DES HE SESAR solution 400 OSED

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Abstract

This document outlines the operational service and environment definition (OSED) for the Schedule Design Solution (SOL2 of MultiModX, TRL2) which aims to design passenger-centric coordinated multimodal schedules for air and rail. The document describes the detailed operational environment and operating method of the SOL400/SOL2, as well as its potential uses cases and the assumptions that were taken in its development. This document is the final version of the deliverable.

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MultiModX

INTEGRATED PASSENGER-CENTRIC PLANNING OF MULTIMODAL NETWORKS

MultiModX

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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

This document outlines the operational service and environment definition of the solution.

The key assumptions to the operational service are that the set of passenger archetypes considered are representative for the entirety of travellers and that there exists multimodal governance to put in place the mutual scheduling of air and rail.

The main stakeholders impacted by the Schedule Design Solution are the aviation and rail community through their schedulers.

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2 Introduction

2.1 Purpose of the document

The purpose of this document is to provide a comprehensive definition of the operational service and environment for the SOL400/SOL2 of MultiModX at TRL2.

This document aims to describe the detailed operational environment, including the operational characteristics, the roles and responsibilities impacted by SOL400/SOL2 and the applicable standard and regulations. Furthermore, it describes the detailed operating method of SOL400/SOL2 and its improvements in regard to the previous operating method for scheduling and coordinating multimodal schedules.

This document serves as a foundational reference for all stakeholders involved in SOL400/SOL2, including project managers, developers, regulatory bodies, and end-users. By providing a detailed operational service and environment definition, this document aims to facilitate the successful implementation and operationalisation of SOL400/SOL2.

2.2 Scope

The OSED presents the operational service and environment of the Schedule Design Solution. The overall scope of the OSED covers the definition of the operational characteristics foreseen as part of the SOL400/SOL2 of MultiModX. Further on is the implementation of the methods and algorithms for integrated schedule design in two iterations:

- implementation of an integrated multimodal schedule design, optimising the schedules for both air and rail services. The optimisation will be based on a mathematical representation of the multimodal scheduling problem for a multi-level network using mixed-integer linear programming. The Schedule Design Solution will take the expected demand levels, the capacity of all modal networks, and the available resources as inputs.

The outcome of the Schedule Design Solution will be a set of schedules for air and rail to be evaluated by the Performance Assessment Solution (SOL1). The solution is able to provide the expected output schedules for the project's case studies.

These activities **address the Objective O4 of the project** as stated by the Grant Agreement (GA):

- Analysis of functional requirements and existing models and algorithms for rail and air schedule design.
- New coordination and cooperation principles for multimodal schedule design.

- Mathematical optimisation models and algorithms for optimal multimodal schedule design considering passenger behaviour (e.g. preferences/constraints regarding transfer times), available vehicles (aircraft, rolling stock), infrastructure capacity, and interdependencies between the air and rail networks.
- Experimental testing and evaluation of the new integrated Schedule Design Solution.

2.3 Intended readership

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

2.4 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 [1] 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 [2] project.

The approaches for optimal railway timetabling from EU FP7 project ON-TIME [3], such as micro-macro models [4], and the integrated passenger-centric multimodal scheduling algorithms from the ERA-NET SORTEDMOBILITY [5] project, like MASP [6], 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 [7] 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 [8] 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 [9] 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 [10], 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 [11], 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 [12] 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 airport. 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.

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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.

2.5 Structure of the document

This document describes the operational and technical characteristics of the Schedule Design Solution (SOL400/SOL2). First, the detailed operational environment will be explained in Section 3.2, through the description of the operational characteristics, the roles and responsibilities involved in the solution and the applicable standards and regulations. Then, the detailed operating method will be developed, along with the improvement to the current operating method. The different use cases will be described. Finally, in Section 4, the key assumptions under which this solution has been developed will be detailed.

2.6 Glossary of terms

Term	Definition	Source of the definition
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
path	A succession of nodes (airports, rail stations) in the graph which represent a possible or potential succession of nodes to travel from a given origin to a given destination.	own elaboration
itinerary	A succession of services (flights or trains) which represent a possible trip for a passenger.	own elaboration
service	A specific train or plane, defined by its starting and ending station/airports and its schedule	own elaboration
unserved demand	Passenger demand that cannot be assigned to specific services either before or after the Schedule optimisation.	own elaboration
air and rail network	Collection of nodes (representing airports or train stations) and relations (connections or transfers) between the nodes.	own elaboration
lexicographic optimisation	multi-objective optimisation method for which the functions to optimised are ranked based on importance.	own elaboration

Table 1: glossary of terms

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2.7 List of acronyms

Term	Definition
ATM	Air traffic management
CNS	Communication navigation surveillance
DES	Digital European Sky
ERP	Exploratory research plan
GA	Grant agreement
ID	Identifier
MS	Milestone
OSED	Operational service and environment description
SESAR	Single European sky ATM research
SESAR 3 JU	SESAR 3 Joint Undertaking
TRL	Technology Readiness Level
DCB	Demand Capacity Balancer

Table 2: list of acronyms

3 Operational service and environment definition (OSED)

3.1 Schedule Design Solution: 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 KPIs 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) and route-based strategies (i.e. new service and service cancellation) 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.

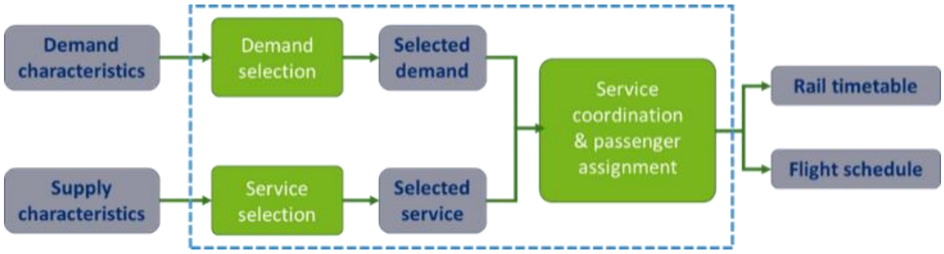

Figure 1: Overview of SOL400/SOL2

SESAR solution ID	SESAR solution title	SESAR solution definition	Justification (why the solution matters?)
SOL400	Schedule Design Solution	Scheduler able to optimise air and rail networks jointly while taking into account capacity constraints and passenger demand	The expected evolution of the SESAR Master Plan considers the inclusion of Passenger Experience as one of the areas where PIs and KPIs will be developed. Moreover, multimodality is taken into account in the latest version of the DES HE requirements, validation, and demonstration guidelines. Finally, the Fly the Green Deal objectives for 2050 states that 90% of the trips in Europe should be possible in less than 4 hours. Therefore, this Solution is a step forward towards passenger satisfaction and multimodal integration.

Table 3: Schedule Design Solution scope

3.1.1 Deviations with respect to the SESAR solution definition

There is no planned deviation to the original solution definition.

3.2 Detailed operational environment

3.2.1 Operational characteristics

It is assumed that the European ATM operational environment to be similar to the current operational environment. Required multimodality governance and enablers are in place (e.g. integrated ticketing and data exchanges), but no significant changes to the ATM operational environment are envisioned by SOL400/SOL2.

As the focus of SOL400/SOL2 is on optimised schedules particularly for multimodal journeys, the focus is on the type of mobility operational environment in which multimodality is supported. Therefore, the most relevant operational environment to assess the planning of networks in the context of multimodality is, as explained below, mid-to-long-distance trips where connectivity and multimodality can provide complementarity to reach less connected regions. Other aspects to consider in the operational environment are the policies that could be deployed to incentivise multimodality, as SOL400/SOL2 could optimise the network and support the overall demand between regions.

The following sections describe in more detail some of the aspects explained above to identify these operational environments that could benefit from SOL400/SOL2.

3.2.1.1 Overall multimodal operational aspects considerations

Overall, multimodal performance will be relevant in the case of:

- Mid-long distance mobility where air and rail options can be comparable in terms of travel time, can complement each other (e.g. having multi-leg trips with more than one mode of transport) and require connections,
- When a multimodal governance is in place.

3.2.1.2 European regional archetypes

European regional archetypes are identified at NUTS 2 level to map ‘travel regions’ types in Europe. The different European regions are classified based on the degree of applicability of multimodal solutions. This will facilitate the evaluation of the impact of multimodality at this ‘travel regions’ level, which could then be extrapolated to other regions of the same level even if not explicitly modelled. This creates, therefore, different suboperational environments based on these regional archetypes.

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

The clustering of the regions is performed considering:

- Socio-demographics (e.g. population density, shares of the population in different age brackets)
- Tourist volumes (e.g. arrivals at tourist accommodation)
- Transport infrastructure (e.g. number of airports, railway line density)
- Innovativeness (e.g. share of the population who ordered goods or services over the Internet)

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

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

SOL400/SOL2 can potentially have different impacts in all these regions. Advanced regions, tend to have more complicated air and rail networks, hence they have a lot of potential for optimisation. However, due to the frequencies of services, these networks might be close to their optimal configuration already and very close to maximum capacity. This is precisely the case of the rail corridor Madrid-Barcelona in Spain. Emerging rural regions tend to have a simpler network and less services, hence multimodal journeys from these regions tend to be long and cumbersome. SOL400/SOL2 could thus also bring potential benefits for these regions. A similar situation arises for conservative regions; they might have a more connected rail and air network, but usually do not enjoy the frequency of services of an Advanced region.

3.2.1.3 Multimodality policy packages

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

- Passenger rights and multimodality: Regulation 261, passenger rights, multimodal digital mobility services, extension of protections for enhanced multimodal passenger rights, and level of integrated ticketing, including operator alliances and rebooking policies.
- Limitation of aviation: Short-haul flight bans.
- Environmental regulations: frequent flyer levy, rail incentivisation, increased CO2 cost.

These policies can be grouped into policy packages which represent different representative operational environments, such as the ones described in Table 4.

Policy Package	Individual policies definition
Reference (no particular policies)	• Passenger rights and multimodality: No integrated tickets • Limitation of aviation: N/A • Environmental regulations: N/A
Multimodality incentivised	• Passenger rights and multimodality: Fully integrated (respecting alliances) • Limitation of aviation: N/A • Environmental regulations: CO2 tax applied to emissions
Multimodality enforced	• Passenger rights and multimodality: Fully integrated (respecting alliances) • Limitation of aviation: Short-haul ban if rail available between regions served by flights and rail service faster than a given threshold (2h30) • Environmental regulations: CO2 tax applied to emissions

Table 4: Example of possible policy packages

As stated in Assumption A5, and in line with the SESAR capability single ticketing, this project assumes that Multimodal governance is already in place. This is essential for the application of multimodal Schedulers such as SOL400/SOL2. Exactly how this multimodal governance is implemented is out of the scope of this project.

All the above-mentioned policies might impact the cost (e.g. with different fuel costs), the demand (e.g. encouraging some travel), the supply (e.g. banning some possible air links), the willingness to use multimodality by the passengers' archetypes (e.g. better protection and integrated ticketing facilities), etc. Therefore, these might motivate airlines and rail companies to cooperate and generate multimodal schedules. In the case of publicly own companies, this optimisation can happen even more easily. As the SOL400/SOL2 Schedule designer is a strategic tool, no tactical policies are considered.

3.2.1.4 Infrastructure characteristics

Besides the previously described mobility considerations, different sub-operating environments could be defined by focusing on the infrastructure characteristics: for example, particular infrastructure nodes which are more likely to be part of multimodal connections (e.g. hub airports with rail links to the airport (or nearby)); or collection of infrastructure nodes (airports and/or rail stations) in less connected regions which provide long-distance mobility by connecting these nodes to hubs using multimodal journeys.

3.2.1.5 Summary of operational environment characteristics

As described, there are different aspects that can be considered for the definition of the operational and sub-operating environments. These will be used to create the experiments in the ERP and/or to analyse the results, i.e., focusing on subparts of the network to produce performance indicators that capture the impact of multimodality on those environments. For example, computing indicators focusing on a given infrastructure node (e.g. a hub airport) after optimising schedules within a nation-wide mobility network.

The operational environments will, therefore, be a combination of regional archetypes, policy packages, and infrastructure characteristics. The experiments defined in the ERP will have to ensure that the different characteristics of the sub-operational environments can be captured.

3.2.2 Roles and responsibilities

We present here a table of possible roles and responsibilities regarding the use of SOL400/SOL2.

Note that it is assumed, according to assumptions A5 and A7 (see FRD) the existence of a multimodal governance, and of air and rail coordination, allowing thus cooperation and communication between the different modes of transport.

Stakeholder	Role	Description of the interaction with the Schedule Design Solution
Airlines	User	They will, in coordination with the rail operators, use the SESAR solution to improve and coordinate their schedule. They might be motivated by external policies or have an internal motivation to use it. Example of their motivations might be: improve general passenger experience, maximise service occupancy (due to improved schedules), minimise passenger travel times, etc. To use the Solution they will provide the necessary input files and run the code. SOL400/SOL2 shall be included in the software available to the user.
Rail Operators	User	They will, in coordination with the airlines, use the SESAR solution to improve and coordinate their schedule. They might be motivated by external policies or have an internal motivation to use it. Example of their motivations might be: improve general passenger experience, maximise service occupancy (due to improved schedules), minimise passenger travel times, etc. To use the solution they will provide the necessary input files and run the code. SOL400/SOL2 shall be included in the software available to the user.

Table 5: SOL400/SOL2 roles and responsibilities

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CNS/ATS description

The Schedule Design Solution is designed to modify the strategic schedule of the flights but not the tactical schedule. Therefore, it will have no impact in CNS/ATM.

3.2.3 Applicable standards and regulations

The Schedule Design Solution will not impact any existing standard or regulation. The existence of Multimodal Governance and coordination between air and rail (assumptions A5 and A7 of the FRD) would encourage the use of the Solution.

3.3 Detailed operating method

There are existing tools to generate separately optimised Schedules for air and rail, however, the Schedule Design Solution is able to optimise the entire network of air and train as a whole, by considering an air layer and a train layer and taking into account the transfer times between airports and train stations, and the passengers' demand.

3.3.1 Previous operating method

As of today, there is no coordination between airlines and railway operators.

3.3.2 New SESAR operating method

SOL400/SOL2 takes the supply (i.e. rail timetable and flight schedules) and demand (i.e. itineraries) characteristics from SOL1 as input and applies time-based (i.e. timetable shift) and route-based strategies (i.e. new service and service cancellation) to the existing rail and air services to generate a coordinated schedule.

The user is expected to provide information on:

Supply information consisting of:

- rail timetable in the standard GTFS format
- flight schedules
- specifications of operating vehicles i.e., number of seats

Infrastructure data consisting of:

- airports and/or rail stations and the corresponding features i.e., capacity, minimal process times, etc.
- minimum connecting times (MCT) intra- and inter-mobility layers, i.e., the time required to travel from rail stations to airports (and vice-versa) and to connect between flights (at airports) and between trains (at rail stations)

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Demand information consisting of:

- Possible itineraries
- Number of passengers who want to travel on the itineraries

SOL400/SOL2 generates coordinated rail timetables and flight schedules. The coordination aims to improve the transfer experience of passengers in the multimodal transport system by:

- Providing more connections to serve more passengers
- Reducing passenger transfer time

SOL400/SOL2 first identifies the demand and services of interest (i.e. transfer demand and corresponding services). It divides the itineraries into connected and not-connected itineraries. As the objective of SOL400/SOL2 is to provide a Multimodal optimised network, itineraries that do not have any connection do not need to be optimised. SOL400/SOL2 will focus on optimising the "selected itineraries" (itineraries with connections, lest them be rail-rail, air-air or rail-air). SOL400/SOL2 calculates the available service capacity, in order to provide optimised schedules that respect the capacity constraints of the services. After that, SOL400/SOL2 selects the potential adjusted services. Note that itineraries represent a collection of services. The selected services contain the services used by the selected itineraries, but also add other services serving the same routes but departing at different times. Additionally, SOL400/SOL2 groups the passengers to be assigned in different groups depending on their taken path (collection of infrastructure visited by the passengers). These passenger groups are allowed to use the new itineraries generated by SOL400/SOL2.

SOL400/SOL2 then applies time-based and route-based strategies to the initial schedules. The time-based strategy refers to time shifting, which keeps the initial service route but shifts the departure time of services at the origin to provide better connections. For the route-based strategy, SOL400/SOL2 adds some new services to allow more connections and cancel some less efficient services. Once the services are coordinated, the passengers may shift their itineraries for better connections or the new connections enable more passengers to travel in the system. SOL400/SOL2 takes the interaction between service coordination and passenger assignment while designing the coordinated schedule.

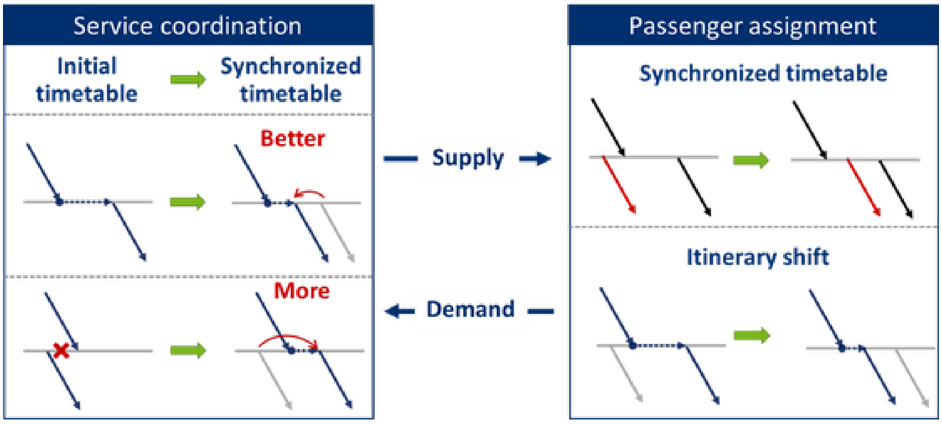

Figure 2: Interaction between service coordination and passenger assignment

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Some operational and assignment constraints are considered in the proposed model to guarantee a feasible schedule. The operational constraints include minimal and maximal running time and dwell time, minimal headway of trains, airport capacity, number of services, and time shift range. The assignment constraints refer to service seat capacity and passenger transfer time.

SOL400/SOL2 evaluates the solution from three objectives: unserved demand, passenger transfer time and timetable deviation. The three objectives are considered in the optimisation according to a lexicographic order

3.3.2.1 Use case: Schedule generation

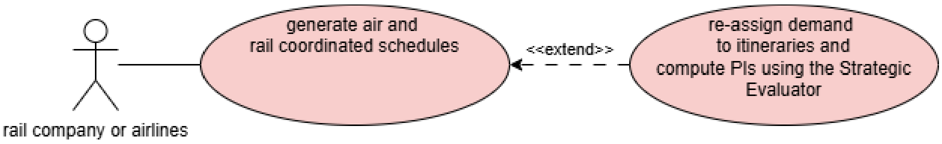

Figure 3: SOL400/SOL2 use case: Schedule generation

Use case: New Schedules generation **Primary actor: Airlines and/or Railway schedule specialist** **Scope: Schedule Designer** **Stakeholders and interests:** • **Airlines and/or railway schedule specialist: wants to generate coordinated schedules between rail and air.** • **Multimodal and passenger experience flagship: wants to improve overall passenger experience.** **Brief: The airline and/or railway schedule specialist wants to generate new optimised schedules for the air and rail network** **Preconditions: Air and rail demand data is available and in the required format. The airline and the railway company are collaborating (as stated in assumptions A5 and A7).** **Minimal guarantee: None** **Success guarantee: New optimised schedules are generated** **Trigger: Airlines and/or railway schedule specialist: wants to generate coordinated schedules between rail and air.** **Main success scenario: The air and railway schedule specialists is able to receive the new coordinated schedules and to assess the improvement with respect to the initial schedule.** **Extension: Integration with Multimodal Performance Framework and the Strategic Evaluator of SOL399/SOL1.**

Condition: The airline and/or railway specialists want to see how the demand changes as a result of schedule optimisation and wants to assess the Multimodal situation of the network using MultiModX Multimodal Performance Framework. **Steps: 1** **Scenario:** **1. The airline and/or railway specialists calculates paths, itineraries and passenger demand on the planned network using the Strategic Performance Evaluator.** **2. The new generated demand is used as an input to generate a second iteration of new schedules.** **This process can be run several times, at the users discretion.**
Use case data: Inputs: flight schedules, rail timetable, connecting times, possible itineraries, passengers assigned to itineraries. The specific files and formats are specified in the FRD. Outputs: new flight Schedules and rail timetable
Auxiliary definitions: none

3.3.3 Differences between new and previous operating methods

As Solution 2 is a Schedule generation tool, it does not affect the SESAR architecture, therefore we leave the following table blank.

Activities (in the SESAR architecture) that are impacted by the SESAR solution	Current operating method	New operating method
One line per activity.		

Table 6: differences between the new and the previous operating method

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4 Key assumptions

ID	Title	Description	Justification	Impact Assessment
A1	Case studies coverage	It is assumed that the three case studies provide an interesting variety in terms of regional specificities and situations of multimodal transport (national case study and international corridor with an integrated HSR station in an airport).	Regional archetypes have been studied and the case studies cover a national and an international case.	Medium
A2	Regional archetypes	It is assumed that results derived from the regional archetypes can be translated and upscaled to a EU level using different regional archetypes as examples	The different regional archetypes represent a real combination of air and rail characteristics within a region or a transport corridor, and thus, the variety of multimodal conditions within the EU	Low
A3	Passenger archetypes coverage	It is assumed that the set of passenger archetypes considered are representative for the entirety of travellers.	Extensive research has been conducted to ensure that those passenger archetypes represent the variety of travellers.	Medium
A4	Data availability	It is assumed that the required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, etc.) are available in the regions under study.	Data are required to execute the solution but modelling assumptions could be established if needed.	Medium

A5	Existence of multimodal governance	It is assumed that a multimodal performance scheme and multimodal governance is in place, allowing cooperation between modes of 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 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	Scenarios, case studies, experiments and use cases will be performed at two distinct times. The reference will be year 2019 using existing pre-COVID data and a baseline targeting a future development in the time frame 2030-2035 with subject data availability.	It is assumed that maturation of the solution from TRL 1 to TRL 2 can be sufficiently performed by using a) historical data and b) one future reference year.	Medium

5 References

5.1 Applicable documents

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

Content integration

[1] ...

Content development

[2] ...

System and service development

[3] ...

Performance management

[4] ...

Validation

[5] ...

System engineering

[6] ...

Safety

[7] ...

Human performance

[8] ...

Environment assessment

[9] ...

Security

[10] ...

Project and programme management

[11] 101114815 MultiModX Grant Agreement, 31/05/2023

[12] SESAR 3 JU Project Handbook – Programme Execution Framework, 13/01/2023, 1.0

5.2 Reference documents

[1] https://cordis.europa.eu/project/id/285243

[2] https://www.transit-h2020.eu/

[3] https://www.sesarju.eu/projects/modus

[4] 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

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[7] 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.

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[12] 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.

Appendix A – Stakeholders identification

A.1 Stakeholders identification and expectations

We present here the possible stakeholders who could benefit from or be impacted by the different components of SOL400/SOL2. This section is in line with section 3.1.3 of the OSED document.

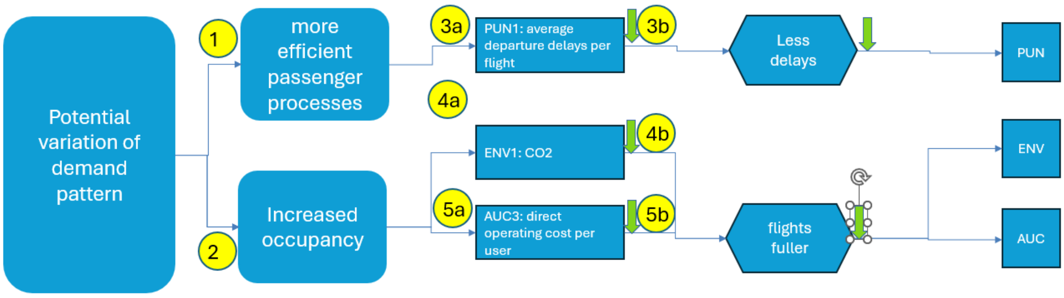
- Airline operators: They are the primary users of the Solution. They are positively impacted by the implementation of coordinated schedules between air and rail. Potential benefits include, improved occupancy of planes, minimisation of costs, improved passenger satisfaction, etc.
- Rail operators: They are also the primary users of the Solution. They are positively impacted by the implementation of coordinated schedules between air and rail. Potential benefits include, improved occupancy of train, minimisation of costs, improved passenger satisfaction, etc.
- Airports: If improved schedules are implemented, airports might expand their catchment area (due to greater connectivity). This is likely to impact positively the number of people visiting the airport in a day. On the contrary, if waiting times are reduced, airports might see a slight decrease in spending from travelers.
- Railway stations: If improved schedules are implemented, some railway station might see a both a higher number of people and a higher number of trains using their facilities.
- GDS (Global Distribution Systems) and organisations such as Amadeus: the results of the experiments of SOL400/SOL2 may be relevant for the integration of multimodality in transport search engines.
- SESAR SJU: the results of the experiments of SOL400/SOL2 can assist the SJU to design the future development and deployment of multimodal initiatives.
- Scientific community. The Schedule design solution is one of the first of its kind in air and rail optimisation. Therefore, the code can be re-used and improved by the scientific community. The results of the experiments can also serve as a basis for future research.
- Cities and Regions urban planners. Results of the experiments conducted for SOL400/SOL2 may serve as a basis for decision making in the development or improvement of certain infrastructure and urban planning at the city level.
- Policy makers and Planners: these stakeholders could have potential interest in the outputs of the Schedule Design Solution to assess the utility in terms of travel time, costs and CO2 emissions reduction of policies looking to encourage alliances between railway companies and airlines (such as single ticketing).

A.2 Benefits impact mechanisms (BIM)

As a multimodal solution, some of the benefits of SOL400/SOL2 lie outside the current SESAR performance framework. In this section we include the predicted benefits of SOL400/SOL2 according to the SESAR performance framework along with the benefits provided by SOL400/SOL2 according to the multimodal Performance framework developed within the project. The main benefits of SOL400/SOL2 according to the SESAR performance framework are a reduction of operating costs, a possible reduction of departure delays and a possible reduction of CO2 emissions per passenger. The benefits and their impact are presented in table 7 and explained in figure 4.

KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
AUC3 Direct operating costs per airspace user	positive impact (ECAC level)	SOL400/SOL2 improves served demand, improving in turn occupancy in certain services. This has a positive effect on directing operating costs, however this effect is low since SOL400/SOL2 only affects connecting itineraries which are the minority of the network.
PUN1 Average departure delays per flight	positive impact (ECAC level)	SOL400/SOL2, by optimising both the air and rail networks, improves the air and rail connections. This can potentially affect departure delays due to commuting passengers not being able to go through all the airport processes on time. This effect is likely to be marginal, but we have decided to include it in this analysis for completeness.
ENV1 kg of CO2 per flight	neutral impact (ECAC level)	SOL400/SOL2 will not directly affect the CO2 emissions per flight, but can increase the occupancy of flights and therefore reduce overall emissions per passengers (See Table 8).

Table 7: SOL400/SOL2 benefits according to the SESAR performance framework



Feature	Impact Area	Indicators	Positive or negative impacts	KPI/KPA/TA

Figure 4: BIM mechanism of SOL400/SOL2 with respect to SESAR architecture.

The main benefits on the SESAR architecture come from underlying changes in demand patterns as a consequence of schedule optimisation. One of the objectives of the optimisation algorithms used is served demand, which is the number of passengers that want to travel and are able to travel. This increase in served demand almost always implies an increased in occupancy level of all services, including planes. In turn, increased occupancy means a more efficient use of the available resources, and in particular a reduction of CO2 emissions per user. We acknowledge that the SESAR KPI ENV1 doesn't take into account emissions per user, rather emissions per flight, and heavier loads usually mean more emissions overall. This is offset with emissions per passengers being lower if the flight is fuller. Additionally, fuller flights imply a reduction of operating costs per user. Finally, by coordinating air and rail schedule, and by the addition of multimodal policies such as integrating ticketing, passengers' processing times will be reduced, reducing delays caused by delayed passengers. All these effects are indirect consequences of schedule optimisation (and to a minor extend multimodal policies), hence the benefits are predicted to be small.

SOL400/SOL2 is most of all a passenger-centric multimodal solution. Therefore, the main benefits of the Solution lie outside the current SESAR performance framework. For this reason, we include here the main benefits provided by SOL400/SOL2 according to the multimodal performance framework developed by the project. The main benefits are presented in table 8. Each benefit is explained individually in SOL400/SOL2 ECO-EVAL.

KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
Kerb to gate time	neutral impact	**Predicted impact:** low. Minimal Kerb to Gate time are assumptions of the model. However, the addition of multimodal policies in scenarios pp10 and pp20 reduce the minimal kerb to gate time.

Total journey time	positive impact	**Predicted impact:** high. SOL400/SOL2 is capable of reducing total journey time on average in an entire network. The extend of this impact is directly correlated with the connecting nature of the network. Since total journey times in direct itineraries remains the same after schedule optimisation, the more connecting itineraries, the greater the potential improvement of the network. In validation exercise 1 of the ERR, the total journey time of connecting itineraries went from 417 minutes to 411 minutes. Additionally, in specific itineraries, the decrease was much more important, leading to gains in time of more than 2 hours.
Passenger time efficiency	neutral impact	**Predicted impact:** low. Passenger time efficiency measures whether passengers can travel using the "best possible option" or are forced to use slower itineraries. On the one hand, SOL400/SOL2 optimises existing connections, potentially increasing passenger time efficiency. On the other hand, SOL400/SOL2 has the potential to generate new but sub-optimal itineraries between given origin and destinations, decreasing passenger time efficiency but allowing more people to reach their destination.
Buffers in itineraries	positive impact	**Predicted impact:** high. SOL400/SOL2 reduces buffers in itineraries significantly. In some experiments realised in the ERR, buffers were reduced from 20 minutes to 16 minutes on average.
Modal share	positive impact	**Predicted impact:** low. The impact of this metric depends again on the nature of the network. In the experiment realised, the application of SOL400/SOL2 did not have a big impact in mode share, but in certain cases, SOL400/SOL2 has the potential to move passengers from air to multimodal itineraries.
Seamless of travel (time)	negative impact	**Predicted impact:** low. Seamless of time measures transition times between modes and stops. This is an average indicator which is influenced by many factors. In all experiments realised seamless of travel decreased slightly after the application of SOL400/SOL2.
Diversity of destinations	neutral impact	**Predicted impact:** low. Diversity of destinations measures to how many different regions a given region is connected. In the experiments realised for the ERR, diversity of destinations remained stable.
Direct operating costs per user	positive impact	**Predicted impact:** low. Due to higher load factors, direct operating costs can be reduced, but this is not one of the main goals of schedule optimisation. Passenger shifting from rail to air can cause an overall increase in direct operating costs. In most of the experiments, costs remained stable but were slightly reduced in several occasions.

Load factor	positive impact	**Predicted impact:** medium. In all experiments in the ERR, load factor improved (for example, from 67.05% to 69.66%). Demand served is one of the objectives of the optimisation of schedules, so improvement is expected. In some situations, for which demand is higher than seat capacity, load factor might improve only marginally.
Demand served	positive impact	**Predicted impact:** medium. Demand served is one of the objectives of the optimisation of schedules. In most experiments realised, demand served improved after schedule optimisation. However, demand served is also affected by network capacity. An already almost full network has limited potential for demand served improvement.
Catchment area of airports	neutral impact	**Predicted impact:** low. In this project, Catchment area is measured as the maximum time it takes to reach said airport. Catchment area can thus decrease if the itineraries to the airport are optimised after the application of SOL400/SOL2. However, catchment area can also increase if a new itinerary is created. Both changes can be considered positive. In the experiments realised catchment area of airports varied.
CO2 emissions	neutral impact	**Predicted impact:** low. CO2 emission is liked to other indicators such as load factor and mode share. CO2 emissions

Table 8: KPIs/PIs developed by the MultiModX project where SOL400/SOL2 can provide benefits.

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