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Abstract

The Disruption Management Solution (SOL401) is designed to manage disruptions effectively by creating passenger-centric adjustments to air and rail planned schedules, train routing and flight diversions. By using initial passenger flow data, it aims to minimize the impact of disruptions on passengers by optimizing “adjusted schedules”, flight diversions and train routing. The solution includes various levels of centralization, from decentralized management to fully centralized optimization across all operators. The objective includes minimizing disconnected passengers, detours, waiting times, and providing replacement services.

Authoring & approval

Author(s) of the document

Organisation name		Date
Nikola Besinovic/TU Dresden	Consortium member	30/07/2025
Christopher Szymula/TU Dresden	Consortium member	30/07/2025
Luis Delgado / UoW	Consortium member	30/07/2025
Michal Weiszer / UoW	Consortium member	30/07/2025
Andrew Cook / UoW	Consortium member	30/07/2025

Reviewed by

Organisation name		Date
Eric Tchouamou Njoya/ BHL	Consortium member	30/07/2025
Luis Delgado / UoW	Consortium member	30/07/2025
Michal Weiszer / UoW	Consortium member	30/07/2025
Andrew Cook / UoW	Consortium member	30/07/2025

Approved for submission to the SESAR 3 JU by¹

Organisation name		Date
Eric Tchouamou Njoya/ BHL	Consortium member	30/07/2025

Rejected by²

Organisation name		Date
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¹ Representatives of all the beneficiaries involved in the project

² Representatives of the beneficiaries involved in the project

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MultiModX

INTEGRATED PASSENGER-CENTRIC PLANNING OF MULTIMODAL NETWORKS

MultiModX

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Table of contents

Abstract	1
1 Executive summary	6
2 Introduction	7
2.1 Purpose of the document.....	7
2.2 Scope	7
2.3 Intended readership	8
2.4 Background	8
2.5 Structure of the document.....	9
2.6 Glossary of terms.....	10
2.7 List of acronyms	10
3 Functional architecture view	12
3.1 SESAR solution overview.....	12
3.2 SESAR solution functional view	17
3.3 High level impact of the SESAR solution on the baseline SESAR architecture	20
4 Functional requirements	22
4.1 Operational requirements	23
4.2 Functional requirements.....	24
5 Assumptions	31
5.1 Common assumptions for disruption management solution	31
5.2 Specific assumptions for disruption management.....	33
5.3 Specific assumptions for passenger reassignment.....	33
5.4 Specific assumptions for service adjustments	34
6 References	35
6.1 Applicable documents	35
6.2 Reference documents	36
7 Annex A – Input/Output formats	38
7.1 A.1 Data approach	38
7.2 A.2 Files summary	38
7.3 A.3 Files Description	39

List of tables

Table 1: glossary of terms	10
Table 2: list of acronyms.....	11
Table 3: SOL401/SOL401 capabilities based on <i>SESAR Capability Model – Operational capabilities – Updated as defined in [17]</i>	15
Table 4: <i>SESAR 401 – Disruption Management Solution Stakeholders</i>	16
Table 5: Systems impacted by SESAR Solution 401.....	21
Table 6: SOL401 requirements summary.....	23
Table A.1: <i>Summary of all input and output files used and generated by the SOL401</i>	38

List of figures

Figure 1: Overview of the DMM structure	12
Figure 2: Network layers of the DMM.....	12
Figure 3: Disruption Management Assessment Pipeline	17
Figure 4: Disruption Management Model – Functionalities. Green: Functions, Grey: Data.....	18

1 Executive summary

The Disruption Management Solution (SOL401) aims to design tactical (on the day of operations) adjusted passenger-centric schedule adjustments for air and rail to manage disruptions. Those adjustments are designed to optimally manage passenger demands by minimizing the effects of disruptions. The initial passenger flows capture the preferences of passengers as they incorporate the sensitivities of passengers with regard to several travel aspects, such as travel time, when selecting a specific path and mode(s) to reach their desired destination. Therefore, the flows of each path determine the demand to satisfy when managing the disruptions. The Disruption Management Solution adjusts multimodal air-rail schedules to optimally accommodate the given demand under disruptions and, therefore, manages the network in a passenger-centric fashion.

Using the available data, the Disruption Management Solution generates adjusted passenger-centric air and rail schedules, i.e. adjusted arrival times (AAT) and adjusted departure times (ADT), with train rerouting, flight diversions, and service replacements on the day of operations. For brevity, we refer to these as adjusted schedules.

Two versions of the Disruption Management Solution are available for managing disruptions to different levels of centralisation: decentralized disruption management (i.e. cooperation managed only within defined alliances) and fully centralised multimodal passenger-centric across all air and rail operators (i. e., full cooperation between all service providers including airlines and railway undertakings).

The objective function for adjusting the schedules represents, by managing the passenger flows, an integration of the following single objectives:

- minimize the number of disconnected passengers;
- minimize the additional detours of passengers
- minimize additional waiting times for passengers;
- minimize the number of replacement services (e.g. air or rail).

This document outlines the functional requirement definitions of the solution.

2 Introduction

2.1 Purpose of the document

This document is the functional requirements document (FRD) that details the functional architecture and requirements for the Disruption Management Solution (SOL401), a solution for the multimodal, passenger-centred disruption management of air and rail networks (TRL2) to optimally manage the passenger demands by minimizing the effects of the disruptions. The outcome of the Disruption Management Solution is a set of adjusted schedules for air and rail.

The primary objective of this document is to detail the functional requirements of the solution and its components, inputs and outputs. First, the document delves into the functional architecture view of the solution through an overview of the solution, the capabilities it covers, and the stakeholders involved. Then, the functional requirements, i.e. the expected behaviour, applicable to the Disruption Management Solution and its components, are listed. Finally, the assumptions taken for the development and application of the solution are detailed.

2.2 Scope

The FRD presents the functional requirements of the Disruption Management Solution. The overall scope of the FRD covers all the activities foreseen as part of the WP6 of the project, which include the definition of the functional requirements for such a solution (summarized in **D6.3 - SOL 401 FRD**), including a review of the state of the art and consultation with the project's Industry Board. The functional requirements are defined with a focus on the functional architecture view (including within the SESAR architecture) and the requirements for the methods and algorithms developed for SOL401 for multimodal, passenger-centred disruption management. Further on is the implementation of the methods and algorithms for multimodal disruption management in two alternatives:

- focus on decentralized solutions, i.e., defined airline alliances optimise their resources independently when faced with disruption.
- focus on centralized solutions, i.e., the optimisation and decision-making process considers all airlines and railway undertakings, with their capabilities and constraints, jointly.

The solution's operational service and environment description are provided in **D6.4 - SOL-3 OSED**.

The results of the algorithms developed as part of the Disruption Management Solution will be evaluated within the Performance Assessment Solution (SOL399). SOL401's capabilities to reduce the impact of different types of disruptions during the day of operation will be illustrated in the experiments as defined in ERP and according to the operational environment defined in the OSED.

These activities **address Objective O5 of the project** as stated by the Grant Agreement (GA), to develop a Disruption Management Solution based on coordinated passengers' reallocation and tactical replanning of services for air and rail services by:

- Analysing the functional requirements and existing models and algorithms for rail and air disruption management.
- Using mathematical optimisation models and algorithms for optimal multimodal disruption management considering tactical replanning for air and rail, including train routing and diversions, along with passenger multimodal rerouting alternatives. This optimisation will consider passenger behaviour (e.g. acceptable re-routing options), available services and interdependencies between air and rail networks.
- Identifying data-sharing requirements to coordinate the solution due to the distributed nature of the decision-making process when dealing with disruption among stakeholders (e.g. airlines, rail operators, airports, passengers).
- Experimental testing and evaluation of the new Disruption Management Solution

2.3 Intended readership

The readers of this document 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 organizations. SOL401 might be particularly relevant for updating the SESAR ATM capabilities, and therefore, the AMPLE3 project could benefit from this document.

2.4 Background

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

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

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

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

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

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

2.5 Structure of the document

Chapter 2 of this document serves as an introduction, providing general information about this functional requirements document. Chapter 3 brings the context of the functional architecture view, containing details such as the supporting reasons for this SESAR solution, the capabilities addressed, and the stakeholders impacted by the SOL401. Chapter 4 outlines the functional requirements. Additionally, a list of validation exercises is provided in this chapter. Finally, Chapter 5 offers supplementary information related to the validation exercises.

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.	Own definition
Adjusted multimodal passenger-centric schedule	Adjusted passenger-centric air and rail schedule includes adjusted arrival times (AAT) and adjusted departure times (ADT), with train rerouting flight diversions and service replacements for a day of operations. For brevity, we refer as to adjusted schedule.	Own definition
Disruption	Refers to a blocked infrastructure element (e.g. air: airport, terminal, runway; rail: station, track section) or reduced capacity. Disruptions are known several hours (or 1 day) before operations.	Own definition
Passenger flow	Refers to an aggregated representation of passengers, travelling along a particular passenger path.	Own definition
Passenger itinerary	Passenger itinerary is a succession of services (flights or trains) which represent a (possible) trip for a passenger.	Own definition
Passenger path	Passenger path is 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 definition

Table 1: glossary of terms

2.7 List of acronyms

Term	Definition
AAT	Adjusted arrival time
ADT	Adjusted departure time
AO	Air Operator
ATM	Air traffic management
ATFM	Air traffic flow management

CASA	Computed-Assisted Slot Allocation
CDM	Collaborative decision making
CTOT	Calculated Take-Off Time
DCB	Demand Capacity Balancing
DES	Digital European Sky
DMM	Disruption Management Model
ETFMS	Enhanced Tactical Flow Management System
FRD	Functional requirements document
GA	Grant agreement
GDPR	General data protection regulation
HE	Horizon Europe
ID	Identifier
MMX	MultiModX
NM	Network Manager
OSED	Operational service and environment description
SESAR	Single European sky ATM research
SESAR 3 JU	SESAR 3 Joint Undertaking
TRL	Technology readiness level
UDPP	User-driven prioritisation process

Table 2: list of acronyms

3 Functional architecture view

3.1 SESAR solution overview

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

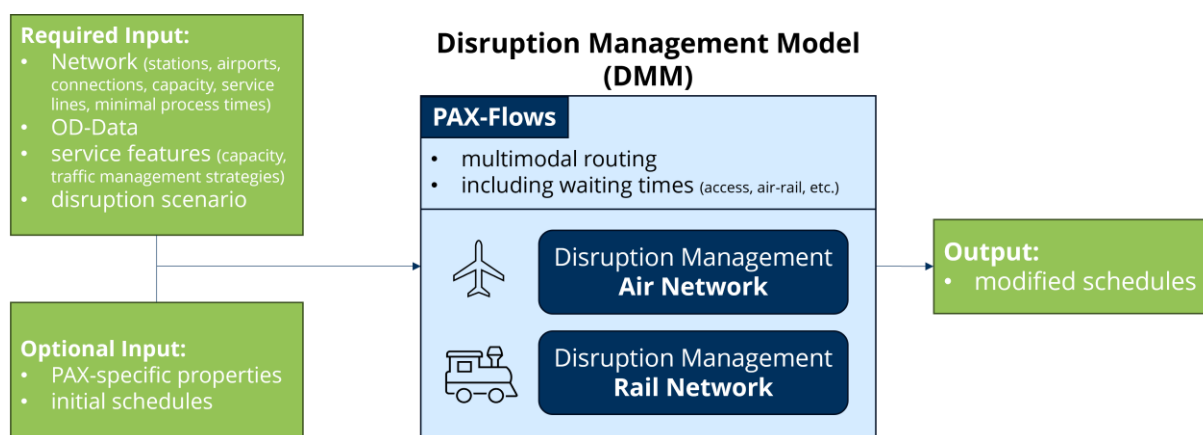


Figure 1: Overview of the DMM structure

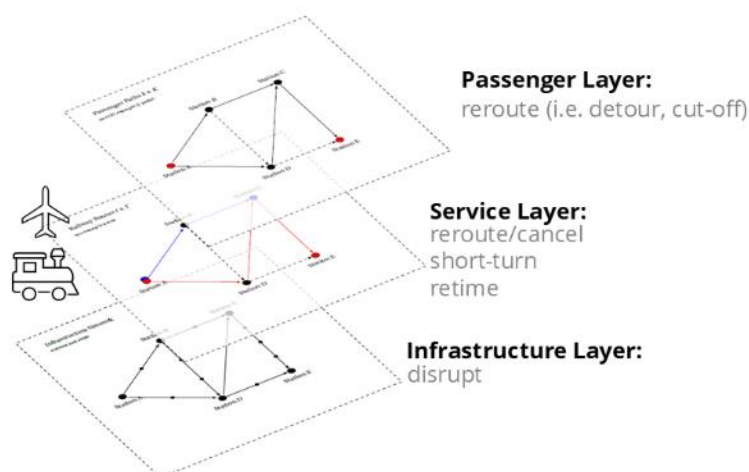


Figure 2: Network layers of the DMM

3.1.1 Supporting reasons for this SESAR solution

Europe's long-term vision documents on aviation research, described in the Flightpath 2050 and the new Fly the Green Deal documents [12], envisage a future in which air transport becomes an integrated part of a multimodal transport system that, by the year 2050, makes it possible for 90% of travellers within Europe to complete their door-to-door journey within 4 hours.

In parallel, the European Commission's Sustainable and Smart Mobility Strategy [13] has defined a multitude of goals and respective flagships that pave the way towards zero-emission, resilient and inclusive mobility, creating seamless and efficient connectivity and establishing the European Union as a connectivity hub. One of the goals is a stronger focus on multimodality, which encompasses, inter alia, a fully integrated and seamless multimodal mobility system and a high-quality transport network with high-speed rail (HSR) services on short-haul distances and clean aviation services improving the coverage of long-haul routes. A seamless passenger experience and interoperability between different transport providers will be enabled by integrating airports as multimodal nodes in the air traffic management (ATM) network, contributing to increasing network resilience and the reliability and predictability of journeys. Coordinated planning and collaborative decision-making, based on information sharing and common situational awareness across transport modes, are key enablers to realise this vision (SESAR JU, 2020).

In recent years, a number of research projects have demonstrated the potential of multimodal coordination mechanisms to increase the efficiency and resilience of the transport network. At the strategic level, schedule synchronisation between different transport networks can significantly reduce total door-to-door travel times by optimising transfer times; this will foster multimodal trips, especially when combined with integrated ticketing, facilitating the use of the most efficient transport mode for each leg of the trip [14]. Furthermore, closer cooperation between air and rail may enhance capacity allocation across modes and address shortages on specific routes or at airports, as well as improve access, egress and connectivity between modes at airport nodes, expanding the possibility for multimodal itineraries beyond airports with medium and long-distance rail stations on them [15] (Modus Consortium, 2021). At the tactical level, coordinated passenger rebooking, rerouting, replanning and dynamic rescheduling can help deal with the many unexpected events that occur in any transport network [16], rendering the transport system more resilient against disruptive events and improving travel time reliability and passenger experience, especially when used in combination with advanced passenger information services [14].

The goal of SOL401 is to develop a Disruption Management Solution based on coordinated air and rail tactical schedule adjustments and passenger reallocation, a step towards innovative multimodal solutions and decision support tools for the coordinated planning and management of multimodal transport networks.

In Europe, capacity-demand imbalances in ATM are mostly managed via the implementation of ATFM regulations. The assignment of slots (CTOT) to regulated flights performed by the Network Manager (NM) as part of the ETFMS using the CASA algorithm focuses on respecting the declared capacities of the implemented regulations while minimizing the total assigned delay. However, there is no consideration of the impact of delays on passengers, who can experience significantly larger delays due to missed connections (this is particularly relevant in the context of multimodality). UDPP Solution enables air operators (AO) to exchange some of the slots so that their expected costs can be reduced partially. However, this approach still provides some limited improvement for passengers as the overall

vision of the impact on their journeys is not considered. And, most importantly, multimodal journeys and how the rail and air network could support and complement each other in case of disruptions in the infrastructure are completely ignored. SOL401 can help to put the focus on the passengers to manage disruptions.

Finally, SOL401 proposes changes to the planned operations using information on the expected disruptions before they necessarily materialise, e.g. on D-1 when some ATFM are planned. This could lead to a proactive collaboration between the NM and AO to adjust the planned operations using CDM principles, as SOL401 can indicate which flights should be adjusted to minimize the impact on passengers' journeys.

SOL401, therefore, contributes to several SESAR JU Objectives, including:

- **Proactive network management:** By leveraging predictable disruptions (hours to a day in advance), SOL401 helps SESAR advance from a reactive ATM to a proactive, data-driven system where CDM with a passenger focus can be fully implemented.
- **Advanced multimodal coordination:** SOL401 enhances SESAR's multimodal vision by integrating rail-air solutions before disruption effects escalate.
- **Improved crisis planning:** SESAR emphasizes improved contingency planning; SOL401 provides a **structured framework** for handling disruptions based on available lead time.

In particular, the benefits of SOL401 to ATM in managing small-scale disruptions include:

- **Proactive schedule adjustments:** Since most disruptions (e.g., gate unavailability, airspace congestion, maintenance closures) are known several hours in advance, SOL401 can optimize rerouting and rescheduling to minimize passenger and network impact.
- **Dynamic slot reallocation:** The tool supports ATM by reducing bottlenecks at busy airports.
- **Optimized rail-air substitutions:** When short-haul flights are affected, SOL401 can suggest high-speed rail alternatives, freeing up airspace for long-haul operations.

Also, SOL401 supports managing large-scale disruptions:

- **Pre-emptive rerouting & resource allocation:** When major disruptions (e.g., storms, ATC strikes, infrastructure/system failures, natural disasters) are predicted one day ahead, SOL401 can proactively adjust flight and rail schedules to minimize chaos.
- **Crisis mitigation strategies:** In cases like volcanic eruptions or widespread strikes, SOL401 can pre-plan rerouting strategies based on anticipated impacts, preventing last-minute cancellations and stranded passengers. Additionally, it can be used to quantify the impacts of crisis managing strategies for closing/reopening airports and airspace.
- **Airspace & airport load balancing:** The tool helps distribute traffic to alternative airports when primary hubs are affected by large-scale disruptions.

3.1.2 ATM capabilities addressed by the SESAR solution

In Table 3, we describe some of the SESAR capabilities that have been identified from AMPLE3 D2.6 – Transformation View 2024 [17]. This document describes the evolution of the European ATM across the ATM Master Plan Vision Phases towards the vision enshrined in the European Master Plan and

considers some aspects of the multimodality that impact ATM [17]. Note that these multimodal aspects are currently being reviewed and updated, partially with the outcome of the 'Multimodality and passenger experience in the SESAR Performance Framework' workshop held on 15 January 2025 (at the University of Westminster, London), attended by members of the MultiModX, PEARL, AMPLE3 and SIGN-AIR projects (inter alia; and as reported under separate cover).

SESAR solution capabilities	Comments on potential updates required at capability level
Demand and Capacity Balancing – Demand and Capacity Balancing (airspace) – Air Traffic Flow Management	SOL401 can provide pre-solving of ATFM regulations (including adjusted arrival/departure times and diversions, taking into account overall passenger-centric network effects). This might render some of the planned ATFM regulations unnecessary if flights are replanned in a collaborative manner preventively, as according to SOL401.
Demand and Capacity Balancing – Demand and Capacity Balancing (airspace) – Collaborative Network Management	SOL401 can provide pre-solving of ATFM regulations (including adjusted arrival/departure times and diversions, taking into account overall passenger-centric network effects). SOL401 can provide information on which flights to replan to minimize the impact of passenger journeys, supporting the collaborative management of demand and capacity balancing processes.
Airspace User Operations – Flight prioritisation – User Driven Prioritisation Process	As SOL401 provides a replanning of operations to deal with disruptions, i.e., with ATFM regulations, the use of UDPP to manage the slots by airspace users, in particular, could interfere with the plan of SOL401. Further research might be required to assess these potential interactions.
Crisis Management - Internal Crisis Management - Air Traffic Diversion Management	SOL401 can propose a diversion plan for aircraft, ensuring the best connectivity for passengers (during larger disruptions).
Information Management – Data Management – Single Ticketing	Single ticketing is an enabler for the mechanisms modelled in SOL401/SOL401.
ATM and U-space Service Delivery Management – Performance Management (operational) – Multimodal Performance Management	SOL 401can be used to determine the most critical nodes/airports in the network from the passenger perspective.

Table 3: SOL401/SOL401 capabilities based on *SESAR Capability Model – Operational capabilities – Updated as defined in [17]*.

3.1.3 Stakeholders impacted by the SESAR solution

Stakeholder	Involvement	Why it matters to the stakeholder
Aviation community (airlines, airports)	Integration of the Disruption Management Solution	The Disruption Management Solution can assist the stakeholder in more effectively managing for the tactical multimodal coordination.
Railway community (railway operators, infrastructure managers)	Integration of the Disruption Management Solution	The Disruption Management Solution can assist the stakeholder in more effectively controlling and managing the multimodal coordination at tactical level.
European and national authorities, regulatory bodies (National and regional governments, European Commission, other decision makers, ERA, EU Joint Research Centre, OECD)	Exploitation of the projects' results	The results of the experiments conducted for SOL401 will be relevant for the decision process of future policies and the integration of multimodality.
GDS (Global Distribution Systems) organisations (Amadeus)	Exploitation of the project's results	The results of the experiments conducted for SOL401 will be relevant for a better integration of multimodality in transport search engines.
Scientific community (ANSP, EUROCONTROL, researchers, academics, conference chairs, coordinators of ongoing and former relevant projects)	Reuse of the project's code, framework, and assumptions Exploitation of the project's results	The Disruption Management Solution can be reused for further research and deepening of the themes covered within the scope of the Solution. Moreover, the results can serve as the basis to direct and justify future research.
Cities and regions, urban planners (ARC regional council members)	Exploitation of the project's results	The results of the experiments conducted for SOL401 can serve as a basis for decision making in the development or improvement of certain infrastructure and urban planning at the city level.
SESAR JU	Planning for the future of multimodal transport and scheduling	The Disruption Management Solution can assist the stakeholder in more effectively managing for the tactical multimodal coordination.
Project Partners	Use of the experiments' results	The project's partners will use the results of the experiments conducted in SOL399 and SOL400.

Table 4: SESAR 401 – Disruption Management Solution Stakeholders

3.2 SESAR solution functional view

3.2.1 Interaction(s) identification

Within MultiModX, SOL401 interacts with the multimodal performance evaluator of SOL399. SOL401 provides, considering the disruptions, adjusted schedules for the day. The passenger reassignment process of SOL399 will identify the passenger itineraries impacted by these adjustments on the operations and reassign as many passengers as possible to the available services. This reassignment is performed by SOL399 as it captures the activities of the airlines and rail operators managing their impacted passengers. SOL401 provides updated schedules that should minimize the impact on passengers.

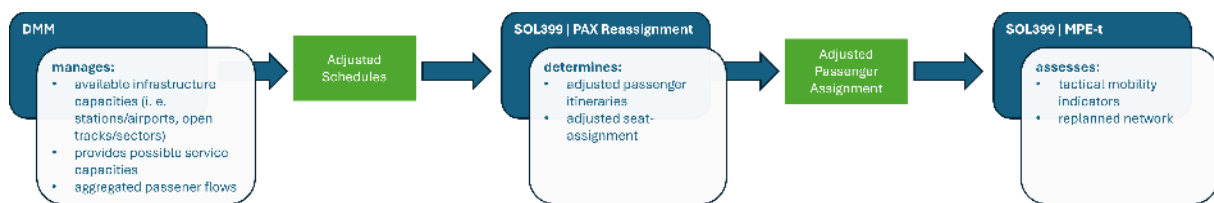


Figure 3: Disruption Management Assessment Pipeline

The replanned network (including the reallocated passengers) could then be further evaluated by SOL399 using the Multimodal Tactical Performance Evaluator (MPE-t) in Fig. 3. This will ‘materialise’ the replanned network, enabling the estimation of multimodal performance indicators (with particular focus on passenger-centric indicators, such as total arrival delay, missed connections, or stranded passengers), considering the decentralized decision making when dealing with missed connections and delays.

With these considerations, the outcome of the disruption management (replanned schedules) needs to be compatible with the elements of SOL399 above mentioned. For more information on this, see the OSED of SOL399.

In its possible deployment in the SESAR architecture, SOL401 will interact with the processes dealing with the planning of ATFM regulations, particularly on D-1 or when significant disruptions are expected on the air or rail network. In those cases, SOL401 will provide a replanning of the air and rail schedules to support collaborative decision-making activities to potentially minimize the impact on passengers. Therefore, as previously indicated, SOL401 would interact with the processes defining the implementation of regulations and flight operations.

Finally, to be functional, SOL401 will require information from different stakeholders, including planned air and rail services, demand flows (or their estimation) including multimodal trips, and information on disruptions and system capacities. Some of these elements might be present with the SESAR architecture, but others might require new interactions, e.g. with rail operators and rail network infrastructure managers.

3.2.2 Functional decomposition

The current baseline SESAR architecture is considered; however, the proposed SOL401 goes beyond this baseline as our focus is on the implication on multimodality. Therefore, some advancements and enablers are assumed to be in place.

SOL401 provides capabilities to manage planned disruptions. The DMM functions, therefore, as a multimodal network manager. It thus resembles the function of capacity management to provide and reallocate network-wide infrastructure and service capacities by considering the aggregated passenger flows in case of disruptions.

The functional decomposition, as described above, implies two particular requirements for SOL401:

- First, SOL401 needs to provide disruption management outcomes consisting of feasible adjusted schedules for the operating services in the network.
- Second, SOL401 needs to consistently consider the given passenger itineraries and the corresponding service and infrastructure capacity requirements to provide a feasible disruption management solution.

The resulting detailed functional requirements of the DMM are provided below.

Disruption Management Model (DMM)

The DMM uses the characteristics of supply, demand and disruptions in combination with disruption management preferences to determine the adjusted schedules for rail and air. The DMM comprises three core functions, which are iteratively applied to determine the optimal, multimodal, passenger-centric disruption management decisions. The overall functional decomposition and the respective interactions among the different functions are displayed in Fig. 4.

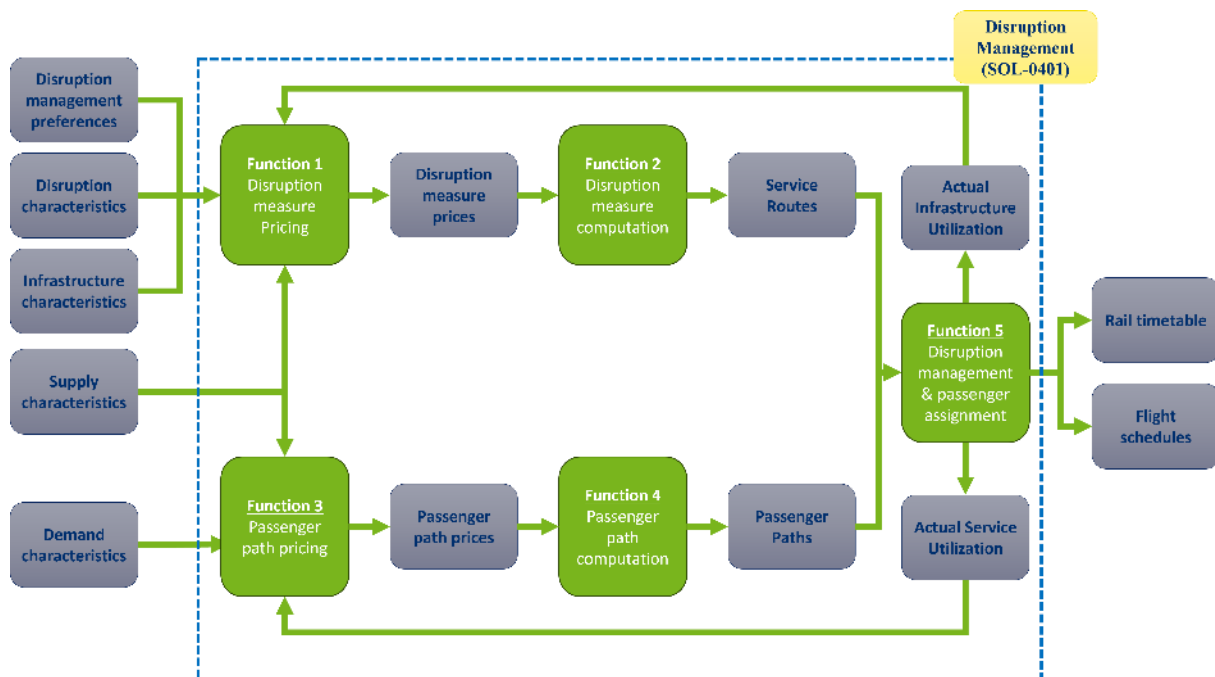


Figure 4: Disruption Management Model – Functionalities. Green: Functions, Grey: Data

- **Function 1 – Disruption measure pricing:** Function 1 computes generalized disruption measure prices for the disruption management of services. The prices are based on the disruption measure information i.e. service (supply) characteristics, the infrastructure characteristics, the disruption management preferences and the infrastructure utilization for every service. The service characteristics provide information on the specific service (i.e. origin, destination, vehicle type). The disruption management preferences consist of the allowed short-turning locations and preferred rerouting alternatives, as well as multiple parameters. Those parameters are the maximum detour factor of the service, the parameter to weigh passenger detours against the number of stranded passengers and a parameter to penalize service cancellations. The infrastructure characteristics provide information on the current disruption, infrastructure capacity, vehicle type, and specific minimal process times, such as minimal train running times or flight plan times. The infrastructure utilization provides information on the current usage of the infrastructure network of the current service's mode. The infrastructure utilization is computed based on the solution of a previous iteration. For the first iteration, the network is assumed to be empty (i.e. zero infrastructure utilization). The function determines generalized prices of the disruption measures for every service for the nominal inputs (i.e. with unutilized infrastructure for the first iteration) and the adapted situation during disruptions (i.e. actual utilization information). Those generalized prices represent the aggregated disruption measure information with a uniform metric (i.e. generalized price), which combines the impacts of the different service characteristics, the disruption management preferences and the infrastructure characteristics within a single value. The prices are computed for all possible disruption management decisions of every service. The price of a disruption measure is calculated as the difference between the passenger benefit (i.e., route-specific travel cost) and the operating cost (i.e., route-specific service operating cost, utilization-dependent infrastructure cost). Function 1 is fed back during the optimization procedure with updated infrastructure utilization and provides the generalized prices for the disruption measures (i.e., disruption measure prices) as output.
- **Function 2 – Disruption measure computation:** Function 2 computes potential disruption measures for disruption management measures based on the disruption measure prices as provided by function 1. For every service, the function computes the cheapest disruption measure (i.e. short-turning, arrival/departure time adjustments, rerouting or cancellation) w.r.t. the currently provided generalized prices. The function returns the alternative service routes for every service, which can be considered in function 5.
- **Function 3 – Passenger path pricing:** Function 3 computes generalized passenger path prices for the adaptive passenger routing. Those prices are based on the passengers' routing information (i.e. the demand characteristics, supply characteristics and the services' utilization) for every OD pair. The demand characteristics provide information on OD demands (i.e. origins, destinations, amount of passengers per class/status, booked alliance) and the passenger's sensitivity to travel time changes. The supply characteristics provide information on the available services and the respectively provided seating capacities (i.e. numbers of economy class, business class, and first-class seats on flights, as well as numbers of first and second class seats in trains, alliance) as well as the location-specific, infrastructural transfer times. The service utilization provides information on the current seat availability. The service utilization is computed based on the solution of a previous iteration. For the first iteration, all services are assumed to be empty (i.e. zero service utilization). The generalized passenger path prices represent the aggregated routing information with a uniform metric (i.e. price), which allows the representation of occurring trade-offs between the respective demand and service

characteristics within a single value for every single network element. The function determines the passenger path prices for every OD pair for the nominal inputs (i.e. unutilized seating capacity) and the adapted situation during disruptions (i.e. actual utilization information), which is fed back during the optimization procedure. Note that only routing alternatives of the same alliance as the initial itinerary are considered and thus correspondingly priced. All OD pairs are considered during the disruption management, whether they are directly affected by the disruption or not, to identify potential capacity bottlenecks and the correspondingly resulting effects i. e. passenger detour or stranding. The function 3 is fed back during the optimization procedure with updated service utilization and provides the generalized prices for the passenger paths measures (i. e. passenger path prices) as output.

- **Function 4 – Passenger path computation:** Function 4 computes potential passenger paths based on the provided passenger generalized path prices of function 3. The function computes the cheapest potential passenger paths w.r.t. the current generalized passenger path prices, by determining the minimal-cost paths in the actual service network. It shall be noted, that the generalized path prices resemble multiple features of a certain path and are thus not necessarily reflecting the actual ticket price, as the ticket pricing is covered by the respective passenger archetypes. The determined paths are returned for every OD pair. The function returns the alternative passenger paths for every OD-pair, which can be considered in function 5.
- **Function 5 – Disruption management & passenger assignment:** Function 5 provides the optimal disruption management solution by simultaneously assigning (adapted) services to the infrastructure/network and passengers flows along their correspondingly computed paths to the assigned services. It further assigns new arrival and departure times to every service. The services, passengers and times are assigned to minimize the overall disruption management cost (i.e. passenger detours, number of disconnected/stranded passengers and total operating cost). The function returns the adapted air and rail timetables and the resulting infrastructure and service utilization. The utilization can be fed back to the pricing functions 1 and 3 to identify further potentially beneficial disruption measures and passenger paths, respectively. The adapted air and rail timetables are provided as the output of SOL401 for further use within the overall MMX-framework.

The overall solution operates in an iterative manner, which provides feasible results (i.e. timetables) with every run. The quality of the results improves with every iteration until optimality (i.e. no new adapted/alternative service routes and new passenger paths can be found by functions 1 and 3, respectively) or premature termination (i.e. it stops after a predefined number of iterations).

3.3 High level impact of the SESAR solution on the baseline SESAR architecture

Technical systems impacted by the SESAR solution	Functions / roles impacted by the SESAR solution	Comments on required updates
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Multimodal Disruption Management	Demand and Capacity Balancing – Demand and Capacity Balancing (airspace) – Air Traffic Flow Management Demand and Capacity Balancing – Demand and Capacity Balancing (airspace) – Collaborative Network Management Airspace User Operations – Flight prioritisation – User Driven Prioritisation Process Crisis Management - Internal Crisis Management - Air Traffic Diversion Management	SOL401/SOL401 provides a replanning of the services considering expected disruptions. Therefore, it will impact the current functionalities of Demand and Capacity Balancing and User Driven Prioritisation Process, as some of these functionalities could interfere with the outcome of SOL401. These could also benefit from SOL401 producing collaborative-decided actions to deal with disruptions, even prior to the need for DCB activities by the architecture. Likewise, Air Traffic Diversion Management, in the case of Crisis Management, could use SOL401 to evaluate the alternatives which minimise the impact on passenger journeys.
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Table 5: Systems impacted by SESAR Solution 401

All the functionalities of SOL401 are independent of the SESAR architecture. Therefore, we don't expect to impact any role or functionality of the SESAR architecture. The only impact we can foresee is that the integration of the Multimodal Disruption Management in the overall disruption management might require functionalities of the SESAR Solutions to process the obtained results. This is, however, pending the outcome of developing the Multimodal Disruption Management itself.

In Table 3, we already identified the SESAR updated Operational Capabilities that might be impacted/affected by this Solution, as defined in AMPLE3 (2024). From those, as indicated in Table 5, the Airspace Management, Arrival/Departure Routes Management, Multimodal Performance Management and the internal Crisis Management could be directly impacted by SOL401, as the computed disruption management results should be implemented (or considered) by those SESAR Capabilities.

4 Functional requirements

The following coding, based on the DES HE requirements and validation/demonstration guidelines [18] is used for the requirements of SOL401: REQ-SOL401-[OP/FR]-[DMM][0-99].[0-999] where:

- OP: Operational requirement
- FR: Functional requirements
- DMM01: General Disruption Management Model
- DMM02: Specific/Service Adjustment Functional Requirements
- DMM03: Specific/Passenger Reassignment Functional Requirements

To simplify the requirements, input, intermediate and output data formats of SOL401 are described in Annex A – Input/Output formats.

Table 6 summarises all the requirements and provides a link to the sub-sections where the requirements are detailed following, once again, the structure provided by the DES HE requirements and validation/demonstration guidelines [18].

SOL401 Element	Requirement Id	Title	Sub-Section
General Disruption Management Model	REQ-SOL401-OP-DMM01.001	Replan operations in a network considering disruptions	4.1.1
General Disruption Management Model	REQ-SOL401-FR-DMM01.001	Input requirement	4.2.1.1
General Disruption Management Model	REQ-SOL401-FR-DMM01.002	Generate schedules usable by Tactical Evaluator	4.2.1.2
Specific/Service Adjustment Functional Requirements	REQ-SOL401-FR-DMM02.001	Apply disruption scenario to initial schedules	4.2.2.1
Specific/Service Adjustment Functional Requirements	REQ-SOL401-FR-DMM02.002	Respect capacity and operation constraints rail and air	4.2.2.2
Specific/Service Adjustment Functional Requirements	REQ-SOL401-FR-DMM02.003	Combine multiple objectives	4.2.2.3
Specific/Service Adjustment Functional Requirements	REQ-SOL401-FR-DMM02.004	Produce adjusted schedules for air and rail	4.2.2.4
Specific/Service Adjustment Functional Requirements	REQ-SOL401-FR-DMM02.005	Adjust only services affected by disruption	4.2.2.5

Specific/Passenger Reassignment Functional Requirements	REQ-SOL401-FR-DMM03.001	Reflect passengers choice	4.2.3.1
Specific/Passenger Reassignment Functional Requirements	REQ-SOL401-FR-DMM03.002	Consider capacities already used	4.2.3.2
Specific/Passenger Reassignment Functional Requirements	REQ-SOL401-FR-DMM03.003	Consider existing and allow new services in adjusted network	4.2.3.3
Specific/Passenger Reassignment Functional Requirements	REQ-SOL401-FR-DMM03.004	Allow passenger rejection	4.2.3.4

Table 6: SOL401 requirements summary.

4.1 Operational requirements

4.1.1 REQ-SOL401-OP-DMM01.001

Identifier	REQ-SOL401-OP-DMM01.001	
Title	Replan operations in a network considering disruptions	
Requirement	SOL401 Disruption Management Solution shall adjust multimodal schedules for air and rail with focus on passenger for a day of operations taking into account a given set of disruptions.	
Status	In progress	
Rationale	Defined in SOL401 OSED	
Category	Operational	

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401

4.2 Functional requirements

4.2.1 General Functional Requirements

4.2.1.1 REQ-SOL401-FR-DMM01.001

Identifier	REQ-SOL401-FR-DMM01.001
Title	Input requirement
Requirement	SOL401 Disruption Management Model shall take as input demand flows (for each itinerary), rail timetables and flight schedules, the network infrastructure characteristics, the service characteristics, a given disruption and the parameters of the disruption management preferences.
Status	In progress
Rationale	The adjusted air and rail schedules are calculated w.r.t. the nominal traffic, the given network and service characteristics, the disruption and the disruption preferences. The format of the demand flows, timetables, infrastructure, service characteristics, disruption and disruption management parameters provided as input is described in Annex A.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.1.2 REQ-SOL401-FR-DMM01.002

Identifier	REQ-SOL401-FR-DMM01.002
Title	Generate schedules usable by Tactical Evaluator
Requirement	SOL401 shall generate schedules that can be used by a Tactical Evaluator (such as SOL399) to assess the performance of the multimodal system on the computed disruption management measures.
Status	In progress
Rationale	Besides the final output of the Disruption Management Model (i. e. adjusted air and rail schedules), the Disruption Management Model shall provide the data such that it can be used by a Tactical Evaluator to assess the performance of the adjusted operations under real-life (i. e. nominally disturbed) conditions.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL40199
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.2 Specific/Service Adjustment Functional Requirements

4.2.2.1 REQ-SOL401-FR-DMM02.001

Identifier	REQ-SOL401-FR-DMM02.001
Title	Apply disruption scenario to initial schedules
Requirement	SOL401 shall take an initial schedule as input and applies disruption management strategies to adapt the services to the current disruption scenario.
Status	In progress
Rationale	The services are adjusted w.r.t. to their initial schedules to prevent early departures and to keep the schedules for unaffected services at their original state. The timetables of the affected services are adjusted (i.e. train rerouting, air diversion, short-turning, cancellation) to mitigate the disruption effects. Both will lead to an overall feasible timetable and thus feasible operational solution.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.2.2 REQ-SOL401-FR-DMM02.002

Identifier	REQ-SOL401-FR-DMM02.002
Title	Respect capacity and operation constraints rail and air
Requirement	SOL401 shall respect the capacity and operation constraints of railway and airline systems.
Status	In progress
Rationale	Considering capacities of air and rail networks (i.e. infrastructural capacities, seating capacities, operational constraints) lead to operationally feasible solution.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.2.3 REQ-SOL401-FR-DMM02.003

Identifier	REQ-SOL401-FR-DMM02.003	
Title	Combine multiple objectives	
Requirement	SOL401 shall allow for combining multiple objectives to cover different scenarios (i.e. with/without airline alliances) while generating the disruption management solution.	
Status	In progress	
Rationale	Having multiple objectives provides to decision makers a possibility to choose their preferred set of objectives, tailored to their specific preferences.	
Category	Functional	

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.2.4 REQ-SOL401-FR-DMM02.004

Identifier	REQ-SOL401-FR-DMM02.004	
Title	Produce adjusted schedules for air and rail	
Requirement	SOL401 shall produce as output adjusted schedules for air and rail.	
Status	In progress	
Rationale	Such adjusted schedules can be given to the dispatchers/network controllers in air and rail networks. Also, can be given to SOL399 Tactical Evaluator for a detailed evaluation.	
Category	Functional	

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.2.5 REQ-SOL401-FR-DMM02.005

Identifier	REQ-SOL401-FR-DMM02.005
Title	Adjust only services affected by disruption
Requirement	SOL401 shall adjust only services which are directly affected by a disruption.
Status	In progress
Rationale	Only directly affected services shall be managed during disruptions to prevent network-wide, unrealistic knock-off effects.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.3 Specific/Passenger Reassignment Functional Requirements

4.2.3.1 REQ-SOL401-FR-DMM03.001

Identifier	REQ-SOL401-FR-DMM03.001
Title	Reflect passengers choice
Requirement	SOL401 shall reflect the choice of passengers under the adjusted schedules and correspondingly reassigns passengers to the services.
Status	In progress
Rationale	During a disruption, passengers may not be able to use their original itineraries/services. Thus, they shall be rerouted and assigned to alternative services.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.3.2 REQ-SOL401-FR-DMM03.002

Identifier	REQ-SOL401-FR-DMM03.002
Title	Consider capacities already used
Requirement	SOL401 shall consider the capacities of services already used by other passenger flows when replanning a network and reassign according to the actual available, adjusted service capacities while minimising the number of passengers stranded.
Status	In progress
Rationale	When reassigning the passengers, the actual capacities of the (potentially adjusted) services and their utilization of other passenger flows shall be considered and aim at minimising the number of passengers who do not have an alternative to reach their destination.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.3.3 REQ-SOL401-FR-DMM03.003

Identifier	REQ-SOL401-FR-DMM03.003
Title	Consider existing and allow new services in adjusted network
Requirement	SOL401 shall consider existing and allow new service connections in the adjusted service network.
Status	In progress
Rationale	When reassigning the passengers, also emerging new connections (i.e. due to rerouting/diversion) shall be considered.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

4.2.3.4 REQ-SOL401-FR-DMM03.004

Identifier	REQ-SOL401-FR-DMM03.004
Title	Allow passenger rejection
Requirement	SOL401 shall allow passenger rejection in the passenger assignment.
Status	In progress
Rationale	During a disruption, network provides reduced capacities or even some routes cannot be reachable. Thus, the related passengers would not be able to reach their destination.
Category	Functional

Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL401
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL401-OP-DMM01.001

5 Assumptions

5.1 Common assumptions for disruption management solution

ID	Title	Description	Justification	Impact Assessment
A1	Data availability	It is assumed that the required data (demand, travel times, infrastructure and corresponding capacity, passenger preferences, flight schedules and rail timetables, etc.) are available.	Data are required to execute the solution but modelling assumptions could be established if needed.	High
A2	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...) and requiring the network manager to cover multimodal aspects.	The interest of the project lies in studying the impact of a multimodal and collaborative framework.	High
A3	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 disruption management..	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
A4	Coordination between air and rail	The disruption management 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

A5	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
A6	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

5.2 Specific assumptions for disruption management

ID	Title	Description	Justification	Impact Assessment
A9	Disruption info	Information about a disruption is completely known, including type, start and end times, and location.	Disruption management decisions require knowledge of the disruption. As our Solution is a tactical approach, it can rely on historical set-ups, where the complete information is available.	Medium
A10	Disruption impact	Services are adapted only if they are directly affected by a disruption	Real-life disruption management measures are usually applied for directly affected services only.	Small
A11	Vehicle and crew	Vehicle rotations and crew schedules are not considered during the disruption management	Due to the tactical scope of our approach and regarding the policy oriented perspective of our project in combination with the steps of operational planning in industry; vehicle rotations and crew schedules are expected to be scheduled at a subsequent planning stage.	Medium
A12	Liabilities	The liabilities for managing the disruptions, e.g. passenger compensation, are not explicitly allocated to the different stakeholders.	As our solution considers the presence of liabilities and the presence of multimodal governance, the liability allocation is expected to have a limited impact on the disruption management outcome.	Low

5.3 Specific assumptions for passenger reassignment

ID	Title	Description	Justification	Impact Assessment
A7	Passenger routing	Passengers are routed along the shortest/fastest available paths within the network	Recent research shows that passengers short-term routing decisions depend on the duration of available routing alternatives.	Medium

5.4 Specific assumptions for service adjustments

ID	Title	Description	Justification	Impact Assessment
A8	Original schedule	The original timetable is feasible and does not exceed capacities or violate other operational constraints	Initial timetables originate from SOL2 or actual operations and will thus be feasible.	Low

6 References

6.1 Applicable documents

This FRD 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] ...

[11]

Project and programme management

[1] 101114815 MultiModX Grant Agreement, 31/05/2023

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[14]<https://www.transit-h2020.eu/>

[15]<https://www.sesarju.eu/projects/modus>

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7 Annex A – Input/Output formats

This Annex presents the format of the input and output datasets for the Disruption Management Model.

7.1 A.1 Data approach

Instead of using a database approach, the input and output of both the DMM are in csv and/or parquet file format. This facilitates the sharing, editing, reviewing and analysis of the different experiments and their outputs.

7.2 A.2 Files summary

Table A.1 provides a summary of all the files used by the SOL401. Some files are shared with the Tactical Evaluator of SOL399, as shown in the table below. The files are divided between Input and Output.

Type	Name	Short description
Input	I1. flight_schedules	I1 in SOL399
Input	I2. GTFS rail	I2 in SOL399
Input	I3. MCT air	I8 in SOL399
Input	I4. MCT rail	I9 in SOL399
Input	I5. flight_schedules_proc_#.csv	IO1 in SOL399
Input	I6. rail_timetable_enriched_#.csv	
Input	I7. transition_layer_connecting_times.csv	IO5 in SOL399
Input	I8. possible_paths_#.csv	IO11 in SOL399
Input	I9. disruptions.csv	List of disrupted network links.
Output	O1. flight_schedules_adjusted.csv	Adjusted flight schedules.
Output	O2. rail_timetable_enriched_adjusted.csv	Adjusted rail timetable.
Output	O3. service_dm_list.csv	Service disruption management list.
Output	O4. odPair_dm_list.csv	OD-Pair affection list.

Table A.1: Summary of all input and output files used and generated by the SOL401

7.3 A.3 Files Description

This section provides for each input, intermediate and output file a description of the different fields contained. This is, therefore, a description of the format of the data used by the Disruption Management Model.

7.3.1 A.3.1 Input files

11. flight_schedules

- Flight schedules to be used to compute paths and itineraries
 - Note that these are flight schedules, not flight plans. Most flight schedules should be available with the required lookahead time for the Solution to produce results that can be deployed. Assumption A4 and A5 ensure that the data are available, and the required governance is in place.
- Finally, it could be possible to re-run the Solution once more information is made available, e.g. optimising the operations for the afternoon in the morning if updated flight schedules are produced. The biggest consideration, in that case, is the time required to implement the outcome of the optimisation from a passenger replanning and operations perspective.

Field	Type	Mandatory	Other info
service_id	string	yes	Unique id per flight
origin	string	yes	ICAO code
destination	string	yes	ICAO code
dept_terminal	string	no	
arr_terminal	string	no	
sobt	datetime	yes	yyyy-mm-dd hh:mm:ss (in UTC time)
sibt	datetime	yes	yyyy-mm-dd hh:mm:ss (in UTC time)
sobt_tz	time delta	yes	(+/-)hh:mm timezone difference with UTC of sobt (should be +00:00 as sobt in UTC already)
sibt_tz	time delta	yes	(+/-)hh:mm timezone difference with UTC of sibt (should be +00:00 as sibt in UTC already)
sobt_local	datetime	yes	yyyy-mm-dd hh:mm:ss (in local time)
sibt_local	datetime	yes	yyyy-mm-dd hh:mm:ss (in local time)
sobt_local_tz	time delta	yes	(+/-)hh:mm timezone difference with UTC of sobt_local

sibt_local_tz	time delta	yes	(+/-)hh:mm timezone difference with UTC of sibt_local
provider	string	yes	airline operating the flight (required if to be considered when computing options)
ac_type	string	yes	aircraft type
seats	int	yes	number seats in aircraft
gcdistance	float	yes	great circle distance between origin and destination (km)

I2. GTFS rail

- Standard GTFS format (e.g. calendar.txt, calendar_dates.txt, stops.txt, stop_time.txt, trips.txt).
- Codes used in GTFS for stops should be consistent (e.g. if country code used) with codes used in other files when referring to train stops (e.g. when having id of rail stops in access/egress files).

I3. MCT air

- Information on MCT for air-air connections (per airport and with standard, international and domestic connections).

Field	Type	Mandatory	Other info
icao_id	string	yes	
standard	int	yes	Used if only one value is to be used, i.e. no differentiation between domestic and international connections
domestic	int	no	Used for domestic connections
international	int	no	Used for international connections

I4. MCT rail

- Information on MCT for rail-rail connections (per rail station). If nothing provided then in config file a default value to be given.

Field	Type	Mandatory
stop_id	string	yes
default transfer time	int	yes

15. flight_schedules_proc_#

- Flight schedules used to compute possible/potential paths

Field	Type	Other info
service_id	string	As in I1. flight schedule
origin	string	ICAO
destination	string	ICAO
dep_terminal	string	
arr_terminal	string	
sobt	yyyy-mm-dd hh:mm:ss	In UTC
sibt	yyyy-mm-dd hh:mm:ss	In UTC
sobt_tz	(+/-)hh:mm	Time zone difference value of sobt and UTC (00:00)
sibt_tz	(+/-)hh:mm	Time zone difference value of sibt and UTC (00:00)
sob_local	yyyy-mm-dd hh:mm:ss	In local time
sib_local	yyyy-mm-dd hh:mm:ss	In local time
sobt_local_tz	(+/-)hh:mm	Time zone difference value of sobt_local and UTC (00:00)
sibt_local_tz	(+/-)hh:mm	Time zone difference value of sibt_local and UTC (00:00)
provider	str	airline id
ac_type	str	
seats	int	number seats in ac
gcdistance	float	Great circle distance (km) from origin to destination
alliance	str	Either the alliance of the airline (as in I15 airline alliances) or the id of the provider if airline not in an alliance
cost	float	Expected average cost of flight (EUR)
emissions	float	Expected emissions of CO2 per pax (kg)

16. rail_timetable_enriched.csv

- Table with rail services in GTFS format with all the stops.
- Here trips between two stops are different rows in the data. So for example service id: 123 could go from stop 1 to stop 2 in the service (123_1_2) or from stop 1 to stop 3 (123_1_3) or from stop 2 to stop 4 (123_2_4), etc.

Field	Type	Other info
trip_id	string	Id of the service encoded in this way: trip_date (e.g. 1_20240101) is service 1 on the 1st of January 2024
stop_id	string	Id of the stop
stop_sequence	string	Id of the stop along the entire train journey
departure_time	yyyy-mm-dd hh:mm:ss	Departure datetime from stop (as in GTFS, so by default in local time)
arrival_time	yyyy-mm-dd hh:mm:ss	Arrival datetime to stop (as in GTFS, so by default in local time)
stop_type	string	Indicator wheter the stop is for (dis-)embarking of passengers (stop_type = 1) or just a through station (stop_type = 0)

17. transition_layer_connecting_times.csv

- Transition times gate-to-platform (G2P), platform-to-gate (P2G) between layers used.

Field	Type	Other info
origin	string	Id of infrastructure of origin, either ICAO code for airport or stop_id for rail stations (as in GTFS)
destination	string	Id of infrastructure of destination, either ICAO code for airport or stop_id for rail stations (as in GTFS)
layer_id_origin	string	name of the layer of origin (either rail or air) to identify if origin is airport or rail station. Note potential changes between rail stations or airports could be allowed (e.g. Atocha - Chamartin)
layer_id_destination	string	name of the layer of origin (either rail or air) to identify if origin is airport or rail station. Note potential changes between rail stations or airports could be allowed (e.g. Atocha - Chamartin)
avg_travel_time	float	travel time between infrastructure (as in I10. infrastructure transitions)

pax_type	str	pax type that this applies (by default all)
mct	float	MCT adding to avg_travel_time the airport/rail processes as required to obtain the total p2p, p2g, g2p and g2g as required.

18. possible_paths_avg_#.csv

- Possible paths to go between regions considering services schedules and connecting times, including the corresponding passenger demands in the nominal (=undisrupted) situation.

Field	Type	Other info
path_id	int	Id of each path
itineraries	int	Number of itineraries for this path
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
path		
option	int	option within origin-destination (i.e., numbering of path for origin-destination)
total_avg_travel_time	float	Average total d2d travel time for itineraries in path
total_travel_time_min	float	Minimum total d2d travel time for itineraries in path
total_travel_time_max	float	Maximum total d2d travel time for itineraries in path
total_avg_cost	float	Average total cost (EUR) for itineraries in path
total_avg_emissions	float	Average total emissions per pax (CO2) for itineraries in path
total_avg_waiting_time	float	Average total waiting time (min) for itineraries in path
nmodes	int	Number of modes in path
earliest_departure_time	datetime timezone	with yyyy-mm-dd hh:mm:ss +00:00. In UTC (even for rail)
latest_arrival_time	datetime timezone	with yyyy-mm-dd hh:mm:ss +00:00. In UTC (even for rail)

journey_type	str	air, rail, multimodal, none
access_avg_time	float	minutes d2infrastructure
egress_avg_time	float	minutes i2d
origin_#	str	id of infratrue of origin for service number # (e.g. origin_0)
destination_#	str	id of infrasture of destination for service nubmer # (e.g. destination_0)
mode_#	str	mode of service # (air, rail)
travel_avg_time_#	float	average travel time (min) for itineraries in path for service #
cost_avg_#	float	average cost (EUR) for itinearies in path for service #
emissions_#	float	average emissions (CO2) kg per pax for itineraries in path for service #
mct_avg_time_#_\$_	float	average MCT between services # and \$_ for itineraries in path
connecting_avg_time_#_\$_	float	average connecting time between services # and \$_
waiting_avg_time_#_\$_	float	average waiting time between services # an \$_
connecting_time_#_\$__max	float	maximum connecting time between services # and \$_
waiting_time_#_\$__max	float	maximum waiting time between services # and \$_
demand	float	actual demand travelling on this path (for nominal situation)

7.3.2 A.3.3 Outputs

O1. flight_schedules_adjusted.csv

- Same format as the initial flight schedules I1.

O2. rail_timetable_enriched_adjusted.csv

- Same format as the initial rail timetable I6.

O3. service_dm_list.csv

- Table to indicate the corresponding disruption management measures per service

Field	Type	Other info
service_id	string	As in I1. flight schedule/I6 rail timetable
origin	string	As in I1. flight schedule/I6 rail timetable
destination	string	As in I1. flight schedule/I6 rail timetable
cancellation_indicator	int	indicates whether a service is cancelled (=1) or not (=0)

O4. odPair_list.csv

- Table to indicate the affection of OD-Pairs

Field	Type	Other info
pair_ID	string	As in I8. possible paths
origin	string	As in I8. possible paths
destination	string	As in I8. possible paths
affection_indicator	int	indicates whether a pair is affected (=1) or not (=0)