by the rail and aviation industries. This is why ensuring that the industry constraints are covered is very important. Timetable deviation is a way of assessing how these constraints are met. This is why we have decided to modify that research objective and success criteria by:

- OBJ-0400-ERP-060: Generate air and rail coordinated schedules that ***take into account*** timetable deviation.
    - EX01-OBJ-0400-ERP-060.1: ***For all experiments timetable deviation should be measured and analysed.***

The validation activities remain unchanged.

4 Validation results

4.1 Summary of project / SESAR Solution 0400 validation results

Project / SESAR solution validation objective ID	Project / SESAR solution validation objective title	Project / SESAR solution success criterion ID	Project / SESAR solution success criterion	Project / SESAR solution validation results	Project / SESAR solution validation objective status
OBJ-0400-ERP-010	Generate air and rail coordinated schedules that accommodate as much passenger demand as possible.	**CRT-0400-ERP-010.1**	For all experiments in validation exercise #1, the demand served after the application of SOL400/SOL2 should be higher than the demand served before its application.	Demand for connected itineraries grows.	OK
		CRT-0400-ERP-010.2	Most stakeholders consider that the defined passenger archetypes considered within the project are representative of reality in validation exercise #2.	Answers: • yes: 11 no: 4	OK
OBJ-0400-ERP-020	Generate air and rail coordinated schedules that minimise waiting times.	**CRT-0400-ERP-020.1**	For all experiments in validation exercise #1, total travel time and waiting times after the application of SOL400/SOL2 should be lower than these times before its application.	Waiting times are reduced and total time in connecting itineraries is also reduced.	OK
OBJ-0400-ERP-030	Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal	**CRT-0400-ERP-030.1**	For all the experiments in validation exercise #1, the generated schedules shall be examined by SOL399/SOL1 Multimodal	All the indicators have been measured.	OK

	performance framework.		Performance Framework, and all the passenger-centric PIs should be measured. These are passenger time efficiency, seamless time, demand served, CO_2 emission, and direct operating cost per user.		
		CRT-0400-ERP-030.2	For all the experiments in validation exercise #1, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the multimodality-related PI should be measured. These are diversity of destinations, modal share, catchment area of airports.	All the indicators have been measured.	OK
OBJ-0400-ERP-040	Generate air and rail coordinated schedules that improve overall network connectivity.	**CRT-0400-ERP-040.1**	For all experiments in validation exercise #1, the selected PIs after the application of SOL2 should be better than	The catchment area of airports improves for certain airports. The diversity of destinations does not change.	Partially OK

			before its application. These are diversity of destinations, passenger time efficiency, and catchment area of airports.	Passenger time efficiency decreases slightly.	
OBJ-0400-ERP-050	Generate air and rail coordinated schedules that improve the network multimodal alternatives.	**CRT-0400-ERP-050.1**	For all experiments in validation exercise #1, the selected PIs disaggregated for multimodal trips after the application of SOL2 should be better than before its application.	The diversity of destination and passenger time efficiency does not increase or decrease. Total journey time improves.	Partially OK
OBJ-0400-ERP-060	Generate air and rail coordinated schedules that minimise total timetable deviation	**CRT-0400-ERP-060.1**	For all experiments, timetable deviation should be measured and analysed. These are diversity of destinations, passenger time efficiency, and catchment area of airports.	Timetable deviation has been measured and analysed.	OK
OBJ-0400-ERP-070	Generate air and rail coordinated schedules that make more efficient use of the network and services.	**CRT-0400-ERP-070.1**	For all experiments in validation exercise #1, the selected KPIs after the application of SOL2 should be better than before its application.	The load factor does improve very slightly, but the direct operating costs do not always decrease.	Partially OK

EUROPEAN PARTNERSHIP
Co-funded by the European Union

			These are load factor, and direct operating costs per user.		
		CRT-0400-ERP-070.2	The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10) in validation exercise #2.	Grades of the parameters considered: min=5.1, max=9.1, avg=6.91. Grades for the adjustment strategies: min=5, max=7.4, avg=5.95	OK
OBJ-0400-ERP-080	Generate air and rail coordinated schedules that decrease passengers' CO_2 emissions.	**CRT-0400-ERP-080.1**	For all experiments CO_2 emission after the application of SOL400/SOL2 should be better than before its application.	CO_2 emissions remain stable.	Partially OK

Table 8: summary of validation exercises results

EUROPEAN PARTNERSHIP

Co-funded by the European Union

4.2 Detailed analysis of MultiModX / SESAR solution 0400 validation results per validation objective

Important note: To increase readability, most of the discussion in the following sections will be qualitative. For the full quantitative results, we recommend reading the appendices A and B. In these appendices, each validation exercise is thoroughly analysed.

4.2.1 OBJ-0400-ERP-010 Results

Objective: Generate air and rail coordinated schedules that accommodate as much passenger demand as possible

Validation:

- Validation EX1: For all experiments, the demand served after the application of SOL2 should be higher than the demand served before its application.
- Validation EX2: A majority of stakeholders consider that the defined passenger archetypes considered within the project are representative of reality.

One of the most important functionalities of SOL400/SOL2 is that it takes into account the dynamic passenger demand when doing the schedule optimisation. Previously, passenger archetypes have been identified. Different passenger archetypes have different sensitivities to price, CO2, and time, leading to different decisions when choosing a transportation mode. The passenger archetypes were validated in the second IB meeting via the question “Should MMX consider an additional passenger archetype?”, to which most members of the IB (11 out of 15) answered that another passenger archetype was not necessary.

Additionally, in the first validation exercise, the PI demand served was measured before and after the application of SOL400/SOL2 over the Spanish air and rail network. It was found that demand improves marginally in most scenarios, except for one in which demand served decreases also marginally. However, the demand for connecting itineraries increases significantly after the application of SOL400/SOL2 (see tables 9 and 10). This proves that SOL400/SOL2 is able to accommodate as much passenger demand as possible, as stated in the research objective. We consider that the validation objective status is OK.

scenario	number of connecting passengers	difference
cs10.pp00.nd02.so00.00	18637	-
cs10.pp00.nd02.so10.01	19592	+5.12%
cs10.pp00.nd02.so10.02	20032	+7.49%

Table 9: number of connecting passengers before and after the application of SOL400/SOL2 in the cs10.pp00.nd02 scenario

scenario	number of connecting passengers	difference
cs10.pp20.nd02.so00.00	20364	-
cs10.pp20.nd02.so10.01	21000	+3.12%

Table 10: number of connecting passengers before and after the application of SOL400/SOL2 in the cs10.pp20.nd02 scenario

4.2.2 OBJ-0400-ERP-020 Results

Objective: Generate air and rail coordinated schedules that minimise waiting times

Validation criterion: For all experiments, total travel time and waiting times after the application of SOL400/SOL2 should be lower than before its application.

Total journey time and waiting time were calculated with several variants

- sum: which is the sum of times taken by all passengers travelling;
- average: which is the average time per passenger.

Additionally, we calculated total and average times at a network level and only focusing on connecting itineraries.

SOL400/SOL2 optimises time in connecting itineraries, reducing travel time of passengers. The results regarding connecting itineraries are shown in tables 11 and 12. To see a more complete breakdown of the results see Appendix A.

scenario	average time on connecting itineraries (min)
cs10.pp00.nd02.so00.00	417.09
cs10.pp00.nd02.so10.01	411.24
cs10.pp00.nd02.so10.02	405.28

Table 11: Average time on connecting itineraries for different scenarios (pp00)

As shown in Table 11, travel time in connecting itineraries decreases significantly. This goes in accordance with waiting times (note that in the project, waiting times are referred to as buffers in itineraries.) The results regarding buffer times are presented here:

scenario	average buffer time per itinerary (min)	sum of all buffer times (min)
cs10.pp00.nd02.so00.00	20.39	380028
cs10.pp00.nd02.so10.01	16.39	321123
cs10.pp00.nd02.so10.02	15.71	314866

Table 12: total and average buffers in itineraries before and after successive applications of SOL2

Therefore, we consider that the validation status of this objective is OK.

4.2.3 OBJ-0400-ERP-030 Results

Objective: Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal performance framework.

Validation criteria:

- For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the passenger-centric PIs should be measured (passenger time efficiency, seamless travel, demand served, CO_2 emission, direct operating cost per user).
- For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the multimodality-related PIs should be measured. These are the diversity of destinations, the modal share and the catchment area of airports.

All the stated PIs were able to be measured and analysed, giving a complete picture of how SOL400/SOL2 acts at a network level, at a regional archetype level, at an OD pair level, and even at a hub level in the case of catchment area of airports. This combination of PIs with their different variants allows us to zoom in and out of the network, giving us the possibility to analyse in deep detail certain OD pairs while not losing the global picture. We consider that this validation objective is OK.

4.2.4 OBJ-0400-ERP-040 Results

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

Validation criterion: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, catchment area of airports).

Diversity of destination is a PI that measures how many regions (at a NUTS3 statistical level) a given region is connected to. It does not change after the application of the current version of SOL400/SOL2. The objective of SOL400/SOL2 are maximising demand served, minimising waiting times, and minimise the deviation from the original schedules. None of these objectives directly contributes to add new

Co-funded by the European Union

connection to the air and rail network, unless there is significant demand between two currently not connecting regions. This can therefore explain why this PI remains un-changed and also means that all the connections of the network are relevant for the current objectives of SOL400/SOL2 since, none of them is removed.

Given an OD pair, passenger time efficiency gives an idea on how many passengers can travel in the "best possible option" with the best possible option defined as the fastest one. This indicator does not vary much after the application of SOL2. However, as shown previously in Tables 10 and 11, the times of connecting itineraries improve significantly after the application of SOL2, meaning that the overall status of the network is better even if passenger time efficiency remains relatively unchanged.

The catchment area of airports is calculated by taking the longest rail journey passengers take from or to a given airport. After the application of SOL400/SOL2, certain catchment areas increase whereas others decrease. These changes must be analysed on a case-by-case basis, but some increases are created by passengers taking longer journeys to go to the airport (which is generally positive for that airport), and some decreases are a consequence of a better connection of that airport with the surrounding areas. Hence, most changes are positive.

Considering all the above indicators, we assess the status of this validation objective as partially satisfactory.

4.2.5 OBJ-0400-ERP-050 Results

Objective: Generate air and rail coordinated schedules that improve the network multimodal alternatives.

Validation criterion: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, total journey time).

Total journey times improve significantly in connected itineraries (Tables 11 and 12), whereas passenger time efficiency and diversity of destinations remain unchanged (as explained in section 4.2.4). Therefore, we consider that this validation objective status is partially OK as well.

4.2.6 OBJ-0400-ERP-060 Results

Objective: Generate air and rail coordinated schedules that take into account timetable deviation.

Validation criterion: For all experiments, timetable deviation should be measured and analysed.

Timetable deviation has been analysed. we present below an example of timetable deviation calculated after schedule optimisation.

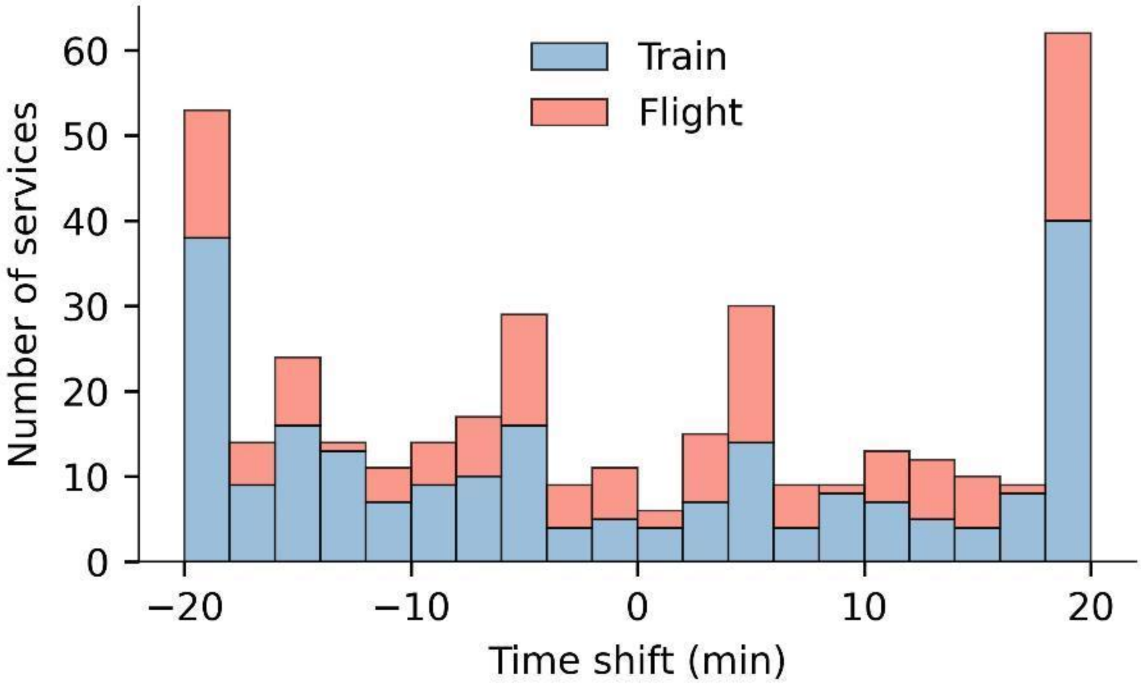

Figure 2: Timetable deviation between cs10.pp00.nd02.so00.00 and cs10.pp00.nd02.so10.01

We see that most trains are shifted and that most trains and planes are shifted by 20 minutes – which is the maximum shift allowed by the model. This indicates that relaxing the 20-minute constraint could lead to even better results. A first step towards this direction could be relaxing this constraint only for rail services. The status of this validation objective is OK.

4.2.7 OBJ-0400-ERP-070 Results

Objective: Generate air and rail coordinated schedules that make more efficient use of the network and services.

Validation criterion:

- Validation EX1: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (load factor, direct operating costs per user).
- Validation EX2: The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).

Regarding validation exercise EX1, we tested the parameters to take into account in the optimisation and the optimisation strategies with the Industry Board. The parameters tested were transfer time, minimum door-to-door time, infrastructure connectivity, served demand, transport costs, revenues, and environmental impact. All parameters were graded on relevance, and all obtained a grade greater than 5, with a 6.91 on average. Additionally, the optimisation strategies timeshift, new services, re-routing, and cancellation of services have been graded on relevance. All obtained a grade greater than

5, with an average of 5.95. This constituted a validation of the parameters and assumptions of SOL400/SOL2. This validation criteria status is, hence, OK.

Regarding validation exercise EX2, load factor increases slightly in all experiments, except for one, for which load factor decreases slightly, However the changes in load factor after schedule optimisation are minimal. These results, although positive overall, are not very significant. Something worth mentioning is that, for all scenarios analysed, the average load factor of the network is around 2/3 of the maximum capacity of the services. We also note that SOL400/SOL2 only modify the connecting itineraries, and hence its effect on load factor is also limited.

Operational costs are defined as price per passenger and are calculated using the fare of the tickets. Operational costs per user do not decrease after the application of SOL400/SOL2. This can be understood paired with the fact that load factors do not improve significantly, and neither does demand served. Up to a certain extent, part of the increase in operational costs can be attributed to people shifting from rail to air. This validation criteria status is partially OK.

4.2.8 OBJ-0400-ERP-080 Results

Objective: Generate air and rail coordinated schedules that decrease passengers' CO2 emissions.

Validation criterion: For all experiments, CO2 emission after the application of SOL400/SOL2 should be better than before its application.

CO2 emissions are calculated per passenger. CO2 emissions are not better after the application of SOL400/SOL2, they remain more or less constant. This could be due to the fact that load factors and served demand do not improve significantly. As CO2 is not significantly worse but the application of SOL400/SOL2 did not significantly improve CO2 emissions in the network, we consider that this objective is partially OK.

4.3 Confidence in validation results

4.3.1 Limitations of validation results

There are several limitations of the validation exercises 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 show-casing 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, and with the consideration of longer distance trips such as to-from the Canary Islands from all the peninsula regions in Spain. As mentioned above, only intra-Spain (domestic) services are considered due to data limitations. We acknowledge that some of the indicators calculated in this validation exercise are less good than originally predicted due to the unimodal nature of the Spanish air and rail network. However, many multimodal trips happen in the international context. Therefore, the next priority will be creating a scenario with international services from/to Spain. Additionally, some of the PIs measured are perhaps too aggregated to truly showcase SOL400/SOL2 potential.

4.3.1.1 Quality of validation results

Validation exercise EX1 is composed of simulations, 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 SOL400/SOL2 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, statistically significant. Operational significance is somehow limited by the assumptions of the project (discussed in section 4.3.1). However, we consider that the simulations realised are sufficiently realistic to offer a complete vision of the potential of SOL400/SOL2.

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 project/ SESAR solution maturity

All the validation criteria have been at least partially met, and most of them are met entirely, showcasing the effort put into the maturity of the Solution. Additionally, given its complexity and performance, SOL400/SOL2 represents a significant improvement from TRL1 projects like TRANSIT or MODUS. Compared to the TRANSIT Timetable Synchronisation Tool, the reach of SOL400/SOL2 is much larger, as it can be used in a much wider network and takes into account industry constraints in much greater detail. Additionally, itinerary attractiveness is calculated by taking into account not only price and distance but also environmental factors like CO2 sensitivity. SOL400/SOL2 has also been validated by industry experts in validation exercise EX1. The combination of all these factors, along with the Maturity Self-Assessment, grants SOL400/SOL2 the TRL2 level.

5.1.2 Conclusions on concept clarification

SOL400/SOL2 is a tool that can allow airlines and rail companies to coordinate schedules at a country-wide level. From the validation exercises, we can extract the following conclusion regarding concept clarification:

- The maximum timetable deviation of single services was initially hard coded to 20 minutes but could become a free parameter in subsequent versions of SOL400/SOL2. SOL400/SOL2 could also allow for different timetable deviation constraints for air and rail to allow a more fine-tuned experience.
- Re-routing strategies (for air, rail, or both) should be implemented in the future.
- To better show the added value of SOL400/SOL2, PIs like direct operating costs, CO_2 emissions, and diversity of destinations could be provided with a “connecting itineraries” variant. This would allow us to gauge the real impact of SOL400/SOL2 in networks that do not have a high proportion of connecting passengers.

SOL400/SOL2 is a schedule optimisation tool, and hence it does not affect the SESAR architecture. The operational feasibility of SOL400/SOL2 depends on the SESAR capability of Single ticketing along with the remaining assumptions of the project regarding airline and rail coordination and cooperation. Technically, SOL400/SOL2 has proven to be effective at optimising air and rail schedules.

5.1.3 Conclusions on technical aspects

Validation exercise EX2 helped in the design of the functional requirements of SOL400/SOL2. In particular, it helped define the following functional requirements.

- SOL400/SOL2 provides optimised flight schedules and rail timetables (REQ-SOL400-OP-SD00.001);

- SOL400/SOL2 takes into account the demand disaggregated by the passenger archetypes as an input (REQ-SOL400-FR-SD01.001);
- SOL400/SOL2 uses the lexicographic optimisation method optimising for unserved demand, waiting times and timetable deviation (REQ-SOL400-FR-SD05.001);
- SOL400/SOL2 optimises schedules using time-based but also route-based strategies (REQ-SOL400-OP-SD05.001).

Validation exercise EX1 confirmed that the solution implemented these functional requirements correctly. SOL2 fulfils all the functional requirements outlined in the FRD except requirement REQ-SOL400-OP-SD05.001, "SOL400 (SOL2) shall optimise train and flight schedules using time-based and route-based strategies". This requirement is only partially fulfilled since route-based strategies (re-routing) are still a work in progress.

5.1.4 Conclusions on performance assessments

As discussed in the ECO-EVAL, given its multimodal status SOL400/SOL2 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. SOL400/SOL2 has a positive impact on this KPA, reducing buffer times and total journey times.
- Interoperability. SOL400/SOL2 has a limited impact on this KPA, minimally affecting the modal share.
- Flexibility. SOL400/SOL2 is able to modify the resilience of a given OD pair, but so far, not the diversity of destinations.
- Cost effectiveness. SOL400/SOL2, in its current implementation, has a limited impact on this KPA.
- Capacity. SOL400/SOL2 has a limited impact on this KPA, improving catchment area of airports and in some cases modal share
- Environment. SOL400/SOL2, in its current implementation, has very little impact on this KPA.

5.2 Recommendations

5.2.1 Recommendations for next R&I phase

To really be able to show the capabilities of Schedule Design Solutions similar to SOL400/SOL2, the network choice is crucial. Some of the indicators measured are worse than expected due to the unimodal nature of the Spanish network. This is why our next priority as a project is to showcase the capabilities of SOL400/SOL2 in the context of Spain with international flights. Although SOL400/SOL2 has been validated theoretically by experts and its application has been validated by the analysis of relevant multimodal PIs, the addition of an extra validation exercise, in which the results of the simulation are presented to experts, would have been a nice addition to the validation activities. Such a validation exercise could serve to see if the (previously validated) constraints and optimisation strategies are working at industry standard and could help define future iterations and refinements of SOL400/SOL2 or a similar Solution. This could help the implementation of more concrete constraints regarding, for example, airport slots.

Re-routing, cancelling, and adding new services are promising optimisation strategies for future SESAR solutions, hence we recommend future research projects to include such optimisation strategies in their concept description. These could be a parameter for a more customised experience (for example allow re-routing but not cancellation, allow different re-routing strategies for air and rail services). Additionally, trains and planes are part of the transportation network of the EU, but not all regions are accessible by these services. SOL400/SOL2 is a scalable solution, with the possibility of adding other layers of transport in the optimisation process, for example, buses or other transportation modes. We recommend the possibility of adding other transportation layers for future R&I developments. Finally, more fine-tuned alliances and single ticketing options could be implemented in the optimisation algorithm to ensure the realism of the Solution.

Most of the gaps identified during the validation exercises will be assessed by adding international flights to the Spanish air and rail network and by showcasing proof of concept of re-routing strategies for the successive dissemination events of the project. In future maturity phases, SOL400/SOL2 should progress towards a marketable product.

More concretely, to progress to higher TRLs the project proposes the following steps:

1. **The Standardisation of the inputs of SOL400/SOL2.** This measure has to be done in jointly with SOL399/SOL1. In order to scale up SOL400/SOL2 it has to be used in different context and with different rail and air operators. Although GTFS is used throughout the transportation industry, air and train schedules had to cleaned and analysed before proceeding to Schedule Optimisation. We propose the implementation of standardisation and validation modules before schedule optimisation. These modules would remove missing information and errors in Schedules, save pre-processing times, and make the tool much more accessible and user friendly
2. **Addition of several configuration options.** To progress towards a mature product, we propose to provide users with configuration options, such as fixing the constraints (like maximum schedule deviation), selecting key services whose schedules should not be altered, choosing between different optimisation strategies and objective functions, etc. This configuration should be done via a user-friendly interface.
3. **Development of a visualisation dashboard.** Along with user-friendly customisation, and apart from the main outputs of SOL400/SOL2 (optimised air and rail timetables), the project should proportionate a visualisation dashboard. This tool should help the user to directly see the services impacted by the optimisation, along with some selected KPIs (from the MultiModX Key Performance Framework).
4. **Additional targeted validations.** SOL400/SOL2 should be validated by different sub-operating environments where Multimodality is already present (such as airports with an integrated train station). Additionally, future validation activities should exclude from the start itineraries

with a single service which are not the target of SOL400/SOL2. To develop a more mature tool other

These four steps are key for the creation of a SOL400/SOL2 prototype, ready to follow the subsequent SESAR validation activities and progress to even highers TRLs.

5.2.2 Recommendations for future R&I activities

New research avenues that could be explored in the future but are beyond the current scope of the project are

- **Study the effect of short-haul flight ban along with schedule optimisation at the airport level for different types of airports.** Short-haul flight bans on their own might cause passengers to take connecting flights. For example, if flights from Madrid to Barcelona are banned, passengers could opt to fly to Madrid connecting via the Balearic Islands or other secondary airports. This could subsequently create a situation in which secondary airports have to deal with increased demand, especially if a flight ban is implemented without providing more and better-connected rail services. Tools like SOL400/SOL2, in conjunction with SOL399/SOL1, provide us with the opportunity to analyse the consequences of these policies and how much schedule optimisation can help a flight ban implementation.
- **Comparison of different optimisation strategies.** Rail and air transport have very different commercial strategies and needs. The implementation of several optimisation strategies could allow us to identify which optimisation strategy works best for each operator and which ones work better jointly.
- **Optimisation with other modes of transportation.** Airports are typically not only connected by trains. Implementing a tool capable of optimising air, bus (or other conventional transportation modes) and rail would be an interesting avenue to explore in future projects. This would mean a step closer to a seamless multimodal experience and to the Flightpath2050 vision.

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] TRANSIT project

[25] MODUS project

[26] ON-TIME project

[27] Bešinović, N., Goverde, R., Quaglietta, E., Roberti, R., 2016. An integrated micro–macro approach to robust railway timetabling, Transportation Research Part B Methodological 87:14-32

[28] SORTED MOBILITY project

[29] Trepat, J., Bešinović, N., 2021. Scheduling multimodal alternative services for managing infrastructure maintenance possessions in railway networks, Transportation Research Part B: Methodological, vol. 154(C), pages 147-174

[30] Ke, Y., Nie, L., Liebchen, C., Yuan, W., Wu, X., 2020. Improving Synchronization in an Air and High-Speed Rail Integration Service via Adjusting a Rail Timetable: A Real-World Case Study in China. Journal of Advanced Transportation 2020, 1-13.

[31] Ke, Y., Nie, L., Yuan, W., 2021. Joint optimization of flight and train timetables for air and high-speed railway integration services with maximum accessibility. Transportmetrica B: Transport Dynamics 10(1), 207-236.

[32] Jiang, Y., Chen, S., an, W., Hu, L., Li, Y., Liu, J., 2022. Demand-driven train timetabling for air and intercity high-speed rail synchronization service. Transportation Letters 15(4), 321-335.

[33] Tan, Y., Li, Y., Wang, R., Mi, X., Li, Y., Zheng, H., Ke, Y., Wang, Y., 2022. Improving Synchronization in High-Speed Railway and Air Intermodality: Integrated Train Timetable Rescheduling and Passenger Flow Forecasting. IEEE Transactions on Intelligent Transportation Systems 23(3), 2651-2667.

[34] Ke, Y., Wu, X., Nie, L., Yao, Z., Chen, Y., 2024. Synchronizing train, aircraft, shuttle, and passenger flows in intermodal timetabling: A time–space network-based formulation and a decomposition algorithm using Alternating Direction method of multipliers. Transportation Research Part C: Emerging Technologies 159.

[35] Buire, C., Marzuoli, A., Delahaye, D., Mongeau, M., 2024. Air–rail timetable synchronisation: Improving passenger connections in Europe within and across transportation modes. Journal of Air Transport Management 115.

[36] MultiModX Consortium, 2025. Operational service and environment description for SOL400/SOL2

[37] MultiModX Consortium, 2025. Scenario definition

[38] EUROCONTROL, 2024. Forecast update 2024-2030. Spring 2024 edition.

Appendix A Validation exercise #01 report

A.1 Summary of the validation exercise #01 plan

The original research objectives have been slightly modified. Originally, validation objective OBJ-0400-ERP-060 was "generate air and rail coordinated schedules that minimise timetable deviation" and its associated success criteria EX01-CRT-0400-ERP-060.1 "for all experiments, the timetable deviation after the application of SOL400/SOL2 should be better than before its application". However, we realised that this objective and validation criteria were not well posed.

SOL400/SOL2 is a schedule optimiser, meaning it takes original schedules and modifies them. Hence, timetable deviation only makes sense **after** the optimisation process, and not before, as was suggested in the original validation criterion. This objective is part of the research question RQ-0400-ERP-060 "**How can optimised air and rail schedules be designed to ensure an efficient and realistic use of the available resources?"** This question main objective is to guide our research to construct a tool capable of progressing to higher TRL and able to be used by the rail and aviation industries. This is why ensuring that the industry constraints are covered is very important. Timetable deviation is a way of assessing how these constraints are met. This is why we have decided to modify that research objective and success criteria by:

- OBJ-0400-ERP-060: Generate air and rail coordinated schedules that ***take into account*** timetable deviation.
    - EX01-OBJ-0400-ERP-060.1: ***For all experiments timetable deviation should be measured and analysed.***

The validation activities remain unchanged.

A.1.1 Validation exercise description and scope

The first validation exercise consists of simulations. Different scenarios are generated using SOL400/SOL2 and these are compared afterwards using the Strategic Performance Evaluator of SOL399/SOL1. The scenarios are defined by the case study (cs), the policy packages applied (pp), the network definition (nd), and the Schedule Designed Solution (so). The scenarios are referenced by their short code csXX.ppYY.ndZZ.soAA.bb (where X,Y,Z,A,b are numbers). The scenarios considered in the MultiModX project are presented in Table A.2 and explained in section A.1.3.

In this context, 4 experiments are performed

- **Experiment 1 -** ***Implementation of SOL400/SOL2 in the baseline scenario -***
  In this experiment, we start from the baseline scenario cs10.pp00.nd02.so00.00 to the scenario cs10.pp00.nd02.so10.01 (i.e., we apply SOL400/SOL2 to optimise the air and rail schedules at a network level and we assign demand to the new itineraries). We then compare the strategic indicators developed by the MultiModX project in these two scenarios using the MultiModal Performance Framework of SOL399/SOL1.

- **Experiment 2 -** ***Implementation of SOL400/SOL2 in the "Multimodality Enforced" scenario -***
  In this experiment, we start from the second reference scenario in MultiModX, which corresponds to the Spanish rail and air network with several multimodal policies applied

cs10.pp20.nd02.so00.00. We compare this scenario with scenario cs10.pp20.nd02.so10.01. using the strategic indicators in developed by the MultiModX project in these two scenarios using the MultiModal Performance Evaluator of SOL399/SOL1.

- **Experiment 3 - *Regional archetype disaggregation* -**
  The performance indicators calculated in Experiments 1 and 2 will be re-analysed with the focus on the regional archetypes developed in the MultiModX project.

- **Experiment 4 - *Iterations of SOL400/SOL2* -**
  The scenario cs10.pp00.nd02.so10.02 is generated. This scenario corresponds to optimise again the air and rail network of the cs10.pp00.nd02.so10.01 scenario (where SOL400/SOL2 has already been applied once). The rationale behind this re-optimisation is that, by re-assigning the demand using the Strategic Evaluator, passengers will make different choices given the different itineraries, and hence by repeating the optimisation process afterwards, the situation of the new network is even better than before.

For simplicity, in the presentation of the results, PIs of experiment 1 and 4 are presented together. In this way the three scenarios cs10.pp00.nd02.so00.00, cs10.pp00.nd02.so10.01, and cs10.pp00.nd02.so10.02 are compared. This does not constitute a deviation from the planned activities.

With this validation exercise, the main use case of SOL400/SOL2 as defined in the OSED "*generate air and rail coordinated schedule*" and its extension *"re-assign demand to itineraries and compute PIs using the Strategic Evaluator"*

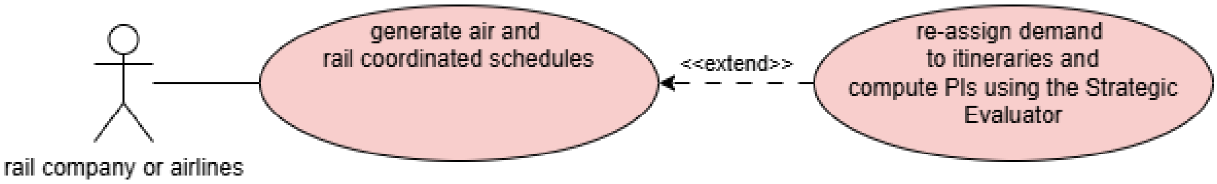

Figure A.1: SOL400/SOL2 use case and extension

The validation objectives addressed by this exercise are

- EX01-OBJ-0400-ERP-010. Generate air and rail coordinated schedules that accommodate as much passenger demand as possible
- EX01-OBJ-0400-ERP-020. Generate air and rail coordinated schedules that minimise waiting times.
- EX01-OBJ-0400-ERP-030. Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal performance framework.
- EX01-OBJ-0400-ERP-040. Generate air and rail coordinated schedules that improve overall network connectivity.
- EX01-OBJ-0400-ERP-050. Generate air and rail coordinated schedules that improve the network multimodal alternatives.

- EX01-OBJ-0400-ERP-060: Generate air and rail coordinated schedules that take into account timetable deviation.
- EX01-OBJ-0400-ERP-070. Generate air and rail coordinated schedules that make a more efficient use of the network and services.
- EX01-OBJ-0400-ERP-080. Generate air and rail coordinated schedules that decrease passengers' CO2 emissions.

The platform used for this validation exercise is software and SOL399/SOL1 Strategic Evaluator and Performance Framework.

The optimisation of schedules realised in cs10.pp00.nd02.so10.01, cs10.pp00.nd02.so10.02, and cs10.pp20.nd02.so10.01 consider many constraints to ensure that results are realistic and well posed. The constraints that are considered in SOL400/SOL2 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.
    - Airport capacity. Maximum airport capacity is considered in the model.
    - Time shift range: Maximum time deviation for each service compared with initial timetable.
- 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. Seat capacity for trains is calculated taking into account all the stations of the specific service.

Additionally, a maximum timetable deviation is implemented. Typically, schedule optimisation is not done by scratch, schedules are rather iterated based on the current ones. Additionally, for airlines, airport slots are a valuable asset, and they are usually reluctant to let their slots go. All the scenarios were generated with a maximum timetable deviation of 20 minutes, which was considered a reasonable value by the Industry Board.

A.1.2 Summary of validation exercise #01 validation objectives and success criteria

Co-funded by the European Union

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-0400-ERP-010	EX01-CRT-0400-ERP-010.1	Fully covered	Generate air and rail coordinated schedules that accommodate as much passenger demand as possible.	For all experiments, the demand served after the application of SOL400/SOL2 should be higher than the demand served before its application.
EX01-OBJ-0400-ERP-020	EX01-CRT-0400-ERP-020.1	Fully covered	Generate air and rail coordinated schedules that minimise waiting times.	For all experiments, total travel time and waiting times after the application of SOL400/SOL2 should be lower than before its application.
EX01-OBJ-0400-ERP-030	EX01-CRT-0400-ERP-030.1	Fully covered	Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal performance framework.	For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework and all the passenger-centric PIs should be measured (passenger time efficiency, seamless time, demand served, CO2 emission, direct operating cost per user).
	EX01-CRT-0400-ERP-030.2	Fully covered		For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the multimodality-related KPI should be measured (diversity of destinations, modal share, catchment area of airports).

EX01-OBJ-0400-ERP-040	EX01-CRT-0400-ERP-040.1	Fully covered	Generate air and rail coordinated schedules that improve overall network connectivity.	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, catchment area of airports).
EX01-OBJ-0400-ERP-050	EX01-CRT-0400-ERP-050.1	Fully covered	Generate air and rail coordinated schedules that improve the network multimodal alternatives.	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, total journey time).
EX01-OBJ-0400-ERP-060	EX01-CRT-0400-ERP-060.1	Fully covered	Generate air and rail coordinated schedules that ***take into account*** timetable deviation.	***For all experiments timetable deviation should be measured and analysed.***
EX01-OBJ-0400-ERP-070	EX01-CRT-0400-ERP-070.1	Fully covered	Generate air and rail coordinated schedules that make a more efficient use of the network and services.	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (load factor, direct operating costs per user).
EX01-OBJ-0400-ERP-080	EX01-CRT-0400-ERP-080.1	Fully covered	Generate air and rail coordinated schedules that decrease passengers' CO_2 emissions.	For all experiments, CO2 emission after the application of SOL400/SOL2 should be better than before its application.

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 SOL400/SOL2. The different scenarios considered are summarised in the following two tables (Table A.2 and A.3).

Category	**Sub-Category**	**Definition**

Co-funded by the European Union

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. The results of the ERR are based on this case study
	cs11: Intra-Spain+International flights	This case study is an extension of the previous one that includes international flights. Although this scenario will not be analysed in the ERR we include it here for completeness.
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 (where a rail alternative under 3h exists).
nd (Network definition)	nd00: Baseline	max connections in connected itineraries: 2
	nd01: Focus on connecting passengers	max connections in connected itineraries: 2 Connections with mixed operators (air) allowed The focus in passenger assignment is on connecting passengers
	nd02: Focus on total passengers	max connections in connected itineraries: 2 Connections with mixed operators allowed The focus in passenger assignment is on total passengers
so (Schedule Optimisation)	so00.00: Baseline	No schedule optimisation
	so01.01	Timeshift strategies in SOL400/SOL2 Maximum timetable deviation of 20 minutes per service.
	so01.X, where X greater or equal to 02	This corresponds to X successive applications of SOL400/SOL2 jointly with SOL399/SOL1 (see the use case diagram Figure A.1)

Table A.2: MultiModX scenarios and nomenclature. We note that since disruptions are not considered for SOL400/SOL2 analysis, we exclude it from this table

For the analysis of SOL400/SOL2 we selected a subset of the scenarios, presented in Table A.3.

Scenario	Comment
cs10.pp00.nd02.so00.00	This is the baseline scenario for this validation exercise.
cs10.pp00.nd02.so10.01	This scenario corresponds to the Spanish air and rail network after one application of SOL400/SOL2. It corresponds to a Solution Scenario.
cs10.pp00.nd02.so10.02	This scenario corresponds to a second application of SOL400/SOL2 in the Spanish air and rail network. It corresponds to a Solution Scenario.
cs10.pp20.nd02.so00.00	This is the second baseline scenario for this validation exercise.
cs10.pp20.nd02.so10.01	This scenario corresponds to a second application of SOL400/SOL2 in the Spanish air and rail network. It corresponds to a Solution Scenario.

Table A.3: Selected scenarios for the evaluation of SOL400/SOL2

In this validation exercise, we have focused on the network definition nd02. This network definition allows itineraries with mixed operators (for example, we are allowing people to take two planes from different airlines), and when assigning passengers to seats, maximising the total passengers is prioritised. We decided for these characteristics to try to maximise the effects of SOL400/SOL2.

In addition to the multimodal policies, the scenarios are defined by the geographical scope. Part of the geographical scope consists in the regional archetypes developed by the project. The different European regions are classified based on the degree of applicability of multimodal solutions.

The analysis identified 3 regional archetypes within Europe which can be considered as sub-operating environments:

1. Advanced urban regions with strong travel activity. These regions are referred as **advanced.**
2. Conservative regions with median travel activity. These regions are referred as **median.**
3. Emerging rural regions with low travel activity. These regions are referred as **emerging.**

   Spain has the three examples of regional archetypes. SOL400/SOL2 can potentially have a different impacts in all these regions.

EUROPEAN PARTNERSHIP
Co-funded by the European Union

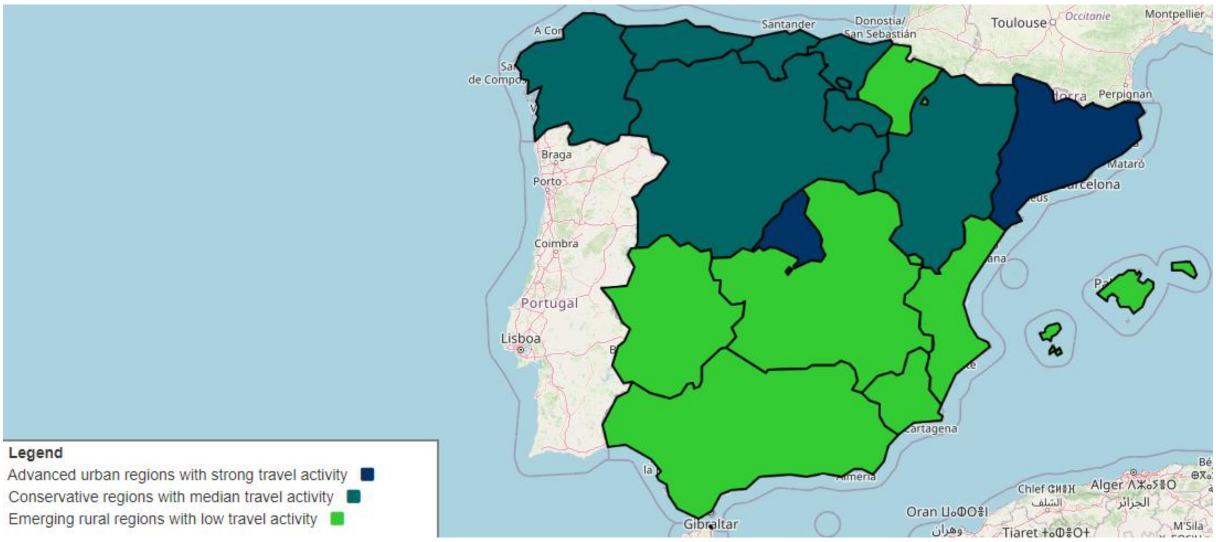

Figure A.2: mapping the clusters to NUTS2 regions in Spain

A.1.4 Summary of validation exercise #01 validation assumptions

For all the scenarios analysed in this validation exercise, the network definition chosen corresponds to nd02 “focus on total passengers”, where air-air connections allowing mixed operators are considered. This extra assumption allows us to maximise SOL400/SOL2 effects.

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

OBJ-0400-ERP-010	Generate air and rail coordinated schedules that accommodate as much passenger demand as possible.	EX01-CRT-0400-ERP-010.1	For all experiments, the demand served after the application of SOL400/SOL2 should be higher than the demand served before its application	N/A	Demand in connected itineraries grows.	OK
OBJ-0400-ERP-020	Generate air and rail coordinated schedules that minimise waiting times.	EX01-CRT-0400-ERP-020.1	For all experiments, total travel time and waiting times after the application of SOL400/SOL2 should be lower than before its application.	N/A	Waiting times are reduced and total time in connecting itineraries is also reduced.	OK

OBJ-0400-ERP-030	Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal performance framework.	EX01-CRT-0400-ERP-030.1	For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework and all the passenger-centric PIs should be measured. These are passenger time efficiency, seamless time, demand served, CO_2 emission, and direct operating cost per user	N/A	All the indicators have been measured.	OK

		EX01-CRT-0400-ERP-030.2	For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the multimodality-related KPI should be measured. These are diversity of destinations, modal share, catchment area of airports.	N/A	All the indicators have been measured.	OK
OBJ-0400-ERP-040	Generate air and rail coordinated schedules that improve overall network connectivity.	EX01-CRT-0400-ERP-040.1	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application. These are diversity of destinations, passenger time efficiency, and catchment area of airports.	N/A	Catchment area of airports improves for certain airports. Diversity of destination does not change. Passenger time efficiency decreases.	Partially OK

OBJ-0400-ERP-050	Generate air and rail coordinated schedules that improve the network multimodal alternatives.	EX01-CRT-0400-ERP-050.1	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application. These are diversity of destinations, passenger time efficiency, and total journey time. These are diversity of destinations, passenger time efficiency, and catchment area of airports.	N/A	Diversity of destination and passenger time efficiency do not increase or decrease. Total journey time improves.	Partially OK
OBJ-0400-ERP-060	Generate air and rail coordinated schedules that ***take into account*** timetable deviation.	EX01-CRT-0400-ERP-060.1	***For all experiments timetable deviation should be measured and analysed***	N/A	Timetable deviation has been measured and analysed.	OK

OBJ-0400-ERP-070	Generate air and rail coordinated schedules that make a more efficient use of the network and services.	EX01-CRT-0400-ERP-070.1	For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application. These are load factor, and direct operating costs per user.	N/A	Load factor does improve very slightly, direct operating costs not always decrease.	Partially OK
OBJ-0400-ERP-080	Generate air and rail coordinated schedules that decrease passengers' CO_2 emissions	EX01-CRT-0400-ERP-080.1	For all experiments, CO_2 emission after the application of SOL400/SOL2 should be better than before its application.	N/A	CO_2 emissions remain stable.	Partially OK

Table A.4: validation exercise #01 results

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

A.3.2.1. OBJ-0400-ERP-010 Results

Objective: Generate air and rail coordinated schedules that accommodate as much passenger demand as possible

Validation: For all experiments, the demand served after the application of SOL400/SOL2 should be higher than the demand served before its application.

Demand served is one of the objective functions of SOL400/SOL2. However, when doing the optimisation process, it is assumed that the underlying demand will not change. This is not the case in real life. When transportation schedules change, so does passenger behaviour. This is why, the optimised schedules provided by SOL400/SOL2 are re-analysed using the Multimodal Performance Framework of SOL399/SOL1. Thanks to the discrete choice model implemented in SOL399/SOL1, we can analyse the changes in demand occurring as a consequence of schedule optimisation. We present here the results concerning served demand:

Experiment 1 and 4 results

scenario	demand served
cs10.pp00.nd02.so10.00	81.82%
cs10.pp00.nd02.so10.01	81.89%
cs10.pp00.nd02.so10.02	81.89%

Table A.5: Total served demand in Spain (cs10) in the the multiple iterations of SOL400/SOL2. The right column corresponds to the scenario, and the left column corresponds to the measured PI

Experiment 2 results

scenario	demand served
cs10.pp20.nd02.so10.00	80.50%
cs10.pp00.nd02.so10.01	80.43%

Table A.6: Total served demand in Spain before and after the application of SOL400/SOL2

Experiment 3 results

regional archetype	percentage before SOL400/SOL2 (cs10.pp00.nd02.so00.00)	percentage after SOL400/SOL2 (cs10.pp00.nd02.so10.01)
advanced	80.26%	80.19%
emerging	86.81%	86.94%
median	83.67%	83.77%
none	92.10%	93.89%

Table A.7: Total demand served per regional archetype after the application of SOL400/SOL2 in the cs10.pp00.nd02 scenario

regional archetype	percentage before SOL400/SOL2 (cs10.pp20.nd02.so00.00)	percentage after SOL400/SOL2 (cs10.pp20.nd02.so10.01)
advanced	75.85%	75.78%
emerging	86.87%	86.77%
median	83.38%	83.55%
none	91.86%	92.42%

Table A.8: total demand served per regional archetype before and after the application of SOL400/SOL2 in the cs10.pp20.nd02 scenario

EUROPEAN PARTNERSHIP
Co-funded by the European Union

Discussion

It is interesting to see what happens at the level of OD pairs, presented in Table A.9:

origin	destination	origin_name	destination_name	difference of demand served before and after optimisation	passengers served before SOL400/SOL2	passengers served after SOL400/SOL2
ES523	ES412	Valencia	Burgos	96.23%	1	52
ES709	ES112	Tenerife	Lugo	90.00%	1	10
ES512	ES618	Girona	Sevilla	87.04%	7	54
ES418	ES522	Valladolid	Castellón/Castelló	80.00%	1	5
ES111	ES612	A Coruña	Cádiz	77.27%	15	67
ES412	ES113	Burgos	Ourense	76.92%	1	11
ES421	ES114	Albacete	Pontevedra	71.43%	4	15
ES412	ES114	Burgos	Pontevedra	70.73%	5	34
ES512	ES522	Girona	Castellón/Castelló	67.21%	16	57
ES114	ES522	Pontevedra	Castellón/Castelló	66.67%	1	3

Table A.9: difference in demand served before and after the application of SOL400/SOL2 in scenarios cs10.pp00.nd02.so00.00 and cs10.pp00.nd02.so10.01

This table shows the OD pairs for which demand served has increased the most after the application of SOL400/SOL2.

For most of these OD pairs, almost all of the demand is served after the application of SOL400/SOL2. This of course, comes at the expense of some OD pairs for which the demand served is worse after the application of SOL400/SOL2, shown in the table below:

Co-funded by the European Union

origin	destination	origin_name	destination_name	difference of demand served before and after optimisation	passengers served before SOL400/SOL2	passengers served after SOL400/SOL2
ES512	ES414	Girona	Palencia	-85.71%	14	2
ES241	ES704	Huesca	Fuerteventura	-80.00%	11	2
ES211	ES111	Álava/Araba	A Coruña	-79.31%	29	6
ES532	ES113	Mallorca	Ourense	-73.33%	16	4
ES243	ES111	Zaragoza	A Coruña	-71.43%	28	8
ES521	ES513	Alicante	Lleida	-68.18%	44	14
ES611	ES522	Almería	Castellón/Castelló	-66.67%	4	1
ES412	ES425	Burgos	Toledo	-63.63%	13	4
ES431	ES424	Badajoz	Guadalajara	-62.50%	16	6
ES512	ES613	Girona	Córdoba	-60.00%	12	4

Table A.10: difference in demand served before and after the application of SOL400/SOL2 in scenarios cs10.pp20.nd02.so00.00 and cs10.pp20.nd02.so10.01

This table shows the OD pairs for which demand served has decreased the most after the application of SOL400/SOL2.

As it can be seen from comparing tables A.9 and A.10, the improvement in some OD pairs comes at the expense of a regression in other OD pairs. However, the improvements generally compensate and the overall situation of the network is better after the application of SOL400/SOL2. In particular, we see that SOL400/SOL2 increases served demand in itineraries that were more demanded to start with and decreases the demand over itineraries that were not very demanded.

Additionally, notice that not in all experiments the total served demand after the application of SOL400/SOL2 is higher than before its application. This is an unexpected result, however, it can be

EUROPEAN PARTNERSHIP
Co-funded by the European Union

explained by changes in passenger behaviour after schedule optimisation. These drops in demand served are minimal and are not affecting negatively network performance. Additionally, if we look specifically at the passengers that are connecting, what we find is the following:

scenario	number of connecting passengers	difference
cs10.pp00.nd02.so00.00	18637	-
cs10.pp00.nd02.so10.01	19592	+5.12%
cs10.pp00.nd02.so10.02	20032	+7.49%

Table A.11: number of connecting passengers before and after the application of SOL400/SOL2 in the cs10.pp00.nd02 scenario

scenario	number of connecting passengers	difference
cs10.pp20.nd02.so00.00	20364	-
cs10.pp20.nd02.so10.01	21000	+3.12%

Table A.12: number of connecting passengers before and after the application of SOL400/SOL2 in the cs10.pp20.nd02 scenario

In all cases, after the application of SOL400/SOL2, the demand on connecting itineraries grows significantly. Accordingly, the status of this objective is deemed satisfactory.

A.3.2.2. OBJ-0400-ERP-020 Results

Objective: Generate air and rail coordinated schedules that minimise waiting times

Validation criterion: For all experiments, total travel time and waiting times after the application of SOL400/SOL2 should be lower than before its application.

Experiment 1 and 4 results

We show here the results in total journey time and waiting time for Spain (cs10). Note that in the project, waiting times are referred to as buffers in itineraries.

scenario	strategic_total_journey_time__sum	strategic_total_journey_time__avg
cs10.pp00.nd02.so00.00	88109665	223.82
cs10.pp00.nd02.so10.01	88224058	223.91
cs10.pp00.nd02.so10.02	88105422	223.62

Table A.13: total and average journey time before and after successive applications of SOL400/SOL2

scenario	buffer_in_itineraries__avg	buffer_in_itineraries__sum
cs10.pp00.nd02.so00.00	20.39	380028
cs10.pp00.nd02.so10.01	16.39	321123
cs10.pp00.nd02.so10.02	15.71	314866

Table A.14: total and average buffers in itineraries before and after successive applications of SOL400/SOL2

Experiment 2 results

scenario	strategic_total_journey_time__sum	strategic_total_journey_time__avg
cs10.pp20.nd02.so00.00	86086170	222.27
cs10.pp00.nd02.so10.01	85986947	222.19

Table A.15: total and average buffers in itineraries before and after the application of SOL400/SOL2

regional archetype	difference between time before and after SOL400/SOL2 in cs10.pp00	percentage of change between before and after
advanced	18855	0.06%
emerging	-6043	-0.02%
median	-37221	-0.18%
none	-89984	-1.48%

Table A.16: total journey time difference for the different regional archetypes for the scenarios cs10.pp00.nd02

regional archetype	total_journey_time_per_pax_cs10.pp20.nd02.so00.00	total_journey_time_per_pax_cs10.pp20.nd02.so10.01
advanced	201.42	200.94
emerging	231.03	231.71
median	219.29	218.49
none	331.40	331.47

Table A.17: average journey time for different regional archetypes and for the scenarios cs10.pp20.nd02

Discussion

If we look at Tables A.13 and A.14 we find that sometimes total time increases both on average and totally. These increases are very small and are probably related with the changes in served demand (if more people travel, the total travel time grows, and if more itineraries are created, average of travel time may also grow). However, SOL400/SOL2 optimises only connecting itineraries, and if we look at those itineraries we find the following results:

scenario	strategic_total_journey_time__avg
cs10.pp00.nd02.so00.00	417.09
cs10.pp00.nd02.so10.01	411.24
cs10.pp00.nd02.so10.02	405.28

Table A.18: average time on connecting itineraries for different scenarios (pp00)

scenario	strategic_total_journey_time__avg
cs10.pp20.nd02.so00.00	416.23
cs10.pp20.nd02.so10.01	411.50

Table A.19: average time on connecting itineraries for different scenarios (pp20)

As we can see, the improvement in total time in connecting itineraries is significant. This decrease in total time is not totally reflected when looking at the total network because the percentage of connected itineraries is quite low.

If we look at Tables A.17 and A.18 we see that for some regions travel time increase whereas for other it decreases. These results are not very significant. This does not mean that SOL400/SOL2 doesn't have an effect on the global network. If we zoom in and look at the OD pairs that are most benefited from the application of SOL400/SOL2 we find the following:

origin	destination	origin_name	destination_name	difference (in mins)
ES220	ES111	Navarra	A Coruña	-185
ES620	ES213	Murcia	Vizcaya/Bizkaia	-170
ES412	ES113	Burgos	Ourense	-159
ES709	ES112	Tenerife	Lugo	-153
ES512	ES615	Girona	Huelva	-136
ES511	ES640	Barcelona	Melilla	-133
ES412	ES424	Burgos	Guadalajara	-113
ES512	ES618	Girona	Sevilla	-94

ES513	ES415	Lleida	Salamanca	-92
ES617	ES432	Málaga	Cáceres	-91

Table A.20: difference in travel time before and after the application of SOL400/SOL2 in scenarios cs10.pp00.nd02.so00.00 and cs10.pp00.nd02.so10.01

This table shows the 10 OD pairs for which the decrease in travel times is more significant. If we compare with Table A.10 we see that

- Girona/Sevilla
- Burgos/Ourense
- Tenerife/Lugo

are common OD pairs that see both a very big increase in demand served along with a big increase in time savings. These are perfect examples of how SOL400/SOL2 can improve connectivity between regions. In general, from 2059 OD pairs,

- 841 are "worse off" (total travel time between these regions worsens). This increase in time affects 152112 passengers
- 952 are "better off" (total travel time between these regions improves). This improvement benefits 22545 passengers.
- 266 are unchanged. 16260 passenger are unaffected.

Therefore, overall most passengers benefit from the time savings.

The results for the scenario cs10.pp20.nd02 are presented in the following

origin	destination	origin_name	destination_name	difference (in mins)
ES213	ES425	Vizcaya/Bizkaia	Toledo	-238
ES620	ES212	Murcia	Guipúzcoa/Gipuzkoa	-173
ES412	ES512	Burgos	Girona	-169
ES111	ES220	A Coruña	Navarre	-118
ES213	ES411	Vizcaya/Bizkaia	Ávila	-109
ES425	ES413	Toledo	León	-97
ES412	ES113	Burgos	Ourense	-88
ES708	ES112	Lanzarote	Lugo	-82
ES513	ES113	Lleida	Ourense	-74
ES513	ES415	Lleida	Salamanca	-72

Table A.21: difference in travel time before and after the application of SOL400/SOL2 in scenarios cs10.pp20.nd02.so00.00 and cs10.pp20.nd02.so10.01

If we compare this table with A.10, we find that

- Murcia/Guipúzcoa
- Vizcaya/Ávila
- Vizcaya/Toledo
- Toledo/León

are among the 10 OD pairs that see both the biggest time savings and the biggest increase in demand served, again, showcasing how SOL400/SOL2 is able to optimise the transportation network. This time, from 2120 OD pairs the situation is the following:

- 873 are worse off. 147940 passenger are affected by this.
- 886 are better off. 224164 passengers benefit from these time savings.
- 282 are unchanged. 14517 passengers are unaffected.

Once again, we see that the regions with positive time savings also correspond with regions with more demand.

The results regarding buffer times are more telling: In all the analysed situations buffer times decrease significantly (see Tables A.14 and A.16), and even after several applications of SOL400/SOL2. This makes sense, as one of the objective functions of SOL400/SOL2 is to minimise buffer times. This makes the network much more efficient.

minimise buffer times. This makes the network much more efficient.

Given the previous discussion, we consider that the status of this objective is also OK.

A.3.2.3. OBJ-0400-ERP-030 Results

Objective: Generate air and rail coordinated schedules capable of being analysed in a passenger-centric multimodal performance framework.

Validation criteria:

- For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework and all the passenger-centric PIs should be measured (passenger time efficiency, seamless of travel, demand served, CO_2 emission, direct operating cost per user).
- For all the experiments, the generated schedules shall be examined by SOL399/SOL1 Multimodal Performance Framework, and all the multimodality-related PIs should be measured. These are diversity of destinations, modal share, catchment area of airports.

For this objective, the passenger-centric and multimodality-related PIs should only be measured, no improvement needed. Some of them are analysed in more detail in other sections of this document, more concretely

- passenger time efficiency is analysed in section A.3.2.4;
- demand served has already been analysed in section A.3.2.8;
- direct operating costs per user are analysed in section A.3.2.7;
- CO_2 emission is analysed in section A.3.2.8;

Co-funded by the European Union

- diversity of destination is analysed in more detail in section A.3.2.4.

The PIs seamless of travel and catchment area of airports need to be measured for this objective. We present here the results of these measurement along with a brief analysis of the results. Note that, no improvement of these indicators is needed for this specific objective.

Given an OD pair, seamless of travel gives an idea on how many passengers can travel in the "best possible option" with the best possible option defined as the fastest one. The closer this indicator is to 100% the better. The final indicator is the average per OD pairs.

Catchment area of airports is calculated by looking at how long it takes people to access a given airport. The catchment "area" of a given airport is the maximum time it takes people to reach it. Hence it gives an idea of how much people are travelling to reach it.

Experiment 1 and 4 results

scenario	seamless of travel
cs10.pp00.nd02.so00.00	83.11%
cs10.pp00.nd02.so10.01	79.99%
cs10.pp00.nd02.so10.02	74.85%

Table A.22: Seamless of time after successive applications of SOL400/SOL2 in the cs10.pp00 scenario

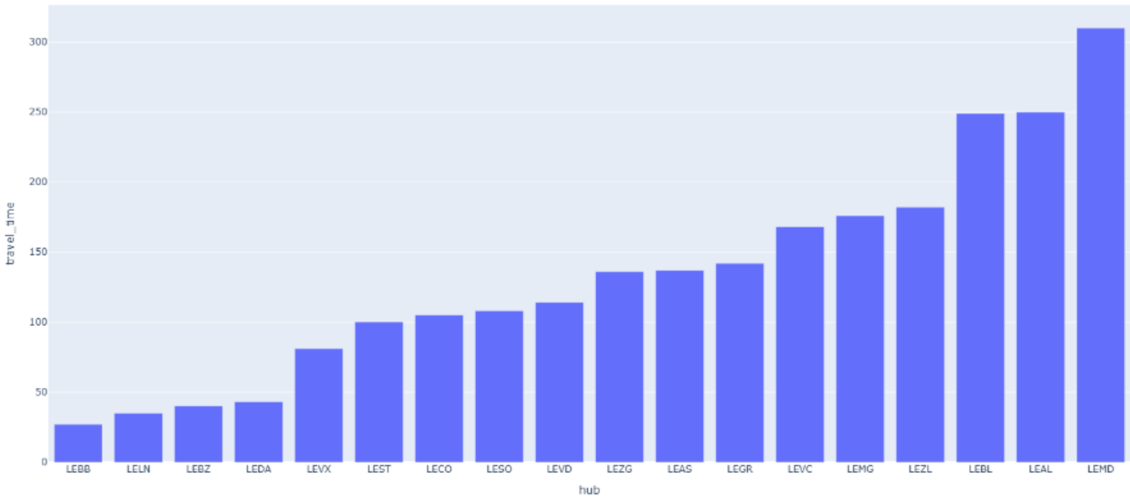

Figure A.3: Catchment area of airports in the cs10.pp00.nd02.so00.00 (before the application of SOL400/SOL2)

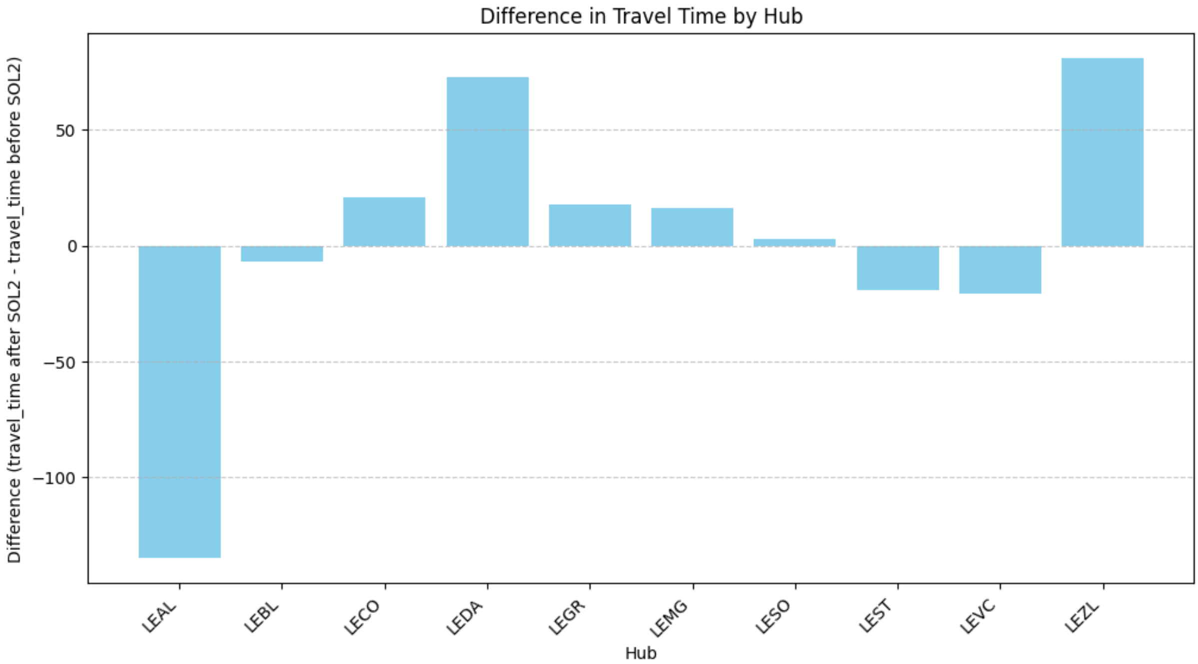

Figure A.4: Difference in time travel from an airport before and after the application of SOL400/SOL2 in the cs10.pp00.nd02 scenario.

Experiment 2 results

scenario	seamless of travel
cs10.pp20.nd02.so00.00	83.04%
cs10.pp20.nd02.so10.01	80.70%

Table A.23: Seamless of time after the application of SOL400/SOL2 in the cs10.pp20 scenario

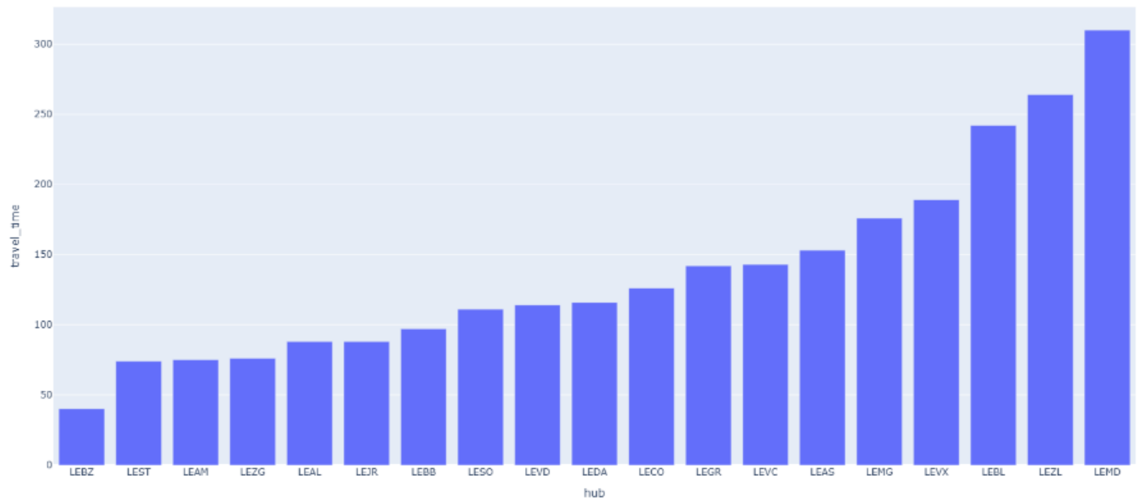

Figure A.5: Catchment area of airports in the cs10.pp00.nd02.so00.00 (before the application of SOL400/SOL2)

Figure A.6: Difference in time travel from an airport before and after the application of SOL400/SOL2 in the cs10.pp20 scenario. Positive times mean greater catchment area after the application of SOL400/SOL2.

Experiment 3 results

Seamless of travel and catchment areas of airports were not measured for each regional archetype since they are not relevant in this situation.

Discussion

Since all the indicators have been measured, both validation objectives are considered successfully achieved. Additionally, we present here a brief analysis of the results.

Seamless of travel decreases after the application of SOL400/SOL2. This is due to the fact that SOL400/SOL2 increases the demand in connected itineraries, and is capable of generating more itineraries for a given OD pair. In this situation, more people travelling also usually means more people travelling in different itineraries (hence, more people travelling in sub-optimal itineraries), hence generating this decrease.

Changes in catchment area of airports are harder to interpret. If more itineraries are generated, then catchment area can increase, since the airport might be connected to a further away region. However, if connecting itineraries are optimised, catchment area of a given airport might decrease as a result. Whether the situation of a given airport is better or worse has to be analysed in a case-by-case basis. We observe that SOL400/SOL2 changes the situation regarding this indicator.

A.3.2.4. OBJ-0400-ERP-040 Results

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

Validation criterion: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, catchment area of airports).

Co-funded by the European Union

Diversity of destination is a PI that measures to how many regions (at a NUTS3 statistical level) a given region is connected to. It is calculated using the itineraries calculated by SOL399/SOL1. Given an OD pair, passenger time efficiency gives an idea on how many passengers can travel in the "best possible option" with the best possible option defined as the fastest one. The closer this indicator is to 100% the better. The final indicator is the average per OD pairs.

Experiment 1 and 4 results

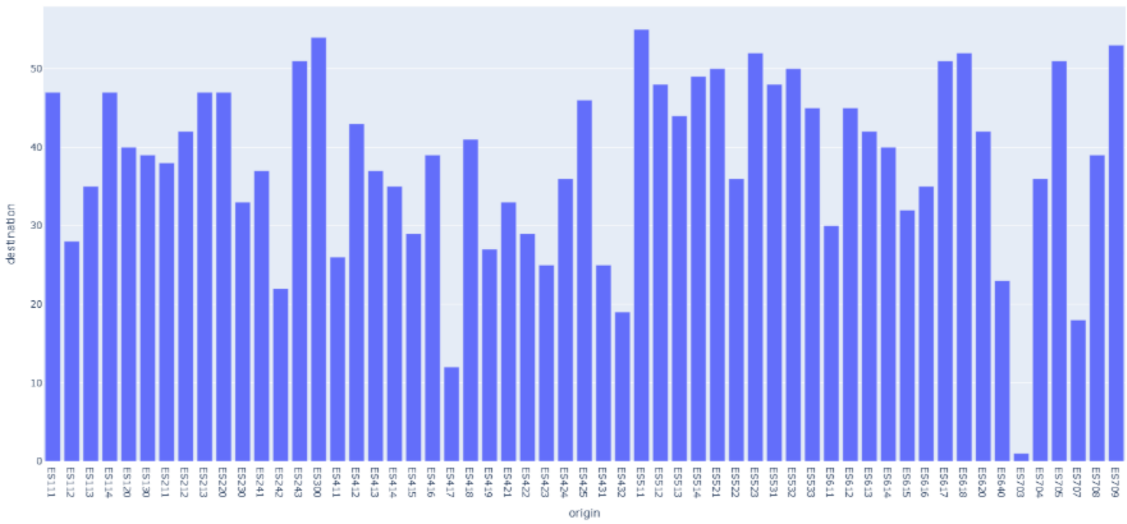

Figure A.7: diversity of destination in scenario cs10.pp00.nd02.

scenario	pax_time_efficiency__total
cs10.pp00.nd02.so00.00	87.75%
cs10.pp00.nd02.so10.01	87.78%
cs10.pp00.nd02.so10.02	87.76%

Table A.24: passenger time efficiency after successive applications of SOL400/SOL2 in the cs10.pp00 scenario

scenario	pax_time_efficiency__total
cs10.pp20.nd02.so00.00	87.96%
cs10.pp20.nd02.so10.01	87.98%

Table A.25: passenger time efficiency after successive applications of SOL400/SOL2 in the cs10.pp20.nd02 scenario

Experiment 2 results

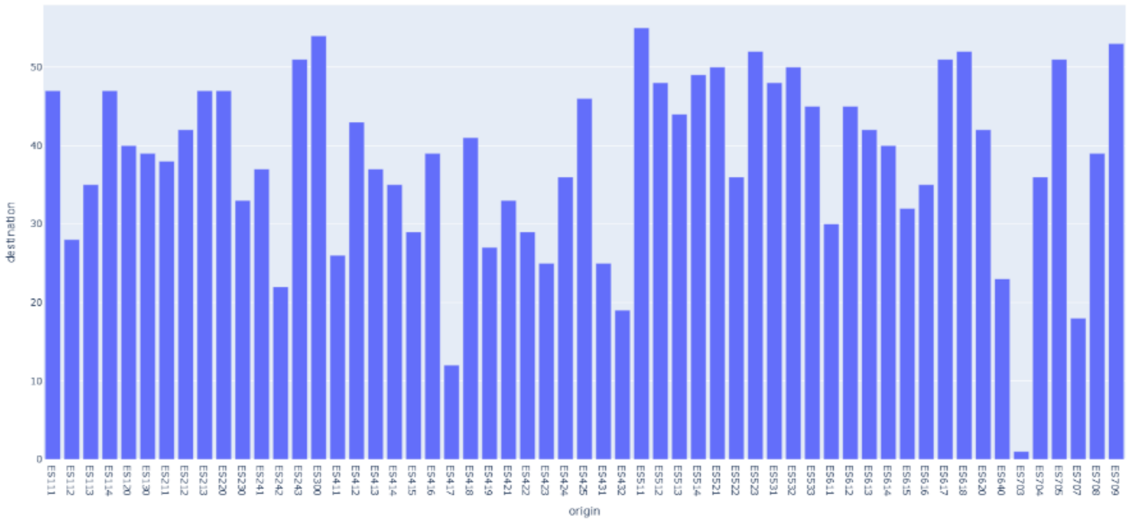

Figure A.8: diversity of destination in scenario cs10.pp20

scenario	pax_time_efficiency__total
cs10.pp20.nd02.so00.00	87.96%
cs10.pp20.nd02.so10.01	87.99%

Table A.26: passenger time efficiency after successive applications of SOL400/SOL2 in the cs10.pp20.nd02 scenario

Experiment 3 results

The PIs not measured for each regional archetype since they are not relevant in this situation.

Discussion

Diversity of destinations does not vary after the application of SOL400/SOL2, i.e., if two regions were not connected before the application of SOL400/SOL2, they will remain that way, and vice versa. The objective of SOL400/SOL2 are maximising demand served, minimising waiting times, and minimise the deviation from the original schedules. None of these objectives directly contributes to add new connection to the air and rail network, unless there is significant demand between two currently not connecting regions. This can therefore explain why this PI remains un-changed, and means that all the connections of the network are relevant for the current objectives of SOL400/SOL2 since, none of them is removed

Regarding catchment area of airports, the change of this indicator usually is a consequence of one of the two things:

- Existing connections to the airport improving due to schedule optimisation. For example, in the cs10.pp00.nd02 scenario, catchment area of the airport LEAL (airport of Alicante), improves from 250 minutes to 115 minutes because of improvements in the connection LEAL to Alicante main station improves dramatically. This creates a decrease in the indicator.

- New connections are created. for example, in the cs10.pp00 scenario A Coruña airport (LECO) becomes connected with a new train from the station San Cristobal of A Coruña which is slower than the previous one, making the catchment area increase from 105 minutes to 126 minutes.

Passenger time efficiency does not improve after successive iterations of SOL400/SOL2, it stays roughly the same.

Due to passenger time efficiency and diversity of destinations not significantly improving, we consider that the status of this objective is partially achieved.

A.3.2.5. OBJ-0400-ERP-050 Results

Objective: Generate air and rail coordinated schedules that improve the network multimodal alternatives.

Validation criterion: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (diversity of destinations, passenger time efficiency, total journey time).

All these PIs have been measured and analysed in previous section, so we go straight to the analysis of the research objective.

Discussion

We have already seen that neither diversity of destination, nor passenger time efficiency improve, but none of them decreases significantly. Total journey time increases or decreases depending on the scenarios (see section A.3.2.2. for a full analysis of this indicator). Both an increase or a decrease in total journey time can mean an improvement of the multimodal network. Given that demand served does not decrease, and total time on average and in connecting itineraries decrease, we consider that this indicator improves after schedule optimisation. Therefore, we consider that this objective is partially OK.

A.3.2.6. OBJ-0400-ERP-060 Results

Objective: Generate air and rail coordinated schedules that take into account timetable deviation.

Validation criterion: For all experiments timetable deviation should be measured and analysed.

Experiment 1 and 4 results

The results regarding timetable deviation are summarise below.

Co-funded by the European Union

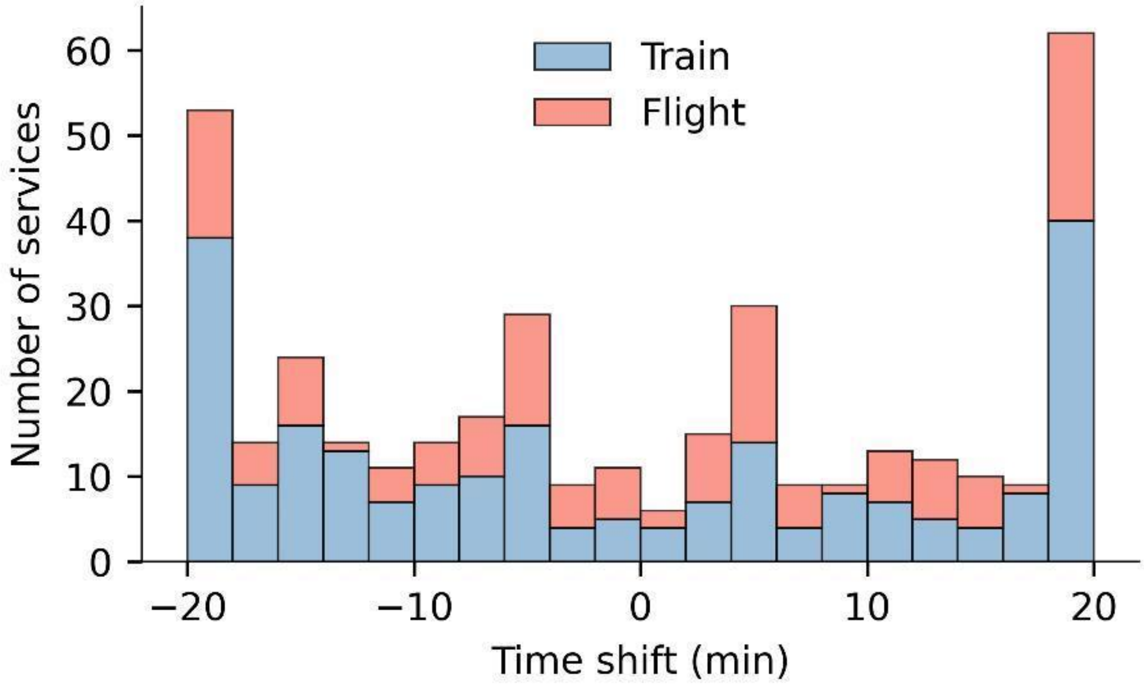

Figure A.9: Timetable deviation between cs10.pp00.nd02.so00.00 and cs10.pp00.nd02.so10.01

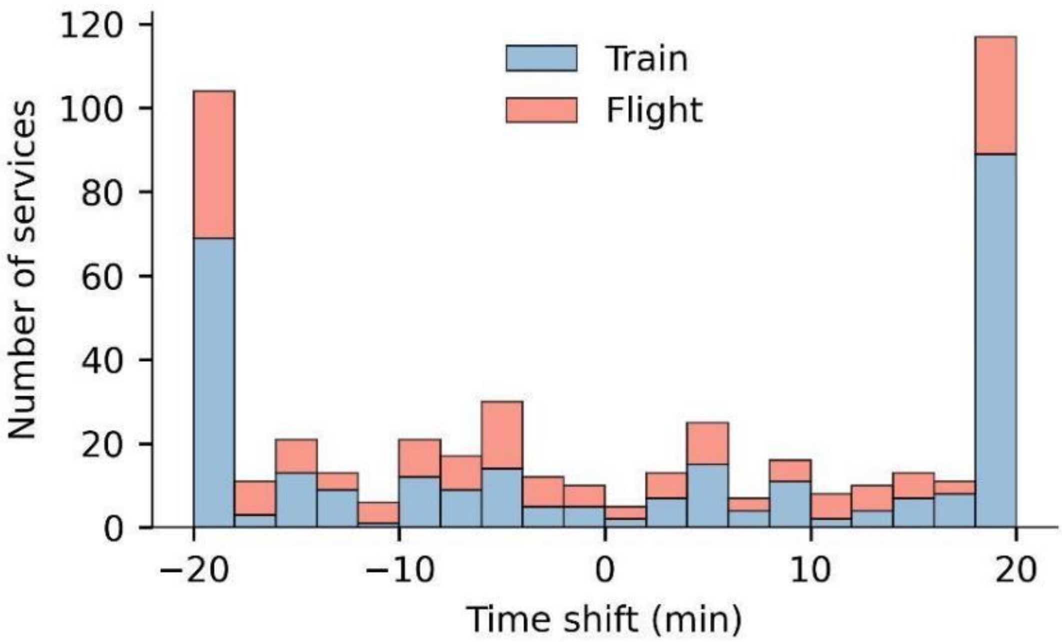

Figure A.10: Timetable deviation between cs10.pp00.nd02.so00.00 and cs10.pp00.nd02.so10.02

These tables show how much are schedules shifted after one or two applications of SOL400/SOL2. We see that mostly trains are shifted, and that most trains and planes are shifted by 20 minutes – which is

Co-funded by the European Union

the maximum shift allowed by the model –, especially after a second application of SOL400/SOL2. This indicates that relaxing the 20 minutes constraint could lead to even better results. A first step towards this direction could be relaxing these constraints only for rail services.

Experiment 2 results

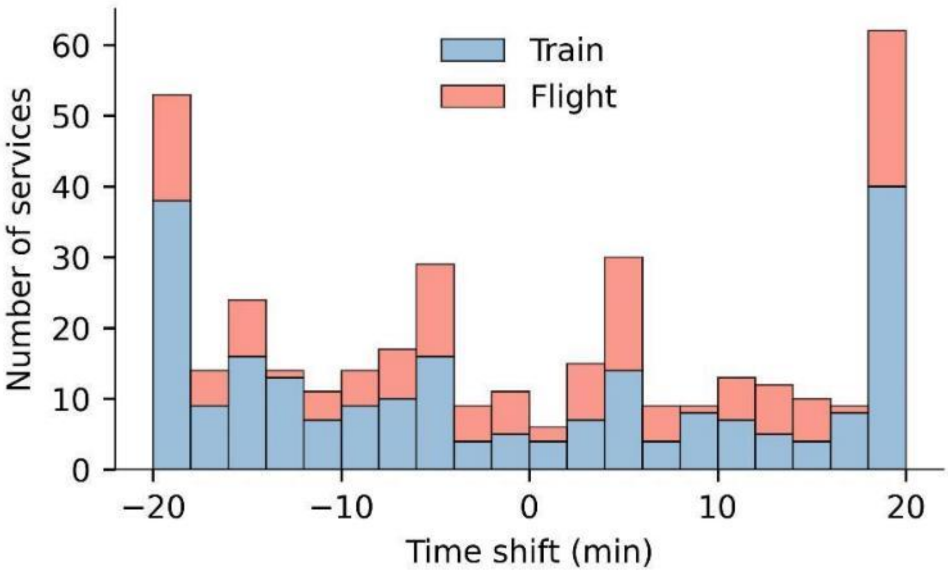

Figure A.11: Timetable deviation between cs10.pp20.nd02.so00.00 and cs10.pp20.nd02.so10.01

The same dynamic happens here, mostly train services are shifted, and most of them are shifted by the maximum amount allowed by the model, i.e., 20 minutes

Experiment 3 results

Timetable deviation was not measured for each regional archetype.

Discussion

Since timetable deviation has been measured and analysed, we consider that the status of this objective is achieved.

A.3.2.7. OBJ-0400-ERP-070 Results

Objective: Generate air and rail coordinated schedules that make a more efficient use of the network and services.

Validation criterion: For all experiments, the selected PIs after the application of SOL400/SOL2 should be better than before its application (load factor, direct operating costs per user).

Experiment 1 and 4 results

The results regarding load factor are presented in the following two tables

scenario	load_factor
cs10.pp00.nd02.so00.00	68.10%
cs10.pp00.nd02.so10.01	68.26%
cs10.pp00.nd02.so10.02	68.27%

Table A.27: load factor between successive applications of SOL400/SOL2

The operating costs per user are presented here:

scenario	operating costs per user (euros)
cs10.pp00.nd02.so00.00	54.41
cs10.pp00.nd02.so10.01	54.49
cs10.pp00.nd02.so10.02	54.40

Table A.28: operating costs after successive applications of SOL400/SOL2

Experiment 2 results

The load factor of the network is presented in the next two tables

scenario	load_factor
cs10.pp20.nd02.so00.00	68.80%
cs10.pp20.nd02.so10.01	68.95%

Table A.29: load factor before and after the application of SOL400/SOL2

mode	load_factor_before_SOL400/SOL2	load_factor_after_SOL400/SOL2
flight	66.65%	67.10%
rail	71.08%	70.89%

Table A.30: load factor for air and rail before and after the application of SOL400/SOL2

The results regarding costs are presented here:

scenario	operating costs per user (euros)
cs10.pp20.nd02.so00.00	54.98
cs10.pp20.nd02.so10.01	55.01

Table A.31: operating costs per user before and after the application of SOL400/SOL2

Experiment 3 results

Load factor was not measured for each regional archetype.

Discussion

Regarding load factor, we see a very slight increase in load factor in all situations and for all modes, except for rail in the cs10.pp20.nd02 scenario, for which load factor decreases slightly. These results although positive overall are not very significant. Note that we can see the effect of the flight ban by comparing the load factors for air and rail between cs10.pp00.nd02 and cs10.pp20.nd02. Something worth mentioning is that, for all scenarios analysed, load factor is around 2/3 of the of the maximum capacity of the services. Considering that demand served is around 80% (meaning that around 1 over 5 people wants to travel but cannot), there is room for improvement in the multimodal network. We also note that SOL400/SOL2 only modify the connecting itineraries, and hence its effect on load factor is also limited.

Operational costs per user do not decrease after the application of SOL400/SOL2. This can be understood paired with the fact that load factors do not improve significantly, and neither does demand served. Up to a certain extent, part of the increase in operational costs in cs10.pp20.nd02 can be attributed to people shifting from rail to air.

Given that the change in these indicators is not negative per se, but is not very significant, we consider that the status of this validation objective, regarding this experiment is Partially achieved.

A.3.2.8. OBJ-0400-ERP-080 Results

Objective: Generate air and rail coordinated schedules that decrease passengers' CO_2 emissions.

Validation criterion: For all experiments, CO_2 emission after the application of SOL400/SOL2 should be better than before its application.

Experiment 1 and 4 results

scenario	CO_2 emissions per passenger
cs10.pp00.nd02.so00.00	20.62
cs10.pp00.nd02.so10.01	20.66
cs10.pp00.nd02.so10.02	20.61

Table A.32: CO_2 emissions (in grams of CO_2) per passengers after successive applications of SOL400/SOL2

Co-funded by the European Union

Experiment 2 results

scenario	CO_2 emissions per passenger
cs10.pp20.nd02.so00.00	19.90
cs10.pp20.nd02.so10.01	19.92

Table A.33: CO_2 emissions before and after the application of SOL400/SOL2

Experiment 3 results

CO_2 emissions were not measured for each regional archetype.

Discussion

CO_2 emissions are not better after the application of SOL400/SOL2, they are very similar. As commented previously this could be due to the fact that load factors and served demand do not improve significantly. As CO_2 is not significantly worse after the application of SOL400/SOL2 we consider that this objective is partially achieved.

A.3.3 Unexpected behaviours/results

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

- We observe a decrease in global demand served. In scenario cs10.pp00.nd02.so10.01, demand served decreases ever so slightly after the application of SOL400/SOL2. This would be due to less passenger being able to travel as a result of schedule optimisation. Although this is decrease is minimal and has no impacts on other performance indicators, it is surprising. It could be due to unexpected behaviours in the coordination of SOL399/SOL1 and SOL400/SOL2.

- The impact on served demand, load factor, cost and CO2 emissions is less than expected. As we have covered already, due to its geographical nature, the Spanish air and rail network is composed of mostly direct itineraries, and SOL400/SOL2 modifies only connecting itineraries. This can explain in part the modest results obtained in these itineraries that look at an overall network level. For future work, we could disaggregate some of these indicators to focus on connecting itineraries, and we want to add international flights to the Spanish air and rail network. This addition is expected to bring much more multimodal itineraries to the network. Additionally, allowing service re-routing holds the promise to improve these indicators.

A.3.4 Confidence in results of validation exercise #01

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

By providing several scenarios, a certain generality of the approach regarding regional archetypes and scheduling situations is already enforced. Of course, different future scenario considerations for different entities, cities or airlines may have different geographical or political situations with different assumptions to consider (e.g. international competition). However, the Schedule Design Solution should be efficient as the network (OD pairs) and demand (through the passenger archetypes, the related demand flows, and sensitivities) have been well defined.

In terms of data, their use and availability, there are some limitations too. For example, we used past operational data to create our planned schedules, treating it as a guide for future planning. For the demand, we used Mobile Network Data (MND). Despite having accurate information about the mode used for the considered individuals (plane, rail or multimodal), we do not have as accurate information about the path and the itinerary taken, hence some assumptions about these have to be made. In the case of international travel, we have to infer the departure/destination airport.

Lastly, we acknowledge that the Spanish air and rail networks offers some limitations in show-casing 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, and with the consideration of longer distance trips such as to-from the Canary Islands from all the peninsula regions in Spain. As mentioned above, only intra-Spain (domestic) services are considered due to data limitations. We acknowledge that some of the indicators calculated in this validation exercise are less good than originally predicted due to the unimodal nature of the Spanish air and rail network. However, many multimodal trips happen in international context. Therefore, the next priority will be creating a scenario with international services from/to Spain.

Although the Spanish passenger archetypes are representative of the MultiModX passenger archetype, missing the "short distance traveller" archetype is a limitation.

A.3.4.2. Quality of validation exercises results

Since the exercise is composed of simulations, 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.3.4.3. 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.4 Conclusions

A.4.1 Conclusions on concept clarification

With this validation exercise, SOL400/SOL2 has proven to fulfil at least partially all the research objectives proposed in the ERP.

It should be noted that SOL400/SOL2, as a schedule optimiser, only focuses on optimising itineraries with connections, and therefore does not have an impact on the network as a whole. The more multimodality is already in place in the original network, the more potential for improvement SOL400/SOL2 brings. With that being said, SOL400/SOL2 has proven its operational feasibility by optimising a multimodal transport network in a way that can later be assessed by SOL399/SOL1 Strategic Performance Evaluator.

A.4.2 Conclusions on technical feasibility

SOL400/SOL2 fulfils all the functional requirements outlined in the FRD. We note that the requirement REQ-SOL400-OP-SD05.001, “SOL400 (SOL400/SOL2) shall optimised train and flight schedules using time-based and route-based strategies” is only partially fulfilled since route-based strategies (re-routing) are still work in progress.

A.4.3 Conclusions on performance assessments

As discussed in the ECO-EVAL, given its multimodal status SOL400/SOL2 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 in multimodality. More information about MultiModX performance framework can be found in SOL399/SOL1 deliverables.

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

- Efficiency. SOL400/SOL2 has a positive impact on this KPA, reducing buffer times and total journey times.
- Interoperability. SOL400/SOL2 has a limited impact on this KPA, minimally affecting the modal share.
- Flexibility. SOL400/SOL2 is able to modify the resilience of a given OD pair, but so far, not the diversity of destinations.
- Cost effectiveness. SOL400/SOL2 in its current implementation has a limited impact on this KPA.
- Capacity. SOL400/SOL2 has a limited impact on this KPA, improving catchment area of airports and in some cases modal share
- Environment. SOL400/SOL2 in its current implementation has a very little impact on this KPA.

A.5 Recommendations

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

- Some of the PIs, for example, load factor and CO_2 emissions could be disaggregated for connecting itineraries. This would allow us to identify better the impacts of SOL400/SOL2 in the itineraries that it targets. This can be implemented in the next version of MultiModX impact assessment framework
- In order to better observe the impacts of SOL400/SOL2 we should focus on air and rail network with a high proportion of connecting itineraries, independently if they are multimodal or single mode itineraries. For this reason, our next priority is to add the international trips to the Spanish network.
- Re-routing can be implemented, in order to maximise potential gains of schedule optimisation. This is already work in progress

EUROPEAN PARTNERSHIP
Co-funded by the European Union

- The 20 minutes service deviation constraints could be relaxed in certain settings to explore new possibilities.
- The integration of SOL400/SOL2 and SOL399/SOL1 should be revised to ensure served demand does not decrease following several successive implementations of SOL400/SOL2.

EUROPEAN PARTNERSHIP
Co-funded by the European Union

Appendix B Validation exercise #02 report

B.1 Summary of the validation exercise #02 plan

As in the ERP SESAR Solution 400.

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 both:

- the relevance of the model, the objectives, the resolution approach, the constraints, and the assumptions of the Solution;
- the interest of the results and calculated performance indicators (Section 4.3).

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 Schedule Design 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-0400-ERP-010. Generate air and rail coordinated schedules that accommodate as much passenger demand as possible
- EX02-OBJ-0400-ERP-070. Generate air and rail coordinated schedules that make a more efficient use of the network and services.

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 were 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 exercises	Exercise validation objective	Exercise success criteria
EX02-OBJ-0400-ERP-010	EX02-CRT-0400-ERP-010.2	Fully covered	Generate air and rail coordinated schedules that accommodate as much passenger demand as possible	A majority of stakeholders considers that the defined passenger archetype is representative of reality
EX02-OBJ-0400-ERP-070	EX02-CRT-0400-ERP-070.2	Fully covered	Generate air and rail coordinated schedules that make a more efficient use of the network and services.	The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).

Table B.1: List of objectives and success criteria

B.1.3 Summary of validation exercise #02 validation scenarios

Since this exercise consisted in presenting SOL400/SOL2 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. Validations assumptions.

B.2 Deviation from the planned activities

There are no deviations with regard to the final version of the ERP.

EUROPEAN PARTNERSHIP
Co-funded by the European Union

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-0400-ERP-010	Generate air and rail coordinated schedules that accommodate as much passenger demand as possible	EX02-CRT-0400-ERP-010.2	A majority of stakeholders consider that the defined passenger archetypes considered within the project are representative of reality in validation exercise #2	N/A	Answers: • yes: 11 • no: 4	OK
OBJ-0400-ERP-070	Generate air and rail coordinated schedules that make more efficient use of the network and services	EX02-CRT-0400-ERP-070.2	The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10) in validation exercise #2	N/A	Grades of the parameters considered: min=5.1, max=9.1, avg=6.91. Grades from the adjustment strategies: min=5, max=7.4, avg=5.95	OK

Table B.2: validation exercise #02 results

The sub-sections below are indicative, and the project can add additional ones if required depending on the scope of validation exercise #02.

Co-funded by the European Union

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

B.3.2.1. OBJ-0400-ERP-010 Results

Objective: Generate air and rail coordinated schedules that accommodate as much passenger demand as possible

Validation:

To accommodate as much passenger demand as possible within the newly coordinated rail and air schedules, it is essential to identify and include the different passenger archetypes present in the demand. Only by doing so will we be in a position to provide a realistic picture that accurately reflects the actual situation.

The MultiModX passenger archetypes were developed using MND (Mobile Network Data) for Spain and similar data sources containing information about trips taken and socio-demographical characteristics of the German population. The different archetypes are based on factors like travel frequency, purpose, and preferred mode of transport. Thus, this approach aims to more accurately reflect passenger needs and preferences.

The passenger archetypes developed during the model are:

1. The short-distance traveller: individuals that make short trips or do not travel at all.
2. The sporadic GenX traveller: individuals that travel for long distances in off-peak periods.
3. The working-age weekday traveller: long distance trips, especially during the workweek.
4. The summer traveller: individuals who tend to travel very long distances, exclusively during the summer.
5. The habitual traveller: individuals who travel with high frequency, typically domestic destinations
6. The sporadic global traveller: individuals who travel to international destinations, with no seasonality preference
7. The holiday globetrotter: individuals who travel to international destinations, especially during holiday periods.

These passengers have different preference when choosing modes, and these are taken into account when assigning them to an itinerary.

During the second Industry Board (IB) meeting, the proposed passenger archetypes were presented, and several questions were raised to assess whether this section was complete and representative of reality. This process aimed to support the overall objective of accommodating the highest possible demand within the newly updated itineraries.

Figure B.1 shows the results of one of these questions, in which participants were asked: *"Should MultiModX consider an additional passenger archetype?"* Fifteen experts in rail, aviation, and transportation answered the question — eleven responded "no" and four responded "yes." These results suggest that the proposed archetypes are indeed representative of the current reality, and therefore this objective can be considered fulfilled.

Co-funded by
the European Union

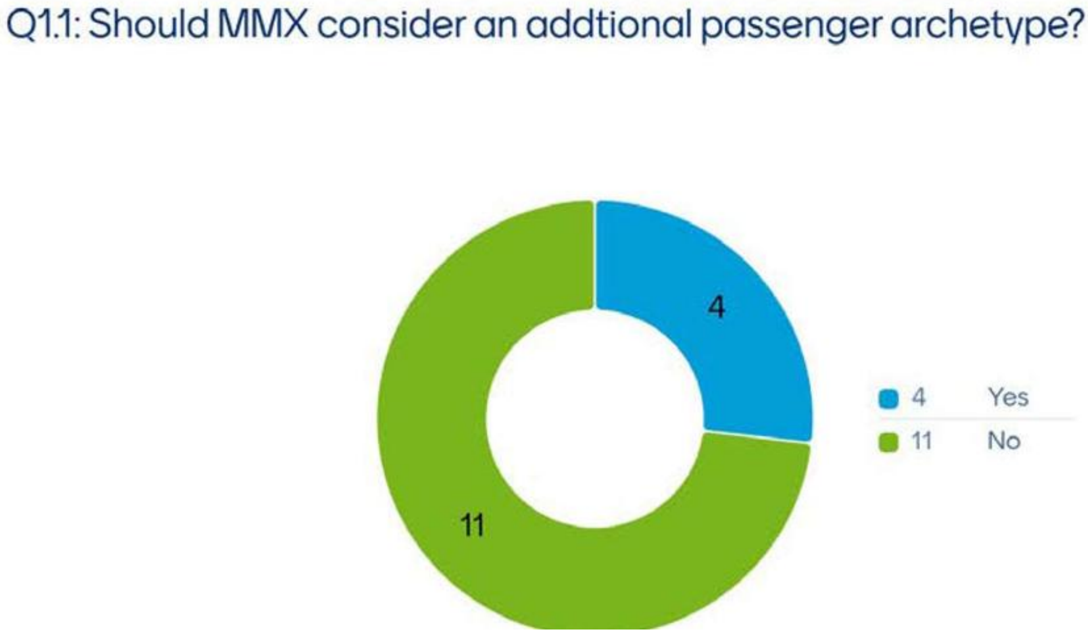

Figure B.1: Answers to the question *Should MMX consider an additional passenger archetype*

B.3.2.2. OBJ-0400-ERP-070 Results

Objective: Generate air and rail coordinated schedules that make a more efficient use of the network and services.

Validation criterion: The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).

Objective: Generate air and rail coordinated schedules that make a more efficient use of the network and services.

Validation criterion: The adjustment strategies are judged relevant for the stakeholders (i.e., they receive an interest score higher or equal to 5/10).

To develop coordinated timetables that make efficient use of the network and available services, it is essential to design a set of adjustment strategies aimed at optimizing the variables most relevant to users.

To this end, during the second IB meeting, experts were asked to assess the relevance of several parameters—such as transfer time, minimum door-to-door time, infrastructure connectivity, served demand, transport costs, revenues, and environmental impact—when evaluating timetables.

Responses were collected using a Likert scale from 0 to 10, where 0 indicated “not relevant at all” and 10 indicated “highly relevant.” The results, shown in Figure B.2, were as follows:

- Transfer time: 9.1
- Minimum door-to-door time: 7.5
- Infrastructure connectivity: 6.3
- Served demand: 6.8

- Transport costs: 8.3
- Revenues: 5.1
- Environmental impact: 5.3
- Others: 0.4

The average score across all parameters (excluding "Others") was 6.91. The lexicographic objective function of SOL400/SOL2 focuses on maximizing served demand (6.8), minimizing transfer times (9.1), and reducing timetable deviations. Therefore, these results help validate the main objectives of the SOL400/SOL2 solution.

Additionally, experts were asked to evaluate the relevance of different adjustment strategies considered in the project, such as: timeshift (air), timeshift (rail), new services (air), new services (rail), rerouting (air), rerouting (rail), cancellation (air) and cancellation (rail). This question also used a 0–10 Likert scale. The responses, also shown in Figure B.3, were as follows:

- Time shift (air): 5.0
- Time shift (rail): 6.4
- New services (air): 5.4
- New services (rail): 6.1
- Rerouting (air): 7.4
- Rerouting (rail): 5.5
- Cancellation (air): 6.7
- Cancellation (rail): 5.1

All strategies received a score of 5.0 or higher, with an average score of 5.95 across all options.

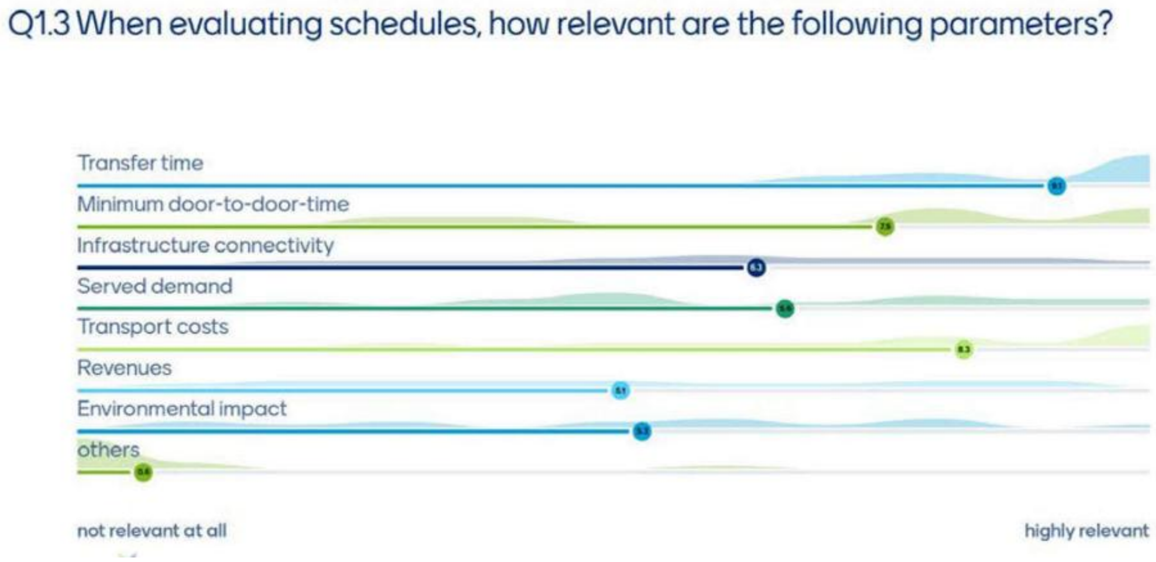

Figure B.2: Answers to the question *When evaluating schedules, how relevant are the following parameters?*

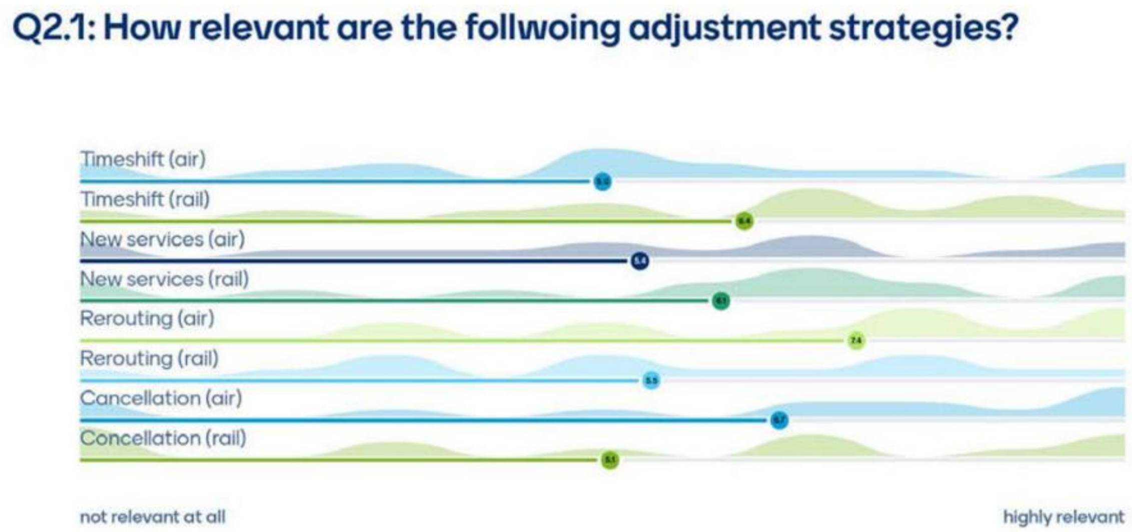

Figure B.3: Answers to the question ***How relevant are the following adjustment strategies?***

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 profile 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 SOL400/SOL2 could be shown in the presentation. Despite the fact that SOL400/SOL2 was adequately introduced, this constitutes a limitation of the results. Only the assumptions basing SOL400/SOL2 are validated in this exercise. The outputs of SOL400/SOL2 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 SOL400/SOL2, rather the assumptions on which the Schedule Design Solution (SOL400/SOL2) is based. The quality of the results is influenced by the number of the stakeholders (a greater sample is always better).

EUROPEAN PARTNERSHIP
Co-funded by the European Union

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 Schedule Design Solution (SOL400/SOL2). The questions asked were relevant on how to attack the problem of Schedule optimisation 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 SOL400/SOL2

- provides optimised flight schedules and rail timetable (REQ-SOL400-OP-SD00.001);
- takes into account the demand disaggregated by the passenger archetypes as an input (REQ-SOL400-FR-SD01.001);
- uses the lexicographic optimisation method optimising for unserved demand, waiting times and timetable deviation (REQ-SOL400-FR-SD05.001);
- optimise schedules using time-based but also route based strategies (REQ-SOL400-OP-SD05.001).

The result of this validation exercise has been key to the design and implementation of these functional requirements of SOL400/SOL2.

B.4.3 Conclusions on performance assessments

The MultiModX Key Performance areas evaluated during this exercise are

- capacity;
- cost effectiveness.

By validating the passenger archetypes, we are validating the split of the demand and the inputs of SOL400/SOL2, which include the demand disaggregated by passenger archetype. Passenger archetypes have different preferences regarding the mode of transport they want to travel with, which influences the overall capacity of the network.

By validating the parameters and the adjustment strategies, we are ensuring that the optimised schedules are realistic and comply with the industry constraints. This has an impact on the cost effectiveness KPA since the constraints determine how much the initial timetable can be modified. The benefits associated with a completely “free” timetable might be greater, but if the resulting schedules are not feasible, they are not useful. From the answers to the question regarding optimisation strategies, we conclude that air and rail must follow very different strategies. Airlines have slots in the airports. These are valuable assets and they are reluctant to give them up. Therefore, strategies that involve rerouting rather than timeshift are judged more relevant. Rail operators, on the other hand, cannot reroute a service so easily, so timeshift strategies are preferred.

B.5 Recommendations

Due to the limited reach of this validation exercise, the recommendations regarding SOL400/SOL2 are assessed in chapter 5 of the main deliverable and in chapter A.5.

EUROPEAN PARTNERSHIP

Co-funded by
the European Union