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Abstract

This document outlines the Functional Requirements (FRD) for the Performance Assessment Solution (SOL399/SOL1 of MultiModX, TRL2). SOL399/SOL1 comprises three distinct but coordinated elements: First, developing a multimodal performance framework with key performance indicators (KPIs) and associated measurement mechanisms. Second, provide a strategic evaluation platform for the assessment of mobility from a multimodal perspective considering flight schedules and rail timetables, enabling the evaluation of strategic actions such as policies or new optimised schedules, and the assessment of replanned operations, i.e., modified flight and rail schedules for the day of operation. Third, developing a platform for evaluating tactical (day of execution) operations considering disturbances with a focus on passenger-centric metrics, enabling the evaluation of the materialisation of the planned operations and Solutions and multimodal support mechanisms.

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This document describes the functional architecture view with information on the Solution, its rationale and the stakeholders that could benefit from it. It also provides a functional view of the different elements of the Solution with their functional decomposition. The FRD includes a list of high-level functional requirements for the different elements of the Solution; and a list of assumptions for the different components. The information is provided for each of the three elements that comprise SOL399/SOL1.

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MultiModX

INTEGRATED PASSENGER-CENTRIC PLANNING OF MULTIMODAL NETWORKS

MultiModX

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1 Executive summary

The Performance Assessment Solution (SOL399/SOL1) aims to develop a multimodal performance framework and a multimodal modelling and evaluation platform for strategic (planning) and tactical (on the day of execution) operations.

The performance framework builds on the work from previous multimodal research projects and extends the work with collaboration with other SESAR ER and IR initiatives.

The multimodal modelling and evaluation platform is divided into two distinct parts:

A Strategic Evaluator, which focuses on the evaluation of flight schedules, rail timetables and other infrastructure characteristics, e.g. minimum connecting times intra and inter-modes, to assess mobility from a passenger-centric perspective, providing metrics at the region, the infrastructure (airport, rail station) and the operator level. This evaluator can also assess replanned operations, with a particular focus on identifying and reallocating impacted passengers.

A Tactical Evaluator, which can simulate the operations as they unfold on the day of execution. This model tracks vehicles (flights and trains) and passengers, providing passenger-centric metrics, e.g. missed connections and total delays. The Tactical Evaluator can model disturbances and the associated mechanisms to manage them (including SOL401/SOL3).

The three components of SOL399/SOL1 (the multimodal performance framework, the strategic evaluator and the tactical evaluator) are complementary and feed into each other. However, they have different technical environments, functional requirements, inputs and outputs, assumptions, and stakeholders impacted by them. Therefore, they are considered separately.

First, the performance framework provides a set of indicators that could be estimated to capture multimodal mobility aspects. This is done from the perspective of SESAR and also considering mobility as a whole. The definition of this framework is built on some assumptions, such as the representativeness of stakeholders involved in its definition. A representative cross-section of stakeholders for the European-wide system is achieved capturing all their needs. This is ensured by relying on MultiModX's Industry Board and dedicated exchanges with other SESAR ER projects (e.g. MAIA, SIGN-AIR) and IR projects (e.g. PEARL, AMPLE3, Travel Wise, JARVIS) and collaboration with the SESAR3's Passenger Experience and Multimodaly Flagship.

Second, the Strategic Evaluator estimates the possible paths for passengers between regions (or infrastructure (airport, rail station)) and, after a process of clustering and filtering, obtains alternatives that are characterised by expected total journey time (considering gate-to-gate mobility), cost, emissions, waiting times (difference between connecting time and minimum connecting time), type of mobility (air, rail or multimodal) and the number of services. These data are then used to disaggregate the origin-destination demand into these possible alternatives considering passengers' preferences (logit model). Finally, passenger flows are further disaggregated into individual services. The outcome allows the

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analysis of mobility, including aspects related to travel time, demand and capacity imbalance, resilience (e.g. number of connections, waiting times, expected travel time if the connection is missed), etc.

The Strategic Evaluator can also assess the impact of modifying some schedules, identifying affected passengers and reassigning stranded passengers, considering aspects such as supply availability on alternative services.

The Strategic Evaluator has assumptions about the passenger archetype coverage and the calibration of the modal choice used to capture the passengers' preferences. It is also assumed that the required multimodal governance is in place (e.g. data sharing infrastructure and inter-mode agreements such as in SIGN-AIR [14]). The model allows for alliances intra and inter-modes to be defined. Finally, it is assumed that the origin-destination demand is fixed and that prices are known in advance for the different alternatives. Some of these assumptions can be relaxed depending on the focus of the analysis (e.g. from analysing expected demand to assessing possible mobility where only connectivity between services is considered).

Third, the Tactical Evaluator uses individual flight and rail schedules and passenger itineraries and simulates them through the day of operation. Building on Mercury Agent-Based Model, it can model the different processes involved in passenger itineraries on their full journey (including the required connection between modes). The evaluator enables the integration of mechanisms to manage passengers' disruptions and can compute low-level passenger-centric metrics such as delay, or missed connections. The simulator can, therefore, assess planned networks (as produced by MultiModX SOL400/SOL2) but also replanned operations as generated when dealing with larger disruptions (e.g. MultiModX SOL401/SOL3).

This document presents the functional architecture disaggregating the functional view of the different components of SOL399/SOL1 into its main elements. It also includes the functional requirements and the assumptions of the different components of this Solution.

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2 Introduction

2.1 Purpose of the document

This document is the functional requirements document (FRD) detailing the functional architecture and requirements for MultiModX's Performance Assessment Solution (SOL399/SOL1). The Solution is comprised of three components:

A performance framework builds on the work from previous multimodal research projects and extends the work with collaboration with other SESAR ER and IR initiatives.

A strategic multimodal evaluator, which focuses on the evaluation of flight schedules, rail timetables and other infrastructure characteristics, e.g. minimum connecting times intra and inter-modes, to assess mobility from a passenger-centric perspective, providing metrics at the region, the infrastructure (airport, rail station) and the operator level. This evaluator can assess the outcome of the Schedule Designer Solution (SOL400/SOL2). The evaluator also provides the option to assess the impact on passenger itineraries of modified schedules and timetables in the event of replanning of operations pre-tactically, e.g. in case of disruption as provided by the Disruption Management Solution (SOL401/SOL3).

A tactical multimodal evaluator, which can simulate the operations as they unfold on the day of execution. This model tracks vehicles (flights and trains) and passengers, providing passenger-centric metrics, e.g. missed connections and total delays. The Tactical Evaluator can model disturbances and the associated mechanisms to manage them. This evaluator can consider either the planned network or the updated operations in case of replanning of schedules/timetables, for example, to deal with a disruption.

The primary objective of this document is to detail the functional requirements of the Solution and its components, with a particular focus on its inputs and outputs for the evaluators.

First, the document presents the functional architecture view of the Solution through an overview of the Solution, the capabilities it covers, and the stakeholders involved. This is provided for the different components of the Solution.

Then, the different components' functional requirements, i.e., the expected behaviour, are listed. Finally, assumptions for the development of these elements are detailed.

2.2 Scope

The OSED presents the operational service and environment of the Performance Assessment Solution. The FRD presents the functional requirements of the Performance Assessment Solution. The overall scope of the FRD covers the definition of the functional architecture view (including within the SESAR architecture) and the requirements for the methods and algorithms developed for SOL399/SOL1.

The Performance Assessment Solution is divided into three components:

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1. A Multimodal Performance Framework provides a set of PIs and KPIs that capture the mobility's multimodal aspects. Focusing on extending the scope of performance assessment and monitoring to include the passenger experience, this framework is developed from two perspectives: from a SESAR point of view, identifying which PIs and KPIs could be considered as part of an extension of the SESAR Performance Framework, and from a general mobility perspective, where the focus is put on regions and infrastructures to understand how mobility between them is performed in a multimodal context.

2. A Strategic Evaluator model, which can assess the mobility between regions and infrastructure given a set of flight and rail schedules and timetables, infrastructure characteristics (e.g. connecting times between modes), origin-destination demand and their characteristics. The Strategic Evaluator should be able to compute the strategic-related multimodal PIs and KPIs defined by the Multimodal Performance Framework. The Strategic Evaluator can assess any given set of schedules; this means that the outcome of the Schedule Generator (MultiModX's SOL400/SOL2) can be used as input by the Strategic Evaluator, enabling the iterative assessment of different coordinated schedules solutions. Moreover, the Strategic Evaluator can assess the impact of replanned operations (i.e., new schedules/timetables on all or some of the planned services) on already planned passenger itineraries. This enables the assessment of MultiModX's Disruption Management Solution (MultiModX's SOL401/SOL3), which reorganises the schedules considering network-impacting disruptions.

3. A Tactical Evaluator model, which can assess a day of operations, including disturbances and disruptions to the system. This evaluator can integrate mechanisms (solutions) that facilitate the multimodal journey of passengers (e.g. fast-track processing at airports). It can assess planned (or replanned) operations as processed by the Strategic Evaluator.

The Strategic and Tactical Ealuator will be applied to different case studies defined for Spain, Germany and Spain-Germany mobility as defined in the Experimental Research Plan (ERP) [11].

These activities **address the Objectives O2 and O3 of the project** as stated by the Grant Agreement (GA):

- **To develop a multimodal performance framework**, including a set of key performance indicators (KPIs) and the associated measurement mechanisms, that enables the comprehensive and rigorous assessment of the performance of multimodal transport systems and multimodal solutions.

- **To develop a multimodal modelling and evaluation framework**, to be integrated into a **Performance Assessment Solution** that supports the design, development and assessment of strategic and tactical multimodal solutions, focusing on scheduling and disruption management.

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,

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policymakers, urban planners, researchers and academics, consultants and advisory firms, technology developers, and environmental organisations.

2.4 Background

Multimodal Performance Framework

Previous work has focused on computing ad-hoc PIs to capture multimodal aspects of mobility. Noteworthy are the works conducted by previous SESAR ER projects, Modus and TRANSIT [15], which already reviewed the current ICAO [6] and SESAR performance schemes [13]. Both projects developed multimodal indicators that account for aspects such as door-to-door travel time, travel time reliability, monetary cost for the passenger, regional connectivity and accessibility, environmental impact, and resilience.

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

The expected evolution of the SESAR Master Plan considers the inclusion of Passenger Experience as one of the areas where PIs and KPIs will be developed. This contributes to the focus on passengers, extending the flight-centric vision of the ATM system. Other current research projects are working on these aspects and will coordinate some of their activities with the work to be conducted as part of SOL399/SOL1, namely, SIGN-AIR [14], MAIA [8], PEARL [12], AMPLE3 [1], Travel Wise [17] and JARVIS [7].

Strategic Multimodal Evaluator

The detailed representation of multimodal transport supply as a layered network (multiplex) enables the evaluation of coordination mechanisms, but it is computationally challenging given the high number of alternatives that may be available for performing a trip. Previous research conducted by TRANSIT [16] has already shown how considering schedules and low-level demand data is required to understand passengers' alternatives and their preferences when using the network.

There is also a need to evaluate how passengers could use the provided system supply in case of disruptions if operations are replanned.

Tactical Multimodal Evaluator

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

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In the context of multimodality, it is important not only to focus on the modelling of flights (or rail services) but also on the passengers and their full itineraries. Previous research has shown that passengers might experience disruptions very differently than airlines (and flights) [3, 5, 10]. For example, a small delay of a flight may result in passengers missing their connection and greatly increasing their total travel time. In the context of multimodality, these discrepancies are expected to increase even further. Moreover, airlines' operational decisions tend to be underpinned by their expected operating costs, which might vary as a function of passenger experience.

Mercury, is a standalone gate-to-gate (extended to door-to-door) flight and passenger mobility simulator specifically developed to tackle these considerations in many previous research projects [4, 5]. Mercury has been successfully used to evaluate door-to-door mobility considering intra-airport processes (kerb-to-gate, gate-to-kerb) and first-last mile [5].

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 explains 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 SOL399/SOL1. Chapter 4 outlines the general functional requirements and those of the two components of the solution. Finally, Chapter 5 details the general assumptions of the solution and those specific to its components.

2.6 Glossary of terms

Term	Definition	Source of the definition
Disruption	Rail or air network disruptions, which are known in advance and produce a significant reduction in supply on the infrastructure of the networks.	Own elaboration
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
Planned network	Instantiation of a strategic experiment computed by the Strategic Performance Evaluator consisting of: supply (flight schedules and rail timetable), demand (passenger itineraries) and infrastructure (access/egress times, minimum connecting times, inter-modes connecting times, passenger processing times).	Own elaboration

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Itinerary	A succession of services (flights or trains) which represent a possible trip for a passenger.	Own elaboration
[Infrastructure] Node	An airport or a rail station.	Own elaboration
Multimodal supporting mechanisms	Mechanisms that tactically support passengers through their multimodal journey, e.g. fast-track at airports dedicated to multimodal passengers to reduce potential missed connections. These mechanisms modify the default behaviour of elements in the system.	Own elaboration
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
Replanned network	A planned network for which flight operations and rail timetables are adjusted to consider the impact of disruptions (cancellations, shifts in schedules (delays) and the addition of new services).	Own elaboration
Logit model	A statistical model which calculates the probability of choosing a specific alternative for each passenger archetype when presented with several options for travelling between a given OD pair.	Own elaboration
Service	A specific flight or train between two stations.	Own elaboration

Table 1: Glossary of terms

2.7 List of acronyms

Term	Definition
ABM	Agent Based Model
AO	Aircraft Operator
API	Application Programming Interface
ATFM	Air traffic flow management
ATM	Air traffic management

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D2D	Door-to-door
D2K	Door-to-kerb
DES	Digital European Sky
FR	Functional Requirements
FRD	Functional requirements document
G2G	Gate-to-gate
G2K	Gate-to-kerb
G2P	Gate-to-platform
GA	Grant agreement
GDS	Global Distribution Systems
GTFS	General Transit Feed Specification
I2I	Infrastructure-to-infrastructure
ID	Identifier
K2D	Kerb-to-door
K2G	Kerb-to-gate
K2P	Kerb-to-platform
KPI	Key Performance Indicator
MCT	Minimum Connecting Time
MPF	Multimodal Performance Framework
MTOW	Maximum Take-off Weight
OD	Origin-Destination
OP	Operational requirements
OSED	Operational service and environment description
P2G	Platform-to-gate
P2K	Platform-to-kerb

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P2P	Platform-to-platform
PI	Performance Indicator
SESAR	Single European Sky ATM Research
SESAR 3 JU	SESAR 3 Joint Undertaking
SIBT	Schedule In Block Time
SME	Strategic Multimodal Evaluator
SOBT	Schedule Off Block Time
TME	Tactical Multimodal Evaluator
TRL	Technology readiness level
WTC	Wake Turbulence Category

Table 2: list of acronyms

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3 Functional architecture view

3.1 SESAR solution overview

Multimodal Performance Framework

The multimodal performance framework developed as part of SOL399/SOL1 relies on a literature review of previous work in the field and interaction and feedback obtained from stakeholders and other related research projects. As shown in Figure 1, the framework identifies three levels of development of potential multimodal indicators:

- Level 1 are indicators currently part of the SESAR3 Performance Framework.
- Level 2 comprises indicators that are currently (or are planned) to be at least modelled by research projects.
- Level 3 contains more ambitious indicators that aim to capture the total experience of passengers in their door-to-door journey.

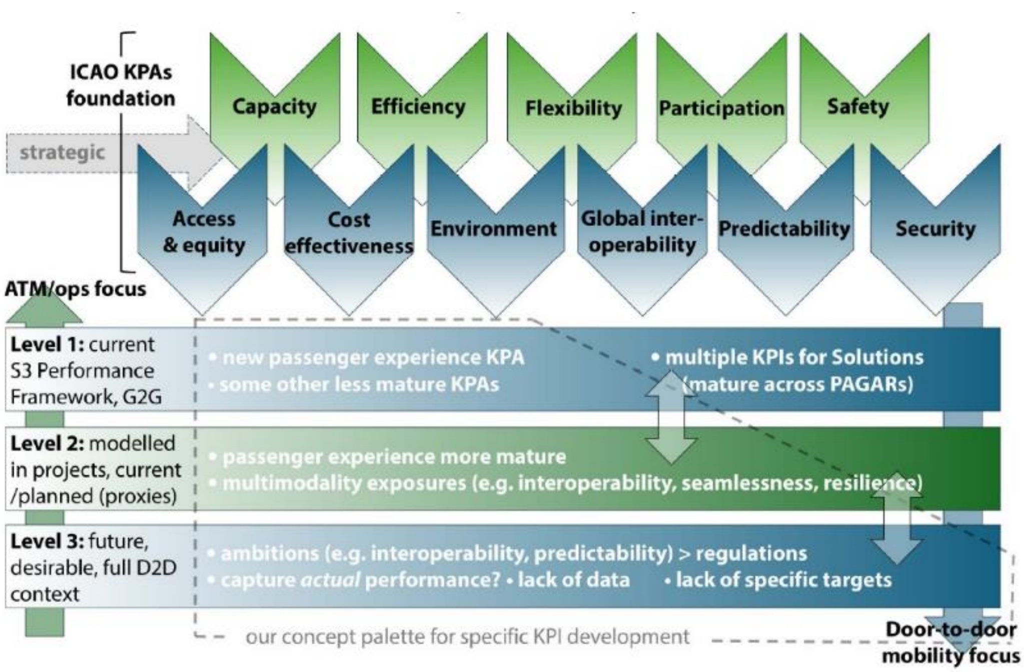

Figure 1: Performance Assessment – Multimodal Performance Framework Concept

It is worth noticing how the same aspects could be found at different levels, e.g. interoperability is a multimodality exposure (at Level 2) while part of the ambitions for full door-to-door performance at Level 3.

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The work performed by SOL399/SOL1 on the further definition of this multimodal performance framework represents an improvement to the European ATM system as these aspects are currently not monitored and are out-of-scope of the system's considerations. The work of SOL399/SOL1 is, by its nature, a starting point for the activities that should be conducted collaboratively with other research activities in the field, namely SIGN-AIR [14], MAIA [8], PEARL [12], AMPLE3 [1], Travel Wise [17] and JARVIS [7]. The Passenger Experience and Multimodality Flagship could organise and further develop these activities.

Strategic Multimodal Evaluator

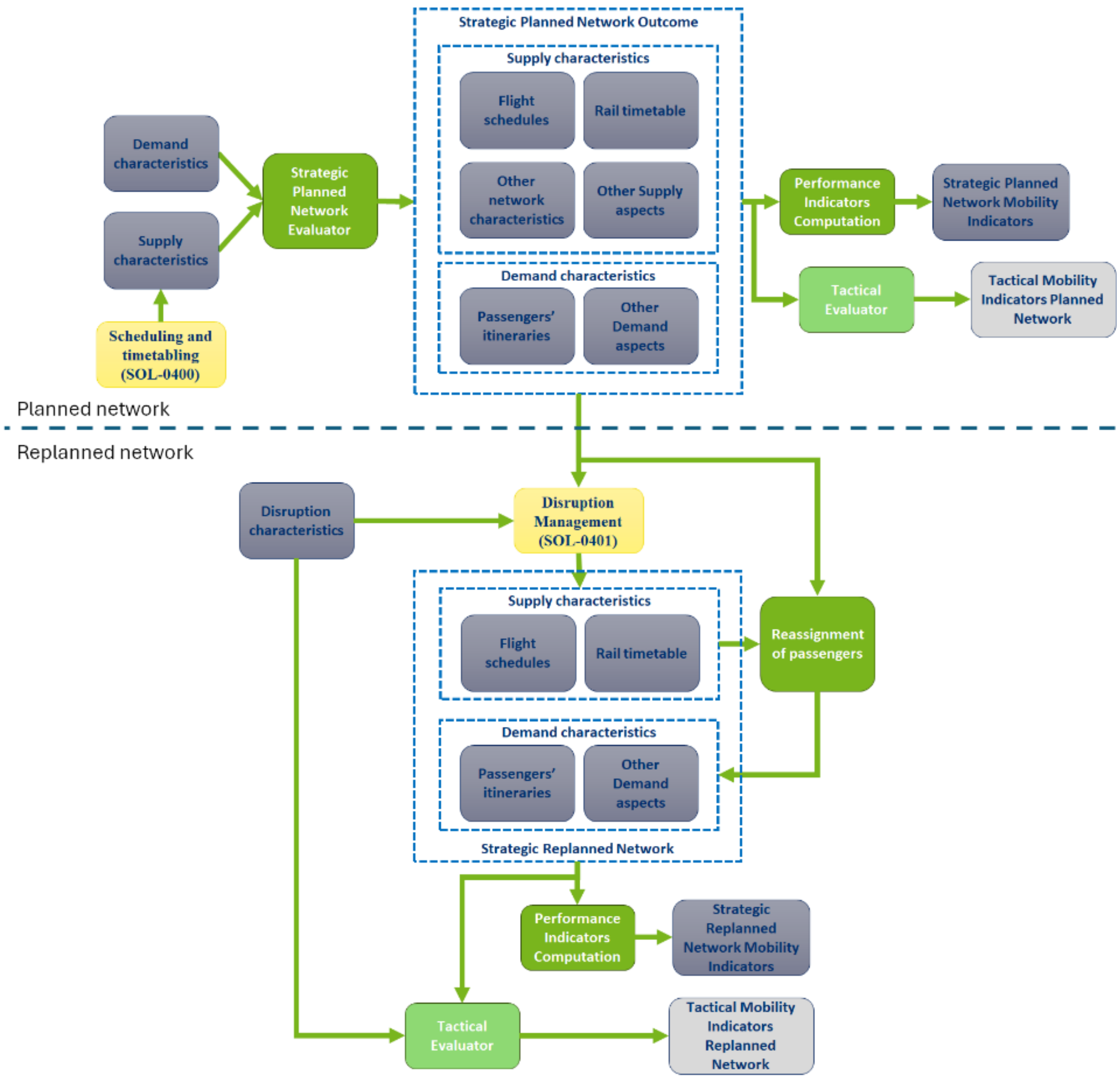

Figure 2: Performance Assessment – Strategic Evaluator Concept

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As shown in Figure 2, the Strategic Multimodal Evaluator is comprised of three main elements:

- **Strategic Planned Network Evaluator**, which, from the characteristics of demand (OD demand) and supply (flight and rail schedules and infrastructure aspects), computes the materialisation of the supply and demand characteristics in the network. As shown, the supply could be any flight and rail schedules provided, including the Scheduling Design Optimiser (MultiModX's SOL400/SOL2) outcome, which aims to improve the connectivity between air and rail layers. Figure 3 presents more details on this element; as shown, possible itineraries along the rail and air network that allow passengers to fulfil their journeys are computed. Then, the demand is disaggregated into flows of passengers who would like to use different services (alternatives). These alternatives can be purely air or rail options or a combination of both (multimodal journeys). Finally, passengers are assigned to services, generating individual passenger itineraries.

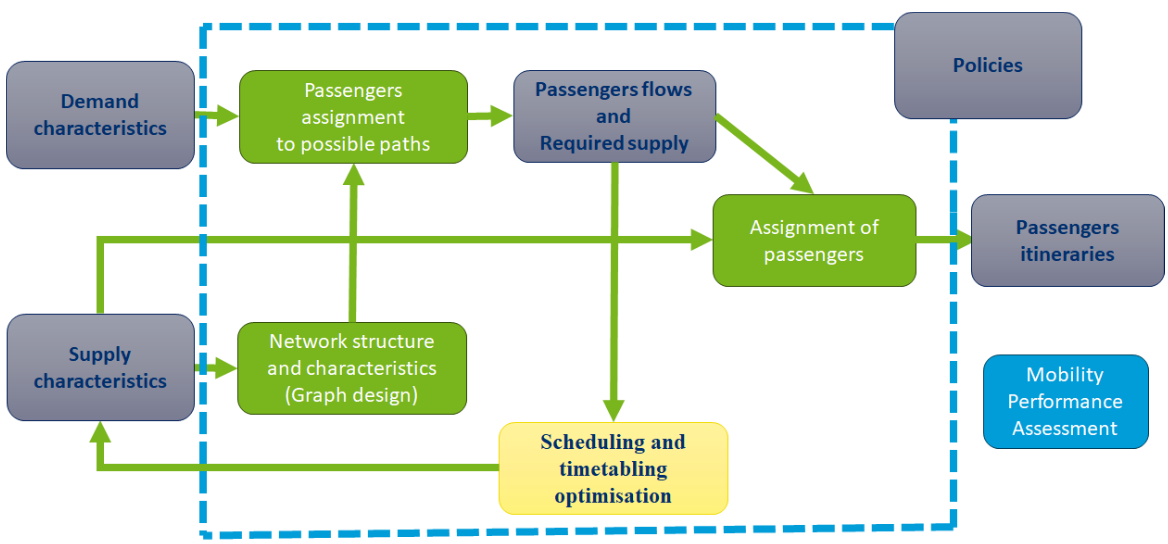

Figure 3: Performance Assessment – Strategic Planned Network Evaluator Concept

- **Passenger Reassignment on Replanned Network**, which assesses the impact of modifying the supply (flight schedules and rail timetable) on the already planned operations. When disruptions impact the network in a significant manner, the air and rail operators will modify their services (e.g. cancelling flights, delaying services). This replanning of operations can be done reactively (just to adjust to the disruption, e.g. by shifting the schedules by the planned ATFM delay), or proactively, for example, by replanning operations to maximise the supplied demand to fulfil passengers' itineraries. This optimised replanning is the objective of MultiModX's Disruption Management Solution (SOL401/SOL3). Therefore, the outcome of the Disruption Management Solution is new flight schedules and rail timetables, which modify some of the originally planned operations. As shown in Figure 2, the Strategic Evaluator can then identify the affected passengers

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and reassign the demand of stranded passengers due to these changes. Finally, the Performance Indicator Computation can assess the outcome of this replanned network.

- **Performance Indicators Computation**, which, considering the outcome of the Strategic Planned Network Evaluator (or the Replanned network analysis), computes mobility performance indicators.

The Strategic Multimodal Evaluator presents several advancements with respect to the current operations and state-of-the-art tools. For example, one could evaluate the impact on the mobility of different policies impacting the supply (e.g. taxes and bans), the impact of changes on infrastructure (e.g. changes to minimum connecting times), business models (e.g. alliances for inter-mode operations), etc.

Tactical Multimodal Evaluator

The Tactical Multimodal Evaluator of the Performance Assessment solution focuses on simulating a day of operations in the network, tracking individual flights and passengers. As shown in Figure 4, the input to the Tactical Evaluator is the individual flight schedules, rail timetables, passenger itineraries and any other tactical, operational parameters (e.g. probability of ATFM regulation, turnaround times, etc.). The model can simulate disturbed conditions, such as day-to-day small delays, and stressed nominal conditions (e.g. ATFM regulations or delays on the ground system linking the rail stations with the airports). Therefore, The Tactical Multimodal Evaluator can assess how the planned operations (as derived from the Strategic Multimodal Evaluator) unfold on the day of operations. Mechanisms can be implemented and integrated into the platform to assess their performance in supporting multimodal journeys (e.g. fast-track at airports for delayed multimodal passengers). Finally, if larger network-wide disruptions, which require some replanning of operations instead of a reactive approach when managing passengers and services, are experienced, the network would be replanned (as presented in the Strategic Multimodal Evaluator description), and the Tactical Multimodal Evaluator could then assess this new network.

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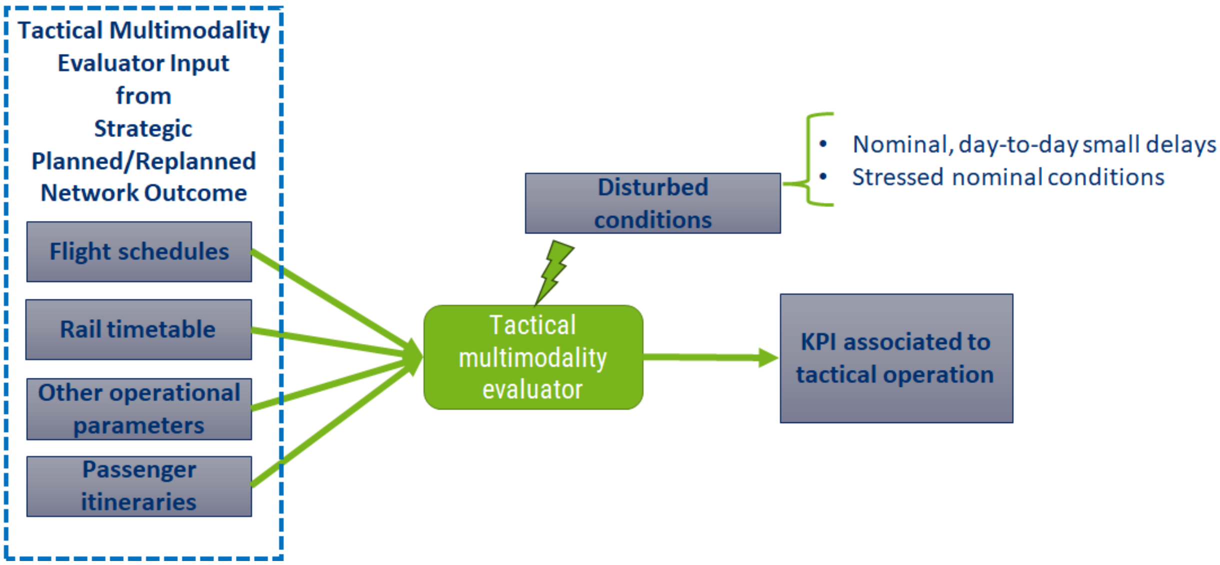

Figure 4: Performance Assessment – Tactical Evaluator Concept

The Tactical Multimodal Evaluator extends Mercury ABM platform developed over several SESAR ER projects from a gate-to-gate simulator to a full multimodal evaluator [4, 5, 18]. The platform can track individual flights, trains and passengers. This facilitates the computation of very low-level passenger-centric indicators, such as missed connections, waiting times, total journey times, etc.

3.1.1 Supporting reasons for this SESAR solution

<u>**Multimodal Performance Framework**</u>

The expected evolution of the SESAR Master Plan considers the inclusion of Passenger Experience as one of the areas where PIs and KPIs will be developed. This contributes to the focus on passengers, extending the flight-centric vision of the ATM system. Therefore, a definition of a shared multimodal performance framework is needed. This should reflect how SESAR KPIs impact multimodality, how multimodality could impact SESAR's indicators and, critically, how the SESAR Performance Framework could be extended to include some of these passenger-centric (multimodal) aspects.

Previous work has focused on computing ad-hoc PIs to capture multimodal aspects of mobility. Noteworthy are the works conducted by previous SESAR ER projects, Modus and TRANSIT [9, 15], which already reviewed the current ICAO [6] and SESAR performance schemes [13]. Both projects developed multimodal indicators that account for aspects such as door-to-door travel time, travel time reliability, monetary cost for the passenger, regional connectivity and accessibility, environmental impact, and resilience. Other current research projects are working on these aspects and will coordinate some of their activities with the work to be conducted as part of SOL399/SOL1, namely, SIGN-AIR [14], MAIA [8], PEARL [12] and AMPLE3 [1]; and more widely with the SESAR Passenger Experience and Multimodality Flagship.

<u>**Strategic Multimodal Evaluator**</u>

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The detailed representation of multimodal transport supply as a layered network (multiplex) enables the evaluation of coordination mechanisms, but it is computationally challenging given the high number of alternatives that may be available for performing a trip. Previous research conducted by TRANSIT [16] has already shown how considering schedules and low-level demand data is required to understand passengers' alternatives and preferences when using the network.

There is a need for a platform that enables the evaluation of mobility considering the joint operations of air and rail services. This Strategic Evaluator should enable the assessment of flight schedules and rail timetables under different assumptions (e.g. integrated ticketing between operators) and policies (e.g. CO_2 emissions costs).

The evaluator will also enable the assessment of replanned operations when dealing with network-related disruptions reallocating passengers on available capacity, and providing passenger-centric indicators.

Tactical Multimodal Evaluator

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

In the context of multimodality, it is important not only to focus on the modelling of flights (or rail services) but also on the passengers and their full itineraries. Previous research has shown that passengers might experience disruptions very differently than airlines (and flights) [3, 5, 9]. In the context of multimodality, these discrepancies are expected to increase. Moreover, airlines' operational decisions tend to be underpinned by their expected operating costs, which might vary due to passenger experience.

3.1.2 ATM capabilities addressed by the SESAR solution

Multimodal Performance Framework

The Multimodal Performance Framework provides a set of PIs and KPIs that can be used to (partially) capture the multimodal aspects of transport. Therefore, it does not interact directly with the SESAR architecture and does not require any particular capabilities from SESAR. However, potential impacts of the Multimodal Performance Framework on SESAR solutions have been identified from AMPLE3 D2.6 – Transformation View 2024 [2] and are detailed in Table 3.

The consideration of some of the PIs and KPIs put forward by the Multimodal Performance Framework might require the SESAR architecture to consider the inputs required to compute the indicators to ensure that these are produced/stored/managed adequately. For example, if arrival delay is considered a PI that should be monitored to assess multimodal passenger mobility, the architecture must ensure this information is accessible/stored.

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Note that the data requirements list will be subject to the Level of the indicator (Level 1, 2 and 3 as described in Section 3.1), e.g. indicators for Level 3 might require more information than the indicators for lower levels, and produced as an outcome of the full development of the Solution and further developed as part of the Passenger Experience and Multimodality Flagship. Therefore, no further considerations can be given at this stage.

Strategic and Tactical Multimodal Evaluator

The Strategic and Tactical Multimodal Evaluators are standalone models to assess planned and realised mobility networks. Therefore, they are not planned to be integrated into the SESAR architecture. However, these platforms could evaluate different SESAR Solutions, particularly by using the Tactical Multimodal Evaluator, which can integrate SESAR Solutions as part of modifications into the Mercury model, producing flight and passenger-centric indicators.

SESAR capabilities identified from AMPLE3 Transformation View 2024

In Table3 we have described some of the SESAR capabilities that have been identified from AMPLE3 D2.6 – Transformation View 2024 [2]. 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 multimodality [2].

SESAR solution capabilities	Comments on potential updates required at capability level
Aerodrome Operations – Aerodrome Accessibility – Door-to-door Journey Disruption Management*	If new modified operations are planned, the Strategic Evaluator should be able to assess these new schedules. The capabilities of this SESAR solution could also be modelled and evaluated in the Tactical Evaluator of SOL399/SOL1.
Aerodrome Operations – Landside Management – Dynamic Airport Resource Allocation	The dynamic management of resources at the airport (landside) is critical to ensure passenger connectivity, particularly with ground modes. Therefore, the capabilities of this solution should consider multimodal aspects and could be evaluated by the Tactical Evaluator of SOL399/SOL1.
Service Delivery Management – Performance Management (operational) – Multimodal Performance Management (Air)*	The Performance Indicators considered by this SESAR Solution should be aligned with the outcome of the assessment of multimodal indicators to be carried out as part of SOL399/SOL1.
Information Management – Data Management – Single Ticketing*	Single ticketing is an enabler for the mechanisms modelled in SOL399/SOL1.

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* These terms are candidates for terminology changes as Change Requests, as discussed below.

Table 3: SESAR Capability Model – Operational capabilities – Updated as defined in [2]

Further to 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 [12], AMPLE3 [1] and SIGN-AIR [14] projects (*inter alia*; and as reported under separate cover). Currently, there is no opportunity to include new capabilities at Level 1. The multimodality capabilities (below) are in scope for inclusion at Level 2 or 3 – also TBD, whilst noting that under #3 below ("Multimodal performance management (air)") is a placeholder for a new capability at Level 3.

1. Regarding "**Aerodrome accessibility** – door-to-door journey disruption management", it was proposed **instead** "Airport connectivity – door-to-door journey facilitation". The rationales were:

- "airport" is used elsewhere in the model, and is more ***inclusive*** (from the multimodal perspective) than "aerodrome";
- "accessibility" is often ***unidirectional*** (cf. 'access' and 'egress' as standard/common terms);
- "journey facilitation" is more ***inclusive*** than "disruption management" (and includes nominal states and strategic planning).

2. Regarding "**Flight prioritisation**", the **addition** of "IROPs" (as a standard IATA term) was proposed. TBD if this would **replace** "Flight delay criticality management" (dependent on what is intended to be covered within this criticality).

3. Regarding "**Multimodal performance management (air)**", using the terminology of "air journey" was discussed, but, on further discussion, it is currently proposed to retain the name as-is. The term "air" in parenthesis (simply) signifies that we should measure performance within the remit of ATM.

2. Regarding "**Single ticketing**", the latest proposal in correspondence is that this be written as "(Single) Ticketing" in the corresponding box to reflect that this also includes one-leg (air) tickets (not only multi-leg air and/or multimodal). This box should ideally be connected to other capability consequences in the model (i.e. actions), even when the ticket is one-leg ('simple'). It was noted that this also carries liability implications (e.g. Reg 261), which could impact (2) and (3), and suggests various dependent PIs (e.g. re. 'a/c wait' (gate), 'a/c accelerate' (e/r)).

3.1.3 Stakeholders impacted by the SESAR solution

We provide the different stakeholders that could be impacted by the SESAR solution disaggregated by component.

<u>**Multimodal Performance Framework**</u>

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Stakeholder	Why it matters to the stakeholder
System Performance Modellers, Decision-makers, Infrastructure managers and other stakeholders concerned with the multimodal monitoring of operations	The Multimodal Performance Framework can support stakeholders, such as decision-makers, infrastructure managers, etc.) who want to consider the impact of their Solutions on the overall passenger experience and mobility (with a particular focus on passenger connectivity).
Aviation community (airlines, airports)	The Multimodal Performance Framework provides PIs/KPIs that are relevant to the aviation community to assess and monitor system performance.
Railway community (railway operators, infrastructure managers)	The Multimodal Performance Framework provides PIs/KPIs which should be relevant to the rail community to assess and monitor the system performance.
European and national authorities, regulatory bodies (National and regional governments, European Commission, other decision-makers, ERA, EU Joint Research Centre, OECD	The Multimodal Performance Framework defines PIs/KPIs which are relevant to the stakeholders and, therefore should be considered by national authorities and regulatory bodies when setting up their policies.
Scientific community (ANSP, EUROCONTROL, researchers, academics, conference chairs, coordinators of ongoing and former relevant projects)	The Multimodal Performance Framework could be reused by future research to set indicators that are relevant to the community and can be used for benchmarking different solutions.
SESAR JU	The SESAR JU can gain a better understanding of how multimodality could impact ATM-related PIs and KPIs and vice-versa. This is required when cost-benefit analysis and benchmarking are needed to be established across different solutions that could affect the same PIs and KPIs. The Multimodal Performance Framework and the validation platforms would be of interest to the assessment of other multimodal solutions by the SESAR JU.

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Project Partners	The project's partners will require the Multimodal Performance Framework and the evaluation platforms to evaluate the effectiveness of MultiModX's SOL400/SOL2 and SOL401/SOL3.

Table 4: ***SESAR 399 – Multimodal Performance Framework Stakeholders***

Strategic Multimodal Evaluator

Stakeholder	**Why it matters to the stakeholder**
Aviation community (airlines, airports)	The evaluation of the scheduling and timetable coordination and integration enables the assessment of the benefits of data sharing and collaboration across stakeholders within aviation and with rail, such as assessing the benefits of establishing alliances with other modes and operators.
Railway community (railway operators, infrastructure managers)	The evaluation of the scheduling and timetable coordination and integration enables the assessment of the benefits of data sharing and collaboration across stakeholders within aviation and with rail, such as assessing the benefits of establishing alliances with other modes and operators.
Infrastructure managers (airport and rail infrastructure operators)	The Strategic Multimodal Evaluator could assess the potential volume of passengers and the connectivity of their infrastructure with the overall network. Infrastructure managers could also assess the impact of improving the inter-mode connectivity (e.g. with reduced minimum connecting times which could be achieved by better use of resources or infrastructure adjustments, such as extension of rail lines).
Passengers' associations	Passengers' associations could be interested in assessing the impact of multimodality on overall mobility (e.g. expected travel time, costs and CO2 emissions).

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European and national authorities, regulatory bodies (National and regional governments, European Commission, other decision-makers, ERA, EU Joint Research Centre, OECD)	The Strategic Multimodal Evaluator provides the possibility to assess different policies and their impact on the multimodal performance. The evaluation results of the different Schedule Design Solution(s) provide insight into the expected impact of multimodality from a policy definition perspective. Examples of policies that could be evaluated include policies which impact the passenger choice (e.g. costs) or supply (e.g. bans), such as changes to taxation (e.g. frequent flyer levy, CO2 charges) or limitations on operations (e.g. flight-bans). The replanning of operations in case of disruptions could also be assessed. This enables quantifying the benefit of cooperation across networks (rail and air) when supporting each other in case of disruptions.
GDS (Global Distribution Systems) organisations (Amadeus)	The results of the experiments conducted by the Strategic Multimodal Evaluator are relevant for better integrating multimodality in transport search engines and identifying connecting nodes that could benefit from these types of integrated tickets.
Scientific community (ANSP, EUROCONTROL, researchers, academics, conference chairs, coordinators of ongoing and former relevant projects)	The Strategic Multimodal Evaluator is generic enough to assess different versions of the Schedule Design Solution. This opens the door to evaluating future research at the network level with the tools developed in MultiModX. It is a platform that enables the evaluation of many different approaches to designing multimodal itineraries. The evaluator also enables the assessment of different replanning strategies to deal with disruptions in the system, i.e., different versions of the Disruption Management Solution. The results with the models' capabilities and limitations can serve as the basis to direct and justify future research.
Cities and regions, urban planners (ARC regional council members)	The Strategic Multimodal Evaluator opens the door to the assessment of development or improvement of particular infrastructure and urban planning at the city level, including the identification of systems that should be enhanced to improve the execution of multimodality. It should be possible to assess the connectivity of their regions as a function of different infrastructure assumptions.

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SESAR JU	The Strategic Multimodal Evaluator platforms would be of interest for the assessment of other multimodal Solutions by the SESAR JU, which have an impact on schedule (or replanning of operations).
Project Partners	The project's partners require a Strategic Multimodal Evaluator to assess the effectiveness of MultiModX's SOL400/SOL2 and SOL401/SOL3.

Table 5: ***SESAR 399 – Strategic Multimodal Evaluator Stakeholders***

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Tactical Multimodal Evaluator

Stakeholder	**Why it matters to the stakeholder**
Aviation community (airlines, airports)	The evaluation of operations and disruption management solutions will enable the assessment of the benefits of data sharing and collaboration across stakeholders within aviation and with rail. Moreover, they can evaluate the robustness of their schedules with respect to nominal and stressed conditions. This could help to improve the padding of their operations. They could assess the number of passengers potentially impacted by delays and missed connections. They could also evaluate the potential number of passengers needing rebooking on specific services.
Railway community (railway operators, infrastructure managers)	The evaluation of operations and disruption management solutions enables the assessment of the benefits of data sharing and collaboration across stakeholders within aviation and with rail. Moreover, they can evaluate the robustness of their timetable with respect to nominal and stressed conditions. They could assess the number of passengers potentially impacted by delays and missed connections. They could also evaluate the potential number of passengers needing rebooking on specific services.
Airport managers	They could assess the impact of mechanisms to manage multimodal passengers on their infrastructure and the benefit of different Solutions to manage air and ground operations on passenger experience (delays and missed connections).
Infrastructure managers	They could assess how changes in the operation of their infrastructure could impact passenger experience (delays and missed connections).

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European and national authorities, regulatory bodies (National and regional governments, European Commission, other decision makers, ERA, EU Joint Research Centre, OECD)	The Tactical Multimodal Evaluator provides the possibility to assess different policies and their impact on the multimodal performance. The results of the evaluation of disruption management support tools will provide insight into the expected impact of multimodality from a policy definition perspective. The Tactical Multimodal Evaluator can assess policies such as duty of care and compensation alternatives. The Tactical Multimodal Evaluator could assess their benefit for passengers and the expected cost to different stakeholders.
Scientific community (ANSP, EUROCONTROL, researchers, academics, conference chairs, coordinators of ongoing and former relevant projects)	The Tactical Multimodal Evaluator is generic enough to assess both planned and replanned networks. Moreover, it can evaluate mechanisms (and Solutions) that support multimodality and assess the impact of any other solution that impacts flight (or rail) operations from the passenger (multimodal) perspective. This opens the door to evaluating future research at the network level with the tools developed in MultiModX. The results with the model capability and limitations can serve as the basis to direct and justify future research.
Cities and regions, urban planners (ARC regional council members)	The results of the experiments can serve as a basis for decision-making in developing or improving specific infrastructure and urban planning at the city level, including identifying systems that should be enhanced to improve the execution of multimodality.
SESAR JU	The Tactical Multimodal Evaluator would be of interest for the assessment of other multimodal (or generic) Solutions by the SESAR JU, assessing their impact on passengers (focusing on multimodal journeys)
Project Partners	The project's partners will require the Tactical Multimodal Evaluator to assess the effectiveness/robustness of MultiModX's SOL400/SOL2 and SOL401/SOL3.

Table 6: ***SESAR 399 – Tactical Multimodal Evaluator Stakeholders***

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3.2 SESAR solution functional view

3.2.1 Interaction(s) identification

Multimodal Performance Framework

The Multimodal Performance Framework provides a set of PIs and KPIs that can be used to (partially) capture the multimodal aspects of transport. Therefore, it does not require any particular interactions with external systems.

Strategic and Tactical Multimodal Evaluator

The Strategic and Tactical Multimodal Evaluators are standalone models to assess planned and realised mobility networks. Therefore, they are not expected to interact with external systems for their execution.

However, the Strategic Multimodal Evaluator will interact with MultiModX's Schedule Design Solution, SOL400/SOL2. This will be done by SOL400/SOL2, which will produce a new set of schedules and timetables to be evaluated strategically. As previously described, the Disruption Management Solution SOL401/SOL3 will generate new (updated) schedules and timetables that the Strategic Multimodal Evaluator will use to reassign impacted passengers to the available supply.

The Tactical Multimodal Evaluator can evaluate these planned operations. Therefore, the Tactical Multimodal Evaluator supports the full assessment of the performance of the Schedule Design Solution SOL400/SOL2 and the Disruption Management Solution SOL401/SOL3 by providing insight into the robustness of these planned operations.

Finally, it is worth noticing that the Tactical Multimodal Evaluator can also assess the impact on multimodality and passenger-related metrics of other mechanisms and/or Solutions. This can be done for mechanisms and Solutions which are directly related to multimodality (such as fast-track at the airports for multimodal passengers, as in [18]) or just that impact ATM operations (such as Dynamic Cost Indexing as in [5]). This is achieved by modifying the code of the Evaluator with the use of Modules (see Section 3.2.2) or a planned external communication API (under development).

3.2.2 Functional decomposition

There are distinct functionalities for the components of SOL399/SOL1, which are in their turn divided into different components as presented below:

Multimodal Performance Framework

The Multimodal Performance Framework is developed by carrying out a state-of-the-art review, obtaining feedback from MultiModX's Industry Board and interacting with other active research projects which are working on these passenger-experience and mobility aspects such as SIGN-AIR [14], MAIA [8], PEARL [12] and AMPLE3 [1].

The different PIs/KPIs are classified into:

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- Level 1, with indicators currently part of the SESAR3 Performance Framework that have, by their nature, a stronger focus on the gate-to-gate component of the passenger journey. Work has been conducted to identify how multimodality could impact the SESAR Performance Framework's currently considered PIs and KPIs.
- Level 2, which comprises indicators that are currently (or are planned) to be at least modelled by research projects. These will mature some aspects of passenger experience and focus on multimodal considerations such as reliability. These have, in turn, been divided between Level 2.1, which is deemed to be adequate to be promoted to Level 1 in a possible new version of the SESAR Performance Framework, and Level 2.2.
- Level 3 containing more ambitious indicators that aim to capture the total experience of passengers in their door-to-door journey. These will represent indicators that can be more desirable but currently not feasible due to several limitations, such as data availability.

The broader approach consists of the following:

1. Building an open access, digital catalogue of indicators across the three levels;
2. Carrying out a two-way gap analysis between the 'capabilities' in the SESAR Target Architecture and the indicator catalogue;
3. Further reviewing the state of the art at the European policy and strategy level to establish what indicators (and data) are necessary at Level 3 to model/monitor the corresponding goals/impacts.

The results will be fed into the ongoing KPI development work of PEARL and, hence, the SESAR Performance Framework. As previously mentioned, the activities of SOL399/SOL1 will start this process in collaboration with other relevant research projects (SIGN-AIR [14], MAIA [8], PEARL [12], AMPLE3 [1], Travel Wise [17] and JARVIS [7]. We expect that SOL399/SOL1 will support starting these activities that the Passenger Experience and Multimodality Flagship will further develop. This is particularly relevant for the open-access digital catalogue, which should be a life space that evolves along the gap analysis as the conditions of the operational environment change (e.g. datasets available, deployment of data collection and processing, etc). The current version of the digital catalogue of indicators can be accessed here: (https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY). Note that currently, members of MultiModX, SESAR 3 Scientific Committee, PEARL, SESAR3 Joint Undertaking Multimodality and Passenger Experience flagship, SIGN-AIR and MAIA have access as contributors to the collaborative site, while the catalogue is accessible via the link publicly in view mode. Finally, it is worth mentioning that the code of MultiModX Evaluators (which includes the implementation of the indicators) will be made public in the project GitHub repository (https://github.com/UoW-ATM/MultiModX).

Strategic Multimodal Evaluator

The current approach to evaluating the flight schedules and the rail timetable comprises 4 Functions which can be used to assess a planned or a replanned network, as shown in Figure 5:

- **Function 1 – Network structure and paths and itineraries computation**: This function uses as input the supply characteristics, i.e., flight schedules, rail timetable, minimum connecting time between services intra and inter modes connections considered, access and egress times to

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infrastructures (airports and rail stations), alliances and operators integrated ticketing, and the demand characteristics (number of aggregated passengers (per passenger archetype) for each origin-destination of interest). Note that the flight schedules and rail timetable could come from historical data, the outcome of some optimisation, e.g. MultiModX's Schedule Design Solution SOL400/SOL2, or even the outcome of replanning operations considering disruptions, e.g. the outcome of MultiModX's Disruption Management Solution SOL401/SOL3.

Many mobility-related changes to the system can be easily evaluated by modifying the Evaluator's input. For example, infrastructure changes (e.g. new access and egress times or improved MCTs), policies (e.g. removing flights within a threshold (flight-ban), or increasing cost of services due to taxes (even only for specific archetypes, such as frequent flyer levy)), or even changes to demand characteristics (e.g. new archetypes or sensitivity towards travel parameters).

Function 1 is composed of three high-level functionalities, with Function 1.1 and 1.2 used for the assessment of planned networks and Function 1.3 used to support the assessment of replanned networks.

Function 1.1 computes potential paths for each OD pair defined by the demand needed to be assigned. The potential paths do not consider if the connections of the services are feasible, i.e., respect their MCT, and are computed for two reasons: first, they direct the search of possible itineraries by Function 1.2 (as explained below), and second, the potential paths could be explored by other solutions, such as MultiModX's SOL400/SOL2, which can identify potential succession of infrastructure nodes (airports, rail stations) which are promising from a mobility perspective, e.g. potentially providing a fast service between a given OD pair as there are services linking them, but do not provide feasible itineraries due to the current schedules.

Function 1.2 first computes all the possible itineraries, considering the service schedules and respecting the MCTs. This search for possible itineraries is done over the potential paths previously computed by Function 1.1. Therefore, the paths used by these possible itineraries will constitute the set of possible paths, which will naturally be a subset of the potential paths. The user can provide for both computations, the potential paths and the possible itineraries, restrictions on how to find these, for example respecting alliances in connections (so only connections between operators within an alliance are enabled) or enabling connections between services respectively of their operator; or the maximum number of connections possible for a given itinerary.

The possible itineraries are then clustered into *equivalent* alternatives for the passengers per mode of transport and number of connections with similar total travel time, total waiting time, total CO_2 emissions and total travel cost. The thresholds used to define that two alternatives are *similar* can be defined in the configuration of the Strategic Multimodal Evaluator by the end user. These clusters are filtered so that only Pareto-equivalent itineraries, with some margins, are maintained per OD pair (i.e., if an itinerary is worse in all objectives (total travel time, total travel cost, etc.) than another itinerary considering those margins, then it is not considered further).

When assessing a replanned network, the possible paths and itineraries are only computed considering the modified schedules and the origin-destination for which passengers are impacted by the disruption, i.e., for which their services are modified (shifted in time (delayed), cancelled, etc.). In this case, Function 1.3 first identifies from the planned passenger itineraries their status on the replanned network. This could

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be: not affected (their itinerary is as planned, none of their services has been replanned), affected and doable (some services they plan on using are replanned but they are either just delayer or their connections are still feasible), and stranded (their services are cancelled or their connections are not feasible in the replanned network). The possible paths and itineraries (Function 1.1. and Function 1.2) are computed considering the demand that needs to find alternative routes (i.e., the passengers who are stranded). In this case, the clustering of alternatives is not conducted, as the objective is not to distribute the flow of passengers but to directly assign passengers to the available itineraries. Instead, further restrictions can be defined to filter out which itineraries are suitable for which passenger. For example, forcing the initial and final node as in the original itinerary, maintaining the same operator, allowing (or not) swap mode, allowing (or not) to depart before the original itinerary, etc.

- **Function 2 – Demand distribution**: The overall task of assigning passengers to the individual services (i.e. itineraries) is a difficult optimisation problem. To manage complexity, the problem is divided into Demand distribution (demand distributed/assigned to a cluster of itineraries) and Passenger assignment (demand assigned within the cluster) steps. In the Demand distribution, the demand is distributed per OD pair, alternative, and passenger archetype with the help of a previously calibrated logit model. The logit model is a statistical model which calculates the probability of choosing a specific alternative for each passenger archetype when presented with several options for travelling between a given OD pair.

  The probability of an archetype selecting a given itinerary alternative (cluster) is based on a linear combination of total travel time, total CO_2 emissions and total travel cost. As shown in the equation below (Equation 1), a utility function is computed for each passenger archetype (a) and alternative (i) between each origin-destination pair.

$$u_a[i] = \alpha_{a\_train} \cdot train_i + \alpha_{a\_flight} \cdot flight_i + \alpha_{a\_multimodal} \cdot multimodal_i \\ + \beta_{a\_time} \cdot travel\_time_i + \beta_{a\_cost} \cdot cost_i + \beta_{a\_co2} \cdot CO2_i$$

Where:
- $train_i$, $flight_i$ and $multimodal_i$ are binary variables (1 or 0) describing the itinerary type, i.e., only one of them will be one depending on the modes used in the itinerary. For example, a multi-leg journey where all modes used are flights (e.g. two flights connecting at LEMD on the route LEBL - LEMD - LECO) will be $train_i$=0, $flight_i$=1 and $multimodal_i$= 0; while a journey with one leg being a train and a second leg being a flight would be $train_i$=0, $flight_i$=0 and $multimodal_i$= 1.
- $travel\_time_i$, $cost_i$ and $CO2_i$ are the total door-to-door expected travelling time, cost (Euros) and CO2 emissions (kg) for alternative i respectivelly. Note that in this context, the alternative is the cluster of *equivalent* individual itineraries, and therefore, these values are the average of all the itineraries within the clusters.
- $alpha_{a\_train}$, $alpha_{a\_flight}$, and $alpha_{a\_multimodal}$ represent the sensitivities of the passenger archetype a toward the modes of transport used; $beta_{a\_time}$, $beta_{a\_cost}$, and $beta_{a\_co2}$ are the sensitivities of the passenger archetype a towards the total travel time, cost and CO_2 emissions respectively.

The logit model, therefore, has different sensitivities depending on the passenger archetypes, and the values of these sensitivities are calibrated based on observed historical demand/trips.

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Given an OD pair, the model will, therefore, compute the utility of each alternative, i.e., each cluster, for each passenger archetype, and translate these into probabilities with Equation 2.

$$P_a[i] = \frac{e^{u_a[i]}}{\sum_{j=1}^{n} e^{u_a[j]}}$$

As shown, the probability of archetype a to select alternative i for a given OD pair depends on the utility of that alternative ($u_a[i]$) and the utility of all n alternatives available between the OD pair. Note that different OD pairs might have different numbers of alternatives (clusters) between them. Finally, the demand will then be distributed among the alternatives based on these probabilities.

This demand distribution is performed over the clustered alternatives instead of over the individual itineraries to reduce the number of alternatives for the logit model. The clusters of itineraries are used as a proxy as each cluster contains the itineraries that are *equivalent* from a passenger's perspective performance (i.e., same (or similar) cost, emissions, total travel time, modes used, number of connections). Therefore, they are *equivalent* from a passenger archetype preference point of view, and the logit model cannot differentiate between them (see Assumptions A12 and A13). After applying Function 2, therefore, the Strategic Multimodal Evaluator provides the flow of passengers who would prefer a given succession of services (itineraries from the cluster). Note that supply capacity aspects are not considered at this step. Once again, this output (demand per cluster) could interest SOL400/SOL2 (Schedule Design Solution), as an analysis of demand/supply imbalance could be performed, and this information can be used to optimise the schedules and timetables.

- **Function 3 – Passengers' assignment**: The next step is to assign passengers to the services (flights and trains), considering their stock capacity (number of seats). For example, given multiple services between A and B with capacity *c* each, we need to accommodate the total number of passengers *p*, where usually *p* > *c* considering that some passengers may be connecting and, therefore, some services could be shared by different itineraries. The problem is formulated as a lexicographic optimisation problem with objectives of maximising the total number of connecting and overall passengers assigned and minimising the differences in service load factors and underutilization, the order of this prioritisation can be set by the user. A combination of restrictions to identify valid itineraries and the objectives used to assign the passengers can be considered a network definition parameter. The problem is then solved by mathematical programming, which will, therefore, disaggregate the flow of passengers into individual itineraries within each cluster. The outcome is individual passengers' itineraries groups assigned to flights and trains.

  When assessing a replanned network, this functionality aims at rebooking the maximum number of passengers impacted by the disruption considering the seats available in the network (i.e., the itineraries of passengers not impacted by the disruption, which could use some capacity). As in the assignment of passengers in the planned network, a lexicographic optimisation is used. Other objectives that can be considered include minimising the arrival delay and maximising the number of passengers maintaining their original path, starting, and/or ending nodes. And, as in the

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planned network, a set of constraints to consider which itineraries are valid for replanning passengers and the objectives considered for the assignment can define a passenger assignment configuration.

- **Function 4 – PIs/KPIs computation**: Mobility (and multimodal) PIs and KPIs can be computed from all the outputs (final and intermediate) the Strategic Multimodal Evaluator produces. These indicators relate to supply and demand usage, but also to overall mobility (e.g. total expected travel time between origin and destinations) and connectivity. Note that indicators defined by the Multimodal Performance Framework will also be considered. For the replanned network, aspects related to the impact of the replanned operations on the passenger itineraries could also be estimated, such as extra travel time with respect to the initial planned itinerary, departure and arrival delay, shift between planned and replanned mode, or demand not fulfilled (stranded passengers).

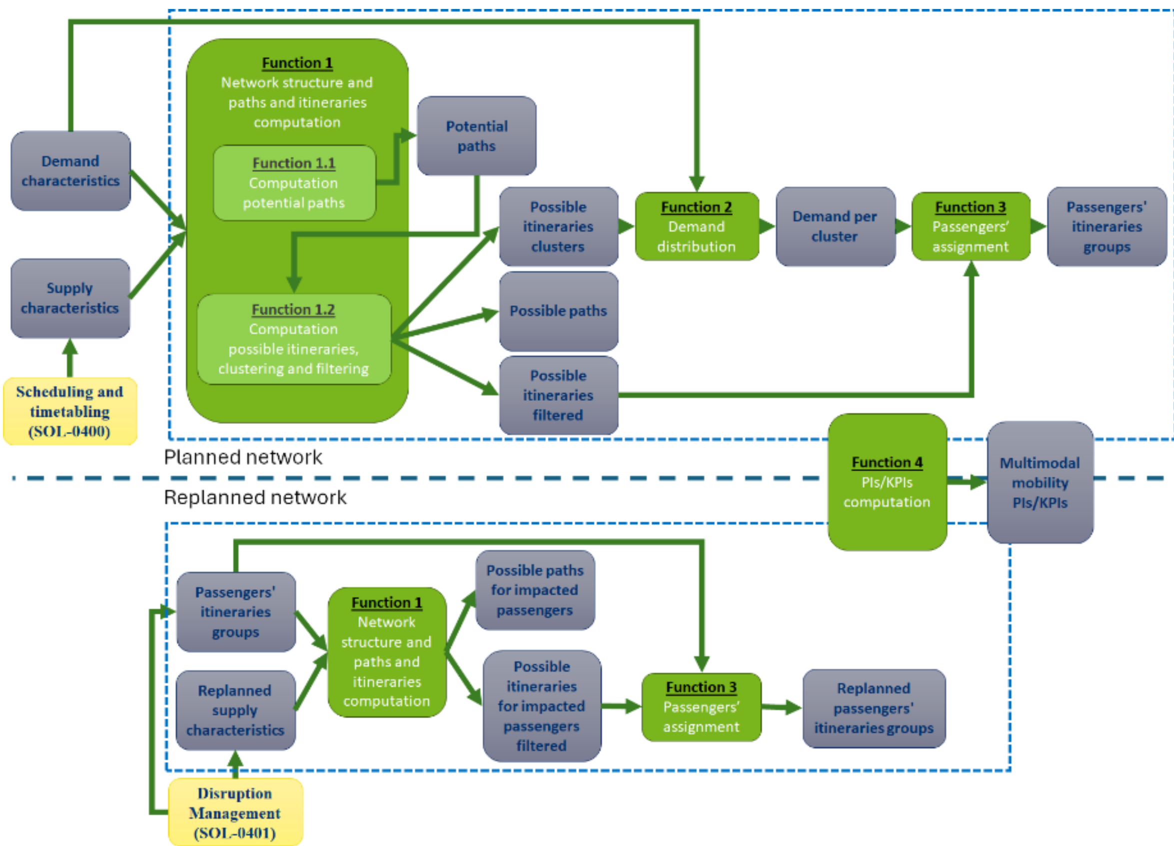

Figure 5: Strategic Multimodal Evaluator – Functionalities

The functional decomposition of the Strategic Multimodal Evaluator ensures that low-level intermediate outputs are generated. This enables the post-processing of the data to create a plethora of mobility PIs. These outputs can also be used by other elements, e.g. the potential and possible paths can be utilised in

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SOL399/SOL1 to expedite the computation if the pipeline needs to be re-run or in Scheduling Design Solution (MultiModX's SOL400/SOL2), to identify promising paths and generate new possible supply elements, e.g. new flight schedules and/or rail timetables, which can then be re-evaluated by re-running the pipeline above-described. This will create a new version of the intermediate and outputs of the evaluator for the same case study.

Real data example:

The Strategic Multimodal Evaluator pipeline is illustrated on a real data example from a case study of intra-Spain mobility between the region ES300 (Madrid) and ES114 (Pontevedra).

The detailed list of all inputs and their format is provided in Annex A – Input/Output formats. Here, we illustrate some of the main elements.

region	station	layer	pax_type	avg_d2i	avg_i2d
ES114	LEVX	air	all	28	27
ES114	LEST	air	all	81	82
ES114	7123004	rail	all	21	21
ES114	7122300	rail	all	26	25
ES114	7122100	rail	all	82	81

Figure 6: Access/Egress times for region ES114.

The input infrastructure data provides information, among others, on access/egress times from door to infrastructure (airport/rail station) (and vice-versa), as can be seen in Figure 6. The access/egress times are average expected times (avg_d2i, avg_i2d, i.e., average door-to-infrastructure (airport or rail station), average infrastructure-to-door), thus giving a representative value and facilitating the comparison between different alternatives. For example, reaching LEVX from region ES114 is estimated to be, on average, 28 minutes, while flying from LEST will require 81 minutes to get to the airport; using the rail station 7123004 will require 21 minutes. Note these are only access and egress times; the processing times (e.g. kerb-to-gate at the airport) are added to these to estimate the time required to reach the initial mode of transport (flight, train) or the destination from deboarding the flight/train.

service_id	origin	destination	dep_terminal	arr_terminal	sobt	sibt	sobt_tz	sibt_tz	sobt_local	sibt_local	sobt_local_tz	sibt_local_tz	provider	act_type	seats	gcdistance
D8_5081	EKYT	LEMG			2019-09-06 08:15:00	2019-09-06 11:55:00	+00:00	+00:00	2019-09-06 10:15:00	2019-09-06 13:55:00	+02:00	+02:00	D8	73H	186	2504
VY_2473	GCRR	LEBL	1	1	2019-09-06 12:15:00	2019-09-06 15:10:00	+00:00	+00:00	2019-09-06 13:15:00	2019-09-06 17:10:00	+01:00	+02:00	VY	321	220	1971
VY_2471	GCRR	LEBL	1	1	2019-09-06 20:20:00	2019-09-06 23:15:00	+00:00	+00:00	2019-09-06 21:20:00	2019-09-07 01:15:00	+01:00	+02:00	VY	320	180	1971
FR_2595	GCRR	EGAA	1		2019-09-06 10:35:00	2019-09-06 14:50:00	+00:00	+00:00	2019-09-06 11:35:00	2019-09-06 15:50:00	+01:00	+01:00	FR	73H	189	2919
FR_1449	GCRR	EGBB	1		2019-09-06 06:25:00	2019-09-06 10:35:00	+00:00	+00:00	2019-09-06 07:25:00	2019-09-06 11:35:00	+01:00	+01:00	FR	73H	189	2789
LS_1202	GCRR	EGBB	1		2019-09-06 18:45:00	2019-09-06 22:55:00	+00:00	+00:00	2019-09-06 19:45:00	2019-09-06 23:55:00	+01:00	+01:00	LS	738	189	2789

Figure 7: Example of flight schedules.

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Figure 7 shows an example of flight schedules used. As shown, the information focuses on origin and destination airports, SOBT and SIBT, provider (airline) and aircraft type and seats available. For rail, standard GTFS data formats are used.

Firstly, Function 1.1 uses the input supply data to compute the potential paths between the regions regardless of connecting times between services. In this case, 99 potential paths are computed.

origin	destination	journey_type	cluster_id	alternative_id	options_in_cluster	total_travel_time	total_cost	total_emissions	total_waiting_time	nservices
ES300	ES114	air	0	ES300_ES114_0	[0, 1, 2, 3, 4, 5, 6, 8, 9]	251.11	134.33	55.14	0	1
ES300	ES114	air	19	ES300_ES114_19	[19, 20, 22, 23, 24, 26, 27]	310	136.23	43.34	0	1
ES300	ES114	rail	7	ES300_ES114_7	[7, 10, 11, 12, 13, 14, 15, 16, 17, 18]	282.4	44.21	12.15	0	1
ES300	ES114	rail	21	ES300_ES114_21	[21, 25, 28, 29]	314.25	46.08	12.66	0	1
ES300	ES114	rail	30	ES300_ES114_30	[30, 31]	352	55.74	15.5	45.5	2
ES300	ES114	rail	32	ES300_ES114_32	[32, 44, 46]	430.67	61.55	17.26	35.67	2
ES300	ES114	rail	43	ES300_ES114_43	[43, 45]	445.5	55.74	15.5	113.5	2
ES300	ES114	rail	47	ES300_ES114_47	[47]	455	70.15	19.77	63	2
ES300	ES114	multimodal	33	ES300_ES114_33	[33, 36, 37, 40, 41, 42, 48, 49]	443.38	145.94	64.19	22.75	2
ES300	ES114	multimodal	34	ES300_ES114_34	[34, 38]	436.5	143.24	46.29	5.5	2
ES300	ES114	multimodal	35	ES300_ES114_35	[35, 39]	436.5	148.31	47.88	47.5	2

Figure 8: Itinerary clusters between region ES300 and ES114.

Next, possible itineraries are computed following the potential paths in Function 1.2 by considering itineraries that respect the MCTs. These are then clustered into possible itineraries clusters, grouping the itineraries into *equivalent* itineraries per mode of transport and number of connections with similar total travel time, total waiting time, total CO_2 emissions and total travel cost. Figure 8 shows possible itineraries clusters in this example (e.g. cluster_id=0 is composed of itineraries 0, 1, 2, 3, 4, 5, 6, 8 and 9, which are direct flights (nservices=1, journey_type=air) with an average total travelling time of 251.11 minutes, a total cost of EUR 134.33, total emissions of 55.14 Kg CO_2 and no waiting time (as there are no connections)).

origin	destination	journey_type	cluster_id	alternative_id	options_in_cluster	total_travel_time	total_cost	total_emissions	total_waiting_time	nservices
ES300	ES114	air	0	ES300_ES114_0	[0, 1, 2, 3, 4, 5, 6, 8, 9]	251.11	134.33	55.14	0	1
ES300	ES114	air	19	ES300_ES114_19	[19, 20, 22, 23, 24, 26, 27]	310	136.23	43.34	0	1
ES300	ES114	multimodal	34	ES300_ES114_34	[34, 38]	436.5	143.24	46.29	5.5	2
ES300	ES114	rail	7	ES300_ES114_7	[7, 10, 11, 12, 13, 14, 15, 16, 17, 18]	282.4	44.21	12.15	0	1
ES300	ES114	rail	21	ES300_ES114_21	[21, 25, 28, 29]	314.25	46.08	12.66	0	1

Figure 9: Pareto non-dominated clusters.

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From the clusters, the possible itineraries filtered are computed by considering only the Pareto non-dominated ones. Figure 9 shows the possible itineraries filtered. As shown, from 11 possible clusters, only five are kept. The itineraries belonging to the Pareto non-dominated clusters are then considered further. Table 7 illustrates the overall process of Function 1.1 and 1.2; note how from the initial 50 fastest itineraries computed, only 32 are kept, and the passengers will have five equivalent alternatives to travel between ES300 and ES114.

Step	**Size**
Potential paths	99
Possible itineraries	50
Clusters	11
Pareto clusters	5
Itineraries in the Pareto clusters	32

Table 7:. Summary of the filtering process for regions ES300 and ES114.

option_number	num_pax
1	679
2	294
3	26
4	155
5	100

Figure 10: Number of passengers per cluster

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In the next step, the passenger demand is assigned to the Pareto clusters by the logit model in Function 2. This process is done per passenger archetype (as demand between regions is provided already per archetype). Figure 10 shows the resulting total number of passengers per cluster (alternative). For example, 679 passengers would like to use alternative 1 (cluster_id=0), which is composed of 9 possible itineraries (one direct flight from LEMD to LEST in this case).

id	option_numbe	alternative_id	path	nid_f1	nid_f2	total_waiting_tim	total_tim	type	volume	fare	volume_ce	pax
2109	8363	ES300_ES114_19	['LEMD', 'LEST']	IB_3880		0	305	flight	294.38	136.23	295	74
2109	8364	ES300_ES114_19	['LEMD', 'LEST']	IB_3894		0	305	flight	294.38	136.23	295	55
2109	8366	ES300_ES114_19	['LEMD', 'LEST']	IB_3876		0	310	flight	294.38	136.23	295	40
2109	8367	ES300_ES114_19	['LEMD', 'LEST']	IB_3874		0	310	flight	294.38	136.23	295	126
2109	8368	ES300_ES114_19	['LEMD', 'LEST']	IB_3878		0	310	flight	294.38	136.23	295	0
2109	8370	ES300_ES114_19	['LEMD', 'LEST']	FR_5315		0	315	flight	294.38	136.23	295	0
2109	8371	ES300_ES114_19	['LEMD', 'LEST']	FR_5317		0	315	flight	294.38	136.23	295	0

Figure 11: Assigned passengers to itineraries.

The passengers are assigned to each itinerary within the Pareto clusters in Function 3, as indicated in Figure 11. For example, 74 passengers are assigned to itinerary 2109 which is a flight by Iberia (IB_3880).

Finally, mobility and multimodal indicators are computed from the outputs of the Strategic Multimodal Evaluator, as illustrated in Figure 12.

indicator	variant	value
strategic_total_journey_time	sum	88349958
strategic_total_journey_time	avg_connecting_itineraries	432.748
pax_time_efficiency	total	0.875
demand_served	total_connecting_itineraries	0.050
buffer_in_itineraries	avg	23.390
cost_per_user	avg	55.046
co2_emissions	avg	20.841
seamless_of_travel	avg	90.005
pax_processes_time	avg	53.078

Figure 12: Multimodal mobility indicators

<u>Tactical Multimodal Evaluator</u>

The Tactical Multimodal Evaluator can be decomposed into three high-level functionalities:

- **Function 1 – Generate Tactical Multimodal Evaluator input**: First, the Tactical Multimodal Evaluator needs to modify, as required, the outcome of the Strategic Multimodal Evaluator so that it can be simulated. In particular, the structure of the passenger itineraries considering any requirement and/or limitation of the Tactical Multimodal Evaluator, e.g. in the current version, rail legs are considered only the beginning or the end of a journey, and the structure of the flight schedules. The Tactical Multimodal Evaluator requires information on the flight schedules, which is not required (and therefore not considered) by the Strategic Multimodal Evaluator. In particular, aspects related to the aircraft performance used to operate the schedules (e.g. MTOW, WTC). Therefore, this functionality focuses on generating flight schedules and passenger itineraries in the format required by the Tactical Multimodal Evaluator, considering its requirements and capabilities, as shown in Figure 13.

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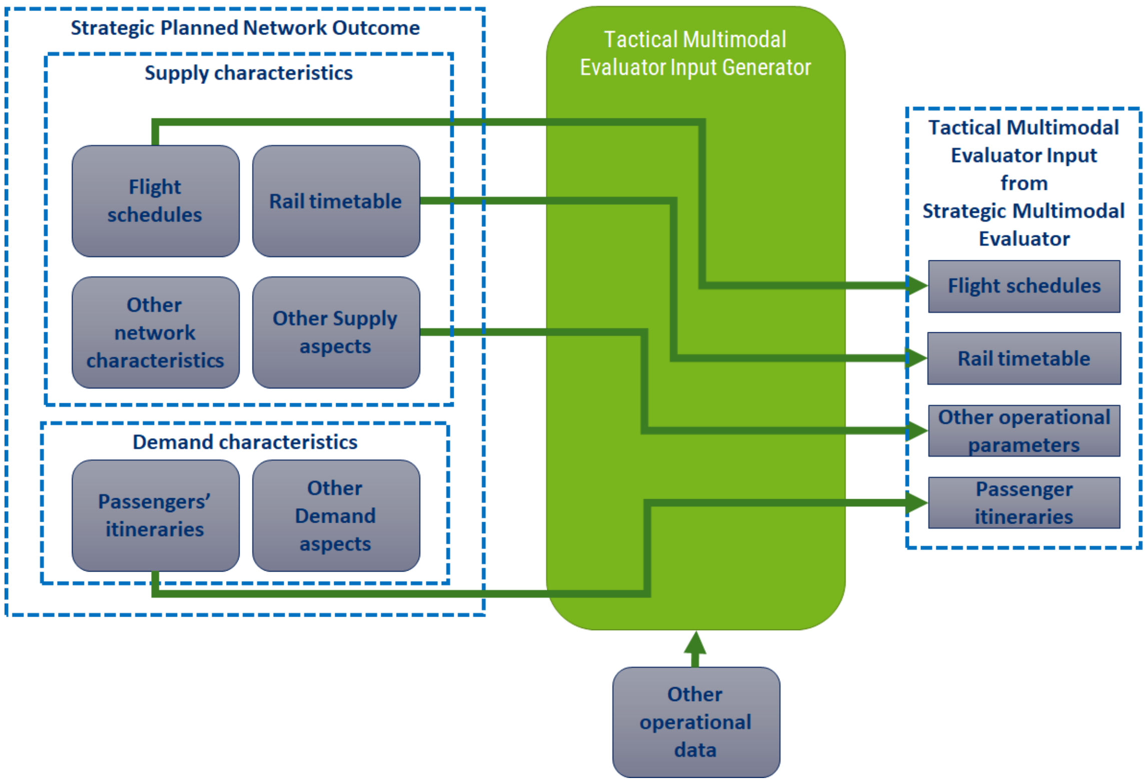

Figure 13: Tactical Multimodal Evaluator input generation from Strategic Multimodal Evaluator output

- **Function 2 – Mercury mobility evaluator**: Mercury is an open-source flight and passenger mobility model extended to enable multimodal operations. Mercury can track individual passengers and services, enabling the computation of low-level mobility indicators and the assessment of mechanisms and Solutions that support (or impact) the passenger journey (including multimodality).
- **Function 3 – PIs/KPIs computation**: The low-level outcome of Mercury can be post-processed to compute mobility (and multimodal) PIs and KPIs, which can be flight and passenger-centric. Note that the stochastic nature of Mercury means that several executions are required, along with statistical analysis of the output, to obtain reliable indicators.

Overall, the function of the Tactical Multimodal Evaluator is to simulate a realisation of the initial input schedules and passenger itineraries on the day of operations in the network, tracking individual flights and passengers.

As discussed, the input into the Tactical Multimodal Evaluator is the output of the Strategic Multimodal Evaluator (flight schedules, rail timetable, individual passenger itineraries) and any other tactical, operational parameters (e.g. probability of ATFM regulation, turnaround times, etc.). Note that these operations can be either the originally planned or replanned schedules and passenger itineraries, which consider network-wide disruptions (as the outcome of Disruption Management Solution (MultiModX's

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SOL401/SOL3)). This enables the evaluation of proactive actions to deal with disruptions instead of a reactive approach when managing passengers and services.

The model can simulate disturbed conditions, such as day-to-day minor delays, and stressed nominal conditions (e.g. ATFM regulations or delays on the ground system linking the rail stations with the airports). Mechanisms can be implemented and integrated into the platform to assess their performance in supporting multimodal journeys (e.g. fast-track at airports for delayed multimodal passengers).

The output of the Tactical Multimodal Evaluator is the realisation of the itineraries and services throughout the day and subsequent associated KPIs.

The Tactical Multimodal Evaluator extends Mercury Agent-Based Modelling platform developed over several SESAR ER projects from a gate-to-gate simulator to a full multimodal evaluator [4, 5, 15]. The platform can track individual flights, trains and passengers. This facilitates the computation of very low-level passenger-centric indicators, such as missed connections, waiting times, total journey times, etc.

Mercury is an open-source flight and passenger mobility model developed over 10 years on several SESAR ER projects (https://github.com/UoW-ATM/Mercury). The model follows an Agent-Based approach describing with Agent and Roles the main components of ATM. Mercury uses an event-driven engine to simulate the main processes. A full day of ECAC-wide operations (around 27K flights and 3M pax) can be simulated in under 25 minutes.

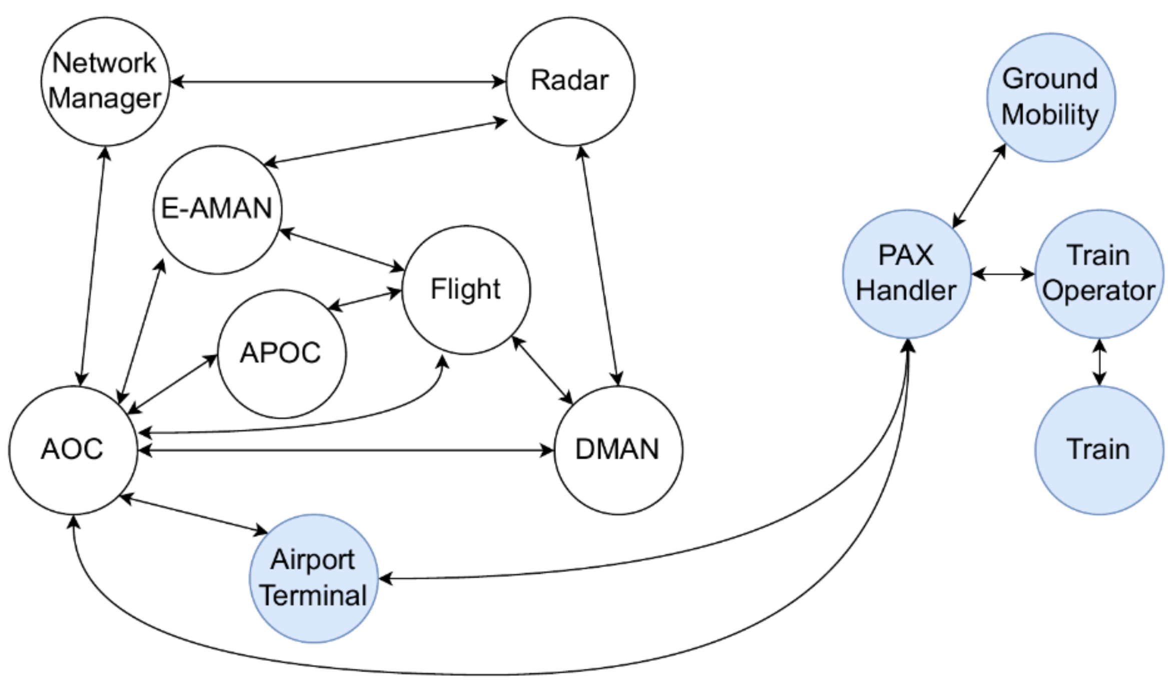

Figure 14: Tactical Multimodal Evaluator model – Agents Architecture

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As presented in Figure 14, the agents (Airline Operating Centres (AOC), Airport Operating Centre (APOC), Flight, etc.) responsible for the functioning of the air network have been extended to enable multimodal operations in the following way:

1. The Airport Terminal Agent includes processes to estimate the kerb-to-gate and gate-to-kerb for multimodal passengers.
2. The Train Operator and Train simulate the arrival and departure of trains to the rail stations where multimodality is enabled. The Train Operator could also reallocate passengers to subsequent trains in case of missed connections.
3. The Ground Mobility agent provides estimations and realisation of times to transfer between air and rail infrastructure.
4. The Pax Handler agent proactively captures the decision-making process of passengers (or travel companions) to rebook passengers for subsequent flights or train services.

The model's by-default version represents ‘basic’ multimodal operations. The flexibility of Mercury enables the extension of the model by creating Modules (which can change the behaviour of Roles) or with External Communications of the model with an external system (API under development), as shown in [4, 18]. This allows, for example, the evaluation of multimodal supporting mechanisms by modifying the by-default behaviour of the agents. For example, modelling a fast track at the airport to process delays multimodal passengers modifying the Airport Terminal Agent [18].

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Real data example:

The Tactical Multimodal Evaluator pipeline is illustrated on a real data example from a case study of intra-Spain mobility.

The detailed list of all inputs and their format is provided in Annex A – Input/Output formats. Here, we illustrate some of the main elements.

nid	pax	avg_fare	ticket_type	origin	destination	access_time	egress_time	d2i_time	i2d_time	leg1	leg2	leg3	rail_pre	rail_post
31	1	274.8	economy	ES111	ES112	115	121	25	91	IB_519	IB_3874			
59	1	274.8	economy	ES111	ES113	115	135	25	105	IB_523	IB_3880			
60	1	181.53	economy	ES111	ES113	115	28	25	18	IB_523				1026
132	19	132.17	economy	ES111	ES130	115	109	25	79	VY_1471				
134	4	132.79	economy	ES111	ES130	143	109	53	79	IB_8359				

Figure 15: Passenger itineraries input for the Tactical Multimodal Evaluator

Figure 15 shows an example of the structure of the input passenger itineraries considering the requirements of the Tactical Multimodal Evaluator. Note, that rail legs are considered at the beginning or the end of a journey and labelled (*rail_pre* and *rail_post*) in Figure 14.

Figure 16 illustrates the input flight schedules required by the Tactical Multimodal Evaluator. The schedules contain information about aircraft performance used to operate the schedules (e.g. MTOW, WTC).

nid	flight_id	callsign	airline	airline_type	origin	destination	gcdistance	long_short_dist	sobt	sibt	aircraft_type	mtow	wk_tbl_cat	registration	max_seats	exclude	domestic	bada_code_ac_model
VY_2473	VY_2473	VY2473	VLG	LCC	GCRR	LEBL	1971	I	2019-09-06 12:15:00	2019-09-06 15:10:00	A321	83	M	VY_2473	220	0	True	A321-131
VY_2471	VY_2471	VY2471	VLG	LCC	GCRR	LEBL	1971	I	2019-09-06 20:20:00	2019-09-06 23:15:00	A320	79	M	VY_2471	180	0	True	A320-214
UX_7029	UX_702	UX7029	AEA	FSC	GCRR	LEBB	1859	I	2019-09-06 08:40:00	2019-09-06 11:30:00	B738	250.83	M	UX_7029	186	0	True	737-700
FR_3049	FR_3049	FR3049	RYR	LCC	GCRR	LEMD	1574	I	2019-09-06 08:10:00	2019-09-06 10:50:00	B738	250.83	M	FR_3049	189	0	True	737-700
IB_3853	IB_3853	IB3853	IBE	FSC	GCRR	LEMD	1574	I	2019-09-06 10:35:00	2019-09-06 13:10:00	A320	79	M	IB_3853	177	0	True	A320-214

Figure 16: Flight schedules input for the Tactical Multimodal Evaluator

The realisation of passenger itineraries after simulation is shown in Figure 17. This output tracks individual passengers and includes low-level mobility indicators (e.g. total arrival delay, missed connections, ground mobility time).

_id	initial_sobt	final_sibt	initial_aobt	final_aibt	modified_itinerary	tot_arrival_delay	connecting_pax	final_destination_reached	multimodal	missed_air2rail	missed_rail2air	ground_mobility_time
61	2019-09-06 15:35:00	2019-09-06 20:50:00	2019-09-06 19:47:24.380680	2019-09-07 07:27:00.000000	True	637	False	True	True	True	False	67.49
157	2019-09-06 14:20:00	2019-09-06 19:35:00	2019-09-06 14:51:11.188765	2019-09-07 07:32:00.000000	True	717	False	True	True	True	False	92.92
170	2019-09-06 04:40:00	2019-09-06 10:49:00	2019-09-06 04:55:49.318364	2019-09-06 10:49:00.000000	False	0	False	True	True	False	False	97.49
186	2019-09-06 07:20:00	2019-09-06 11:45:00	2019-09-06 08:08:58.684235	2019-09-06 12:47:00.000000	True	62	False	True	True	True	False	92.59
201	2019-09-06 05:05:00	2019-09-06 09:46:00	2019-09-06 05:10:18.836478	2019-09-06 09:46:00.000000	False	0	False	True	True	False	False	103.72

Figure 17: Output passenger itineraries

As mentioned above, several executions of simulation are required to obtain statistically reliable results. Multiple individual runs are averaged in order to compute higher-level indicators, such as shown in Figure 18.

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indicator	variant	value
total_arrival_delay	total	3.686
total_arrival_delay	missed_connection	275.724
stranded_pax	total	0.000
stranded_pax	missed_air2rail	0.000
stranded_pax	missed_rail2air	0.537
stranded_pax	abs	72.300
ratio_stranded_pax	total	0.048
missed_connections	total	0.004
missed_connections	abs	1445.900
missed_connections	abs_missed_air2air	1216.100
missed_connections	abs_missed_air2rail	176.200
missed_connections	abs_missed_rail2air	53.600
missed_connections	missed_air2rail	0.000
missed_connections	missed_rail2air	0.000
missed_connections	missed_air2air	0.003
total_journey_time	total	87335386.043

Figure 18: Output indicators

<u>**Integration of Solutions SOL399/SOL1, SOL400/SOL2 and SOL401/SOL3**</u>

As previously explained, the integration of SOL400/SOL2 (Schedule Design Optimisiser Solution) and SOL401/SOL3 (Disruption Management Solution) is produced in the Strategic Multimodal Evaluator. Both solutions provide updated planned (and replanned) networks, i.e., flight schedules and rail timetables, which become new inputs into the model. Particularly:

- SOL400/SOL2 – Schedule Design Optimiser Solution:
  - SOL400/SOL2 receives as input the outcome of executing SOL399/SOL1 Strategic Evaluator, i.e., the assessment of the current/initial network with the information on potential and possible paths, demand, passenger preferences, etc. See Annex A – Input/Output formats for a description of the different data formats used.
  - SOL400/SOL2, in turn, produces new schedules and timetables for flights and rails. These can become the input into the Strategic Evaluator pipeline (i.e., input into Function 1) enabling the assessment of these planned operations. Note that this is similar to evaluating any other schedules or rail timetables.
  - Finally, the outcome of the planned network, after being processed by the Strategic Multimodal Evaluator, can be executed by the Tactical Multimodal Evaluator to evaluate its performance on the day of operations.
  - Suitable comparisons between executions of the pipeline with the initial network and with the optimised network (as computed by SOL400/SOL2) will enable the assessment of the benefits/drawbacks of such optimisation.
- SOL401/SOL3 – Disruption Management Solution:
  - In this case, SOL401/SOL3, considering the disruptions (drop in capacity in the system), produces an updated planned network (new schedules and rail timetables) for the whole network or part of it. These new flight schedules and rail timetables are then used by the Strategic Multimodal Evaluator of SOL399/SOL1 (Function1.3) to identify passengers' itineraries impacted by the changes and compute alternative itineraries

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for them. Then, using Function 3, those passengers are reassigned to the available capacity in the system.

- This replanned network can, therefore, be assessed from a planning perspective (e.g. number of passengers successfully rebooked, number of passengers stranded).
- Finally, as with SOL400/SOL2, the replanned network could be evaluated by the Tactical Multimnodal Evaluator to assess its performance when executed.

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
Multimodal Performance Management	Service Delivery Management – Performance Management (operational) – Multimodal Performance Management (Air)	The Performance Indicators considered by this SESAR Solution should be aligned with the outcome of the assessment of multimodal indicators to be carried out as part of SOL399/SOL1.

Table 8: Systems impacted by SESAR Solution 399

All the functionalities of SOL399/SOL1 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 Multimodal Performance Framework might require some data to be stored/processed by SESAR Solutions to estimate the PIs and KPIs. This is, however, pending the outcome of developing the Multimodal Performance framework itself.

In Table 3, we already identified the SESAR updated Operational Capabilities that might be impacted/affected by this Solution, as defined in AMPLE3 [2]. From those, as indicated in Table 5, only the Multimodal Performance Management (Air) Capability could be directly impacted by SOL399/SOL1, as the PIs and KPIs defined should be implemented (or considered) by this SESAR Capability.

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4 Functional requirements

The following coding, based on the DES HE requirements and validation/demonstration guidelines [19] is used for the requirements of SOL399: REQ-SOL399-[OP/FR]-[MPF/SME/TME][0-99].[0-999] where:

- OP: Operational requirement
- FR: Functional requirements
- MPF01: Multimodal Performance Framework
- SME01: Strategic Multimodal Evaluator – General
- SME02: Strategic Multimodal Evaluator – Itineraries computation
- SME03: Strategic Multimodal Evaluator – Demand disaggregation
- SME04: Strategic Multimodal Evaluator – Passengers assignment
- SME05: Strategic Multimodal Evaluator – PIs/KPIs computation
- TME01: Tactical Multimodal Evaluator – General
- TME02: Tactical Multimodal Evaluator – Platform
- TME03: Tactical Multimodal Evaluator – PIs/KPIs computation

As shown by their coding, the functional requirements for SOL399/SOL1 can be divided into the three components of the solution: Multimodal Performance Framework, Strategic Multimodal Evaluator and Tactical Multimodal Evaluator. The requirements for the Evaluators are, in turn, divided between different aspects of the evaluators (e.g. general, itineraries computation, demand disaggregation).

The Multimodal Performance Framework aims to start the activities required to build a performance indicators catalogue. The Strategic Multimodal Evaluator focuses on evaluating flight schedules, rail timetables and other infrastructure characteristics from a strategic perspective (i.e., before the day of operations) and reassigning demand into a potentially replanned network. The Tactical Multimodal Evaluator can simulate the schedules and passenger itineraries as they unfold on the day of execution.

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

Table 9 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 [19] .

SOL399 Component	Requirement Id	Title	Sub-Section
Multimodal Performance Framework	REQ-SOL399-OP-MPF01.001	Provide multimodal PIs and KPIs	4.1.1.1

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Multimodal Performance Framework	REQ-SOL399-FR-MPF01.001	Build catalogue indicators Level 1	4.1.2.1
Multimodal Performance Framework	REQ-SOL399-FR-MPF01.002	Build catalogue indicators Level 2	4.1.2.2
Multimodal Performance Framework	REQ-SOL399-FR-MPF01.003	Build catalogue indicators Level 3	4.1.2.3
Strategic Multimodal Evaluator	REQ-SOL399-OP-SME01.001	Assess mobility between regions planned and reallocate passengers if replanned operations	4.2.1.1
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME01.001	Network and infrastructure inputs	4.2.2.1.1
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME01.002	Infrastructure and capacities compliance	4.2.2.1.2
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME01.003	Generate passenger itineraries	4.2.2.1.3
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME01.004	Generate information usable by schedule optimiser	4.2.2.1.4
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.001	Origin-destination demand input	4.2.2.2.1
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.002	Compute possible paths and n-fastest itineraries	4.2.2.2.2
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.003	Respect minimum connecting times and integrated ticketing	4.2.2.2.3

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Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.004	Cluster itineraries into equivalent alternatives	4.2.2.2.4
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.005	Identify passengers affected status	4.2.2.2.5
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME02.006	Compute possible alternative itineraries for stranded passengers	4.2.2.2.6
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME03.001	Distribute demand on clusters	4.2.2.3.1
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME04.001	Produce individual passenger itineraries	4.2.2.4.1
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME04.002	Reasign only impacted passengers on replanned networks	4.2.2.4.2
Strategic Multimodal Evaluator	REQ-SOL399-FR-SME05.001	Compute Strategic PIs/KPIs	4.2.2.5.1
Tactical Multimodal Evaluator	REQ-SOL399-OP-TME01.001	Assess a day of operations	4.3.1.1
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME01.001	Network and infrastructure inputs	4.3.2.1.1
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME01.002	Infrastructure and capacities compliance	4.3.2.1.2
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME01.003	Use Strategic Multimodal Evaluator output as input	4.3.2.1.3
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME02.001	Simulate the realisation day of operations	4.3.2.2.1
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME02.002	Incorporate by-default behaviour to manage multimodality	4.3.2.2.2

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Tactical Multimodal Evaluator	REQ-SOL399-FR-TME02.003	Calibrated nominal levels disturbance system	4.3.2.2.3
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME02.004	Enable the modelling of higher levels of delay and ATFM regulations at airports	4.3.2.2.4
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME02.005	Integration mechanisms manage multimodality	4.3.2.2.5
Tactical Multimodal Evaluator	REQ-SOL399-FR-TME03.001	Compute Tactical PIs/KPIs	4.3.2.3.1

Table 9: SOL399 requirements summary.

4.1 Multimodal Performance Framework

4.1.1 Operational requirements

4.1.1.1 REQ-SOL399-OP-MPF01.001

Identifier	REQ-SOL399-OP-MPF01.001	
Title	Provide multimodal PIs and KPIs	
Requirement	SOL399/SOL1 Multimodal Performance Framework shall provide a set of PIs and KPIs that capture the mobility's multimodal aspects.	
Status	Satisfied	
Rationale	Defined in SOL399/SOL1 OSED	
Category	Operational	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

4.1.2 Functional requirements

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4.1.2.1 REQ-SOL399-FR-MPF01.001

Identifier	REQ-SOL399-FR-MPF01.001	
Title	Build catalogue indicators Level 1	
Requirement	SOL399/SOL1 Multimodal Performance Framework shall build a catalogue of indicators grouping in Level 1 current indicators used in SESAR3 Performance Framework, which could impact (or be impacted by) multimodality.	
Status	Satisfied	
Rationale	These indicators are already used by the SESAR Performance Framework and impact (or can be impacted) by multimodal mobility.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL399-OP-MPF01.001

4.1.2.2 REQ-SOL399-FR-MPF01.002

Identifier	REQ-SOL399-FR-MPF01.002
Title	Build catalogue indicators Level 2
Requirement	SOL399/SOL1 Multimodal Performance Framework shall build a catalogue of indicators grouping in Level 2 indicators currently (or planned to be) modelled by current research projects relating to multimodality. These indicators will be divided between Level 2.1, candidate to be promoted to Level 1, and Level 2.2.
Status	Satisfied

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Rationale	These indicators are modelled by research projects and consider multimodal aspects. Therefore they should be identified and documented.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL399-OP-MPF01.001

4.1.2.3 REQ-SOL399-FR-MPF01.003

Identifier	REQ-SOL399-FR-MPF01.003	
Title	Build catalogue indicators Level 3	
Requirement	SOL399/SOL1 Multimodal Performance Framework shall build a catalogue of indicators grouping in Level 3 with ambitious indicators aiming to capture the total passenger experience in their door-to-door journey.	
Status	Satisfied	
Rationale	These indicators fit with the ambitions to capture mobility in the door-to-door context.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	SPR-INTEROP/OSED Requirement	REQ-SOL399-OP-MPF01.001

4.2 Strategic Multimodal Evaluator

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4.2.1 Operational requirements

4.2.1.1 REQ-SOL399-OP-SME01.001

Identifier	REQ-SOL399-OP-SME01.001	
Title	Assess mobility between regions planned and reallocate passengers if replanned operations	
Requirement	SOL399/SOL1 Strategic Evaluator model shall assess the mobility between regions (and infrastructure) given a set of flight and rail schedules and timetables, infrastructure characteristics (e.g. connecting times between modes), origin-destination demand and their characteristics. It shall also reassign passenger itineraries if a replanned network is provided.	
Status	Satisfied	
Rationale	Defined in SOL399/SOL1 OSED	
Category	Operational	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

4.2.2 Functional requirements

4.2.2.1 General Functional Requirements

4.2.2.1.1 REQ-SOL399-FR-SME01.0001

Identifier	REQ-SOL399-FR-ME01.001
Title	Network and infrastructure inputs

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Requirement	SOL399/SOL1 shall take as input rail and air timetables and the network infrastructure data (minimum connecting time, expected average access time, expected average egress time, etc.).	
Status	Satisfied	
Rationale	The objective of the Multimodal Evaluators is to assess the performance of planned operations in a given network infrastructure. Therefore, these must be provided as input. The format of these datasets are described in Annex A.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.1.2 REQ-SOL399-FR-SME01.002

Identifier	REQ-SOL399-FR-ME01.002	
Title	Infrastructure and capacities compliance	
Requirement	SOL399/SOL1 shall respect the capacity (seats) and operation constraints (e.g. headway on train stations, minimum turnaround time at airports) of railway and airline systems.	
Status	Satisfied	
Rationale	The capacity of the systems must be respected to produce feasible solutions.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

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SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.1.3 REQ-SOL399-FR-SME01.003

Identifier	REQ-SOL399-FR-SME01.003	
Title	Generate passenger itineraries	
Requirement	SOL399/SOL1 shall generate passenger itineraries given the demand between origin and destination regions (or infrastructure) and schedules/timetable for air/rail services.	
Status	Satisfied	
Rationale	These passenger itineraries associated with the services (schedules) will constitute the input the Tactical Multimodal Evaluator will use to assess their performance when operated. The format of the input and output datasets is described in Annex A.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.1.4 REQ-SOL399-FR-SME1.0004

Identifier	REQ-SOL399-FR-SME01.004
Title	Generate information usable by schedule optimiser
Requirement	SOL399/SOL1 shall generate information on schedules/timetables that can be used by a Scheduler Optimiser (such as SOL400/SOL2) to modify the services so that the passenger experience is improved.

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Status	Satisfied	
Rationale	Besides the final output of the Strategic Multimodal Evaluator (individual passenger itineraries and associated multimodal PI/KPIs), the Strategic Multimodal Evaluator must generate data that can be used by a Schedule Optimiser to modify the planned operations to improve connectivity: information on potential and possible paths in the network that passengers could use to satisfy their demand (as described in Annex A – Input/Output formats in IO6. potential_paths_#.csv and IO8. possible_paths_avg_#.csv respectively); and information on demand-capacity imbalances in the network (as percentage of demand between OD-pairs satisfied).	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.2 Network structure and paths and itineraries computation requirements

4.2.2.2.1 REQ-SOL399-FR-SME02.001

Identifier	REQ-SOL399-FR-SME02.001
Title	Input REQ for Strategic Multimodal Evaluator
Requirement	SOL399/SOL1 shall take the origin-destination demand for which itineraries need to be computed as input.
Status	Satisfied
Rationale	The possible itineraries the network can serve are computed only on itineraries serving the origin-destination demand. The format of the demand provided as input is described in Annex A.
Category	Functional

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Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.003

4.2.2.2.2 REQ-SOL399-FR-SME02.002

Identifier	REQ-SOL399-FR-SME02.002	
Title	Compute possible paths and n-fastest itineraries	
Requirement	SOL399/SOL1 shall compute potential and possible paths and possible n-fastest itineraries between the origin and destinations of the demand based on the schedules and network infrastructure data.	
Status	Satisfied	
Rationale	The Strategic Multimodal Evaluator should be able to compute a set of alternatives (n), which allows the connection of the different origin-destinations. These alternatives will be computed as, at first instance, it is considered that passengers overall prefer faster options. Therefore, initially, the n-fastest options will be computed by the Strategic Multimodal Evaluator.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.004

4.2.2.2.3 REQ-SOL399-FR-SME02.003

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Identifier	REQ-SOL399-FR-SME02.003	
Title	Respect minimum connecting times and integrated ticketing	
Requirement	SOL399/SOL1 shall respect minimum connecting times between modes and services and any restriction regarding operators with integrated ticketing, such as alliances.	
Status	Satisfied	
Rationale	The connections between services shall be feasible from a minimum connecting time and ticketing perspective.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.2.4 REQ-SOL399-FR-SME02.004

Identifier	REQ-SOL399-FR-SME02.004
Title	Cluster itineraries into equivalent alternatives
Requirement	SOL399/SOL1 shall cluster the itineraries between ‘equivalent’ alternatives from a passenger perspective and filter the options to keep only competitive alternatives regarding passengers' preferences.
Status	Satisfied

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Rationale	From the fastest n alternatives, some will be 'equivalent' in the sense of Assumption A12 (it is assumed that itineraries with similar total travel time, total cost, total emissions, number of connections and modes are equivalent); as according to Assumption A13, it is considered that passenger archetypes are sensitive when selecting an itinerary to total travel time, total cost, total emissions and modes of transport (air, rail, multimodal); and possibly to number of connections, total waiting time and buffers and modes.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.004

4.2.2.2.5 REQ-SOL399-FR-SME02.005

Identifier	REQ-SOL399-FR-SME02.005
Title	Identify passengers affected status
Requirement	SOL399/SOL1 shall identify the status of passengers planned in the network when services are replanned. The replanning can include the temporal shift of services, delays, of flights and rails; cancellation of flights and rail services (for rail potentially partial cancellation, i.e. from, to or between a given set of stops); addition of new services. Passenger itineraries should be classified between: • Unaffected • Delayed • Affected but not stranded (i.e., connecting passengers who can make their connection). From those some will be delayed other on-time. • Affected needing replanning (i.e., stranded either for cancellation of a service or for using connections that are no longer feasible).

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Status	Satisfied	
Rationale	SOL399/SOL1 must identify the status of passengers to be able to compute passenger-centric indicators considering the replanning of the network. Identifying which passengers need to be replanned is required to assess which alternatives (if any) are possible for them.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.2.6 REQ-SOL399-FR-SME02.006

Identifier	REQ-SOL399-FR-SME02.006
Title	Compute possible alternative itineraries for stranded passengers
Requirement	SOL399/SOL1 shall compute possible alternatives for passengers who would be otherwise stranded if the network is replanned. These alternatives should satisfy the minimum connecting time between services and the capacities of the services (considering passengers not reallocated using some of the capacity). Moreover, the user should be able to provide constraints on the flexibility that can be used by passengers including: • If new itineraries must respect (or not) the original operators/alliances. • If the new itineraries must be between services in the same alliance. • If the new itineraries must maintain the original path. • If the new itineraries must maintain at least one of the modes used. • If the new itineraries must maintain the initial infrastructure node. • If the new itineraries must maintain the arrival infrastructure node. • If the new itineraries must depart at the same time or after the initial itinerary.
Status	Satisfied

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Rationale	Capacities of services must be maintained considering the seats already used by passengers who are already in the system and do not need to be rebooked. The flexibility allows SOL399/SOL1 to evaluate the impact of different rebooking policies.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

4.2.2.3 Demand disaggregation requirements

4.2.2.3.1 REQ-SOL399-FR-SME03.001

Identifier	REQ-SOL399-FR-SME03.001	
Title	Distribute demand on clusters	
Requirement	SOL399/SOL1 shall distribute the demand between origin and destination pairs based on passengers' archetype characteristics among the cluster of itineraries available for each OD pair, reflecting the passengers' choice.	
Status	Satisfied	
Rationale	Demand will be distributed among the cluster of equivalent itineraries for each OD pair, as defined by Assumption A12, based on the preferences of passengers captured by the characteristics of their archetypes, in line with Assumption A13.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

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SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.004

4.2.2.4 Passengers assignment requirements

4.2.2.4.1 REQ-SOL399-FR-SME04.001

Identifier	REQ-SOL399-FR-SME04.001	
Title	Produce individual passenger itineraries	
Requirement	SOL399/SOL1 shall produce individual passengers' itinerary groups, assigning the maximum possible number of passengers while prioritising connecting passengers to individual itineraries (and corresponding services (flights and trains)) based on the passenger flows, respecting the capacities of the services. The end user shall be able to provide the order of the selected objectives (and possible thresholds) considered for this assignment among: maximise total number of passengers, maximise connecting passengers, minimise load factor difference between services, minimise under utilisation of services, a combination of maximisation of passengers assigned and underutilization of services.	
Status	Satisfied	
Rationale	Based on the passengers' preferences, these need to be assigned to individual itineraries (and hence services), respecting stock capacities, maximising the number of passengers assigned, and prioritising connecting passengers, in line with Assumption A14.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.003

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SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.004

4.2.2.4.2 REQ-SOL399-FR-SME04.002

Identifier	REQ-SOL399-FR-SME4.0002	
Title	Reassign only impacted passengers on replanned networks	
Requirement	SOL399/SOL1 shall consider the capacities of services already used by other itineraries when replanning a network and reassigning only a subset of passengers while minimising the number of passengers stranded. In this case, the user can provide the order to satisfy different objectives with thresholds, if desired between: • Maximising the total number of reaccommodated passengers. • Minimising the arrival time delay to their final destination. • Maximising the passenger who maintains their initial path. • Maximising the number of passengers who depart from the same infrastructure node as originally planned. • Maximising the number of passengers who arrive to the same infrastructure node as originally planned.	
Status	Satisfied	
Rationale	Only passengers impacted by the replanning of the network should be reassigned to services respecting the itineraries of passengers not impacted by the replanning of operations and aiming at minimising the number of passengers who don't have an alternative to reach their destination.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001

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SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.003

4.2.2.5 PIs/KPIs computation requirements

4.2.2.5.1 REQ-SOL399-FR-SME05.001

Identifier	REQ-SOL399-FR-SME05.001	
Title	Compute Strategic PIs/KPIs	
Requirement	SOL399/SOL1 shall compute the Multimodal Performance Framework's strategic-related multimodal PIs and KPIs, particularly for planned networks and passenger-centric indicators for the passengers impacted by a replanning of the network.	
Status	Satisfied	
Rationale	Based on the outcome of the passengers' itineraries and services, multimodal PIs and KPIs shall be computed to assess the performance of the strategic (re)planned system.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-SME01.001
SATISFIES	Functional Requirement	REQ-SOL399-FR-SME01.004

4.3 Tactical Multimodal Evaluator

4.3.1 Operational requirements

4.3.1.1 REQ-SOL399-OP-TME01.001

Identifier	REQ-SOL399-OP-TME01.001

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Title	Assess a day of operations	
Requirement	SOL399/SOL1 Tactical Evaluator model shall assess a day of operations, including the *nominal* disturbances of the system and larger disruptions.	
Status	Satisfied	
Rationale	Defined in SOL399/SOL1 OSED	
Category	Operational	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

4.3.2 4.3.2 Functional requirements

4.3.2.1 General Functional Requirements

4.3.2.1.1 REQ-SOL399-FR-TME01.001

Identifier	REQ-SOL399-FR-TME01.001
Title	Input REQ for Multimodal Evaluators
Requirement	SOL399/SOL1 shall take as input rail and air timetables and the network infrastructure data (minimum connecting time, expected access time, expected egress time, etc.).
Status	Satisfied
Rationale	The objective of the Multimodal Evaluators is to assess the performance of planned operations in a given network infrastructure. Therefore, these must be provided as input. The format of these datasets are described in Annex A.
Category	Functional

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Relationship	Linked Element Type	Identifier
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.1.2 REQ-SOL399-FR-TME01.002

Identifier	REQ-SOL399-FR-TME01.002	
Title	Infrastructure and capacities compliance	
Requirement	SOL399/SOL1 shall respect the capacity (seats) and operation constraints (e.g. headway on train stations, minimum turnaround time at airports) of railway and airline systems.	
Status	Satisfied for airports, considered implicitly based on rail timetable for railway.	
Rationale	The capacity of the systems must be respected to produce feasible solutions.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.1.3 REQ-SOL399-FR-TME01.003

Identifier	REQ-SOL399-FR-TME01.003
Title	Use Strategic Multimodal Evaluator output as input

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Requirement	SOL399/SOL1 shall be able to take as input the output of the Strategic Multimodal Evaluator to assess how the strategically planned network performs on the day of operations.	
Status	Satisfied	
Rationale	The Tactical Multimodal Evaluator should be able to assess how the (re)planned network behaves operationally in terms of service schedules/timetables and planned passenger itineraries. The Tactical Multimodal Evaluator needs to be able to transform, as required, the output of the Strategic Multimodal Evaluator to create the input for the model. Annex A describes the format of the different input and output files.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.2 Platform Requirements

4.3.2.2.1 REQ-SOL399-FR-TME02.001

Identifier	REQ-SOL399-FR-TME2.0001
Title	Simulate the realisation day of operations
Requirement	SOL399/SOL1 shall simulate the realisation on the day of operations while tracking individual passengers and services (flights and trains).
Status	Satisfied

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Rationale	The Tactical Multimodal Evaluator must track services and passengers so that passenger-related metrics can be computed, e.g., missed connections. To assess the (re)planned operations, their realisation shall be simulated.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.2.2 REQ-SOL399-FR-TME02.002

Identifier	REQ-SOL399-FR-TME02.002	
Title	Incorporate by-default behaviour to manage multimodality	
Requirement	SOL399/SOL1 shall incorporate by-default behaviour to manage multimodal passenger itineraries, including managing missed connections and rebooking in the next available service.	
Status	Satisfied	
Rationale	The Tactical Multimodal Evaluator shall be able to simulate a by-default behaviour capturing a 'basic' multimodal operation, including rebooking in case of missed connections. This sets the base for the evaluation of mechanisms (and Solutions) which can improve (or modify) the behaviour of the different actors (and systems) involved in the multimodal operations.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399

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SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.2.3 REQ-SOL399-FR-TME02.003

Identifier	REQ-SOL399-FR-TME02.003	
Title	Calibrated nominal levels disturbance system	
Requirement	SOL399/SOL1 shall be calibrated with nominal levels of disturbance in the system without significant network-wide effects to represent a nominal day of operations.	
Status	Satisfied	
Rationale	The Tactical Multimodal Evaluator simulates the day of operations, which means that by default, some disturbance is modelled (e.g. ATFM delay, ground mobility variance). In its baseline, the model shall represent the disturbance on operations expected on a 'nominal' day when no significant network-wide impacts are expected.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.2.4 REQ-SOL399-FR-TME02.004

Identifier	REQ-SOL399-FR-TME02.004
Title	Enable the modelling of higher levels of delay and ATFM regulations at airports
Requirement	SOL399/SOL1 shall allow the definition of higher levels of delays (disruptions) and ATFM regulations.
Status	Satisfied

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Rationale	To assess the resilience of the planned operations, mechanisms and Solutions to manage multimodality, the model must allow the evaluation of higher levels of delays in the system so that disrupted situations can be evaluated (e.g. high amount of ATFM delay at key hub airports).	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

4.3.2.2.5 REQ-SOL399-FR-TME02.005

Identifier	REQ-SOL399-FR-TME02.005	
Title	Integration mechanisms manage multimodality	
Requirement	SOL399/SOL1 should allow the integration of new mechanisms to manage multimodality for their evaluation.	
Status	Satisfied	
Rationale	One of the capabilities of the Tactical Multimodal Evaluator is its ability to assess the impact of mechanisms besides the solutions SOL400/SOL2 and SOL401/SOL3 that manage multimodality (e.g. fast-track processing at airports) on the performance of passenger-related metrics. Therefore, there's a need for mechanisms to be integrated in the evaluator.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

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4.3.2.3 4.3.2.3 PIs/KPIs computation requirements

4.3.2.3.1 REQ-SOL399-FR-TME03.001

Identifier	REQ-SOL399-FR-TME03.001	
Title	Compute Tactical PIs/KPIs	
Requirement	SOL399/SOL1 shall compute the tactical-related multimodal PIs and KPIs defined by the Multimodal Performance Framework based on the simulation outputs.	
Status	Satisfied	
Rationale	Understandable PIs and KPIs need to be computed from the simulations to assess the performance of the (re)planned operations and mechanisms/Solutions to manage multimodality. As the Tactical Multimodal Evaluator is a stochastic model, several runs must be executed per case study to obtain statistically representative results.	
Category	Functional	
Relationship	**Linked Element Type**	**Identifier**
ALLOCATED_TO	SESAR Solution	SOL399
SATISFIES	Operational Requirement	REQ-SOL399-OP-TME01.001

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5 Assumptions

5.1 Common assumptions for *Performance Assessment Solution*

ID	Title	Description	Justification	Impact Assessment
A5	Existence of multimodal governance	It is assumed that a multimodal performance scheme and multimodal governance are in place, allowing cooperation between modes of transport (shared data, information, incentive, integrated ticketing…).	The project is interested in studying the impact of a multimodal and collaborative framework.	High

5.2 Specific assumptions for *Multimodal Performance Framework*

ID	Title	Description	Justification	Impact Assessment
A1	Stakeholders representativeness	The validation of the performance framework relies on the interaction with stakeholders. It is assumed that the pool of stakeholders is representative of the European-wide system and captures all their needs.	The Industry Board and pannel of stakeholders approached to validate the performance framework is large (at least 20 members) and comprises stakeholders of the different elements of multimodality: airlines, rail operators, airports, etc. Feedback with other research projects (e.g. PEARL, AMPLE3, SING-AIR, MAIA) are also envisioned.	Low

5.3 Specific assumptions for *Multimodal Evaluators*

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ID	Title	Description	Justification	Impact Assessment
A2	Case studies coverage	It is assumed that the three case studies defined in the ERP (intra-Spain, intra-Germany and Spain-Germany) 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). This will impact the validation and calibration of the performance assessment Strategic and Tactical Evaluators.	Regional archetypes have been studied, and the case studies cover national and international cases.	Medium
A4	Data availability	It is assumed that the required data (demand for each passenger archetype, travel times, infrastructure capacity, passenger preferences, distribution of delays and disruptions, etc.) are available in the regions under study.	Data are required to execute the Strategic and Tactical Evaluators but modelling assumptions can be established if needed.	Medium

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A9	Considered times	Scenarios, case studies, experiments and use cases are constructed to be representative of a nominal day in 2030.	First, it is assumed that maturation of the solution from TRL 1 to TRL 2 can be sufficiently performed by using. Second, flight data is based on a busy day in 2019, which, according to [20], would be slightly higher than the average expected day in 2030. Similar behaviour is expected by selecting a busy and nominal day in 2023 for rail; and passenger demand from MND of a busy day in September 2022.	Medium
A10	Disruption knowledge	It is assumed to have information on the disruption impacting the operations. This assumption can be relaxed as required.	The Evaluators need to know the information on the external disruption and disturbances for their evaluation.	Low
A11	Close system evaluation	It is assumed that paths, itineraries and strategic and tactical alternatives are considered within the schedules, timetables and paths available in the case study model.	The input of the Strategic and the Tactical Evaluator will consider the network defined in the case studies. Therefore, the scope to compute alternatives and to assess the performance is limited by the scope of these networks.	Medium

5.4 Specific assumptions for *Strategic Multimodal Evaluator*

ID	Title	Description	Justification	Impact Assessment

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A3	Passenger archetypes coverage	It is assumed that the set of passenger archetypes considered represents the entirety of travellers, as required for the disaggregation of demand by the Strategic Evaluator.	Extensive research has been conducted to ensure that those passenger archetypes represent the variety of travellers.	Medium
A6	Fixed demand per OD pair	It is assumed that the demand for each OD pair is fixed, meaning that the choice of passengers to travel is independent of the schedules (there will be no more or less demand). Their destination will not change as a result of the schedule optimisation for the Strategic Evaluator.	It is considered sufficiently precise to have demand flows per OD pair and archetype for each scenario (including the impact of policies). The reaction of demand to the supply is considered to have a potential small impact only.	Medium
A7	Coordination between air and rail	The Strategic Evaluator considers the rail and air network, leaving aside other long-distance ground transportation modes such as long-distance buses.	The scope and focus of the project 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 in the Strategic Evaluator.	The price reaction to the demand through an economic model is considered out of the scope and interest of the project. Price variations may come from the policies defined in the scenarios.	Low

5.5 Specific assumptions for *Network structure and paths and itineraries computation*

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ID	Title	Description	Justification	Impact Assessment
A12	Itineraries performance equivalence	It is assumed that itineraries with similar total travel time, total cost, total emissions, number of connections and modes are equivalent.	The passenger archetypes are considered sensitive only to these parameters and, therefore, not impacted by other factors (see A13).	Medium

5.6 Specific assumptions for *Demand distribution*

ID	Title	Description	Justification	Impact Assessment
A13	Passenger archetype sensitivity	It is considered that passenger archetypes are sensitive when selecting an itinerary to total travel time, total cost, total emissions and modes of transport (air, rail, multimodal); and possibly to number of connections, total waiting time and buffers and modes.	Total travel time, total cost, total emissions and mode of transport are the key factors influencing the passenger preference for the different alternatives. This is subject to be reviewed and improved in further versions.	Medium

5.7 Specific assumptions for *Passengers assignment*

ID	Title	Description	Justification	Impact Assessment

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A14	Equivalence of alternatives when planning network	All itineraries within a given cluster (equivalent as defined by A12) are considered equivalent, and passengers are assigned to individual services with the objective of maximising the total number of passengers served.	As per A12 and A13, the passengers are considered not sensitive to parameters not considered in the cluster definition. Therefore, any itinerary within the cluster of equivalent itineraries is considered usable by the passengers from the flow assigned to that cluster.	Low
A15	Equivalence of alternatives when replanning itineraries	For passengers impacted by a disruption, it is assumed that they no longer consider their preferences in terms of cost, emissions and travel time. All alternatives which take them to their final destination are valid as long as they meet the constraints imposed in the replanning (e.g. maintain (or not) the mode, path, etc.). The objective is to assign the maximum volume of passengers so they can reach their final destination, with the possibility of considering the minimisation of the difference with respect to their initially planned arrival time.	When reassigning passengers being impacted by a disruption in updated flight schedules and rail timetables, the passenger is already on the day of travel (or close). Their preferences were considered when planning the network (before the disruption), but now they just want to get to their final destination as close to their planned time as possible.	Medium

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A16	Stock availability	When assigning passengers to itineraries (either in A14 or A15), it is assumed that the stock of seats available per service is accessible through the system. Any required data sharing and coordination are in place (see A5).	When planning the network, the system assumes that multimodal governance exists (e.g. integrated ticketing (see A5)). So, it is assumed that the ticketing system can access seat stocks from all required operators. When replacing the operations due to disruptions, it is assumed that a coordinated approach is performed between operators. Therefore, the required governance should be in place (see A5).	Medium
A17	Passengers rebooking is feasible	When reassigning passengers to itineraries, it is assumed that there is enough time available to notify and rebook the impacted passengers and that the required data and governance infrastructure are in place. This means that some time is expected to exist since the identification of the disruption (or its forecast) and the implementation of the reallocation of passengers into the modified schedules and timetables.	The Disruption Management Solution can replan the flight and rail operations considering the impact of a current (or forecast) disruption in the system. Passengers impacted by the modified services are rebooked into the available seats by the Strategic Evaluator (A15). The data and governance required are already assumed to be in place (see A5, A16); therefore, the technology required to notify passengers impacted is assumed to be in place. If some time is required, this might impact the look-ahead required to replan operations but not necessarily its outcome.	Low

5.8 Specific assumptions for *Tactical Multimodal Evaluator*

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In addition to the assumptions mentioned above, when assessing the Strategic Multimodal Evaluator's output, its assumptions apply to the Tactical Multimodal Evaluator. However, it should be noted that the Tactical Multimodal Evaluator can evaluate any schedules and itineraries, not only the ones from the Strategic Multimodal Evaluator.

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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] ...

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

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[6] ICAO (2014). EUR Performance Framework (ICAO EUR Doc 030)

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[13] PJ19-W2-CI (2023). D4.4. DES Performance Framework

[14] SING-AIR -- Implemented Synergies. Data Sharing Contracts and Goals between transport modes and air transportation -- https://sign-air.eu/

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[15] TRANSIT Consortium (2021). D3.1 Multimodal Performance Framework

[16] TRANSIT Consortium (2021b). D4.1 Methodologies and Mobility Analytics Algorithms for the Analysis of the Door-to-Door Passenger Journey

[17] Travel Wise - TRansformation of AViation and rAirway soLutions toWards Integration and SynergiEs. https://cordis.europa.eu/project/id/101178579

[18] Weiszer, M., Delgado, L. and Gurtner, G. (2024). Evaluation of passenger connections in air-rail multimodal operations. SESAR Innovation Days 2024

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7 Annex A – Input/Output formats

This Annex presents the format of the input and output datasets for the Strategic Multimodal Evaluator and the Tactical Multimodal Evaluator.

A.1 Data approach

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

Both the Strategic and the Tactical Multimodal Evaluator use the standard of TOML (Tom's Obvious Minimal Language [4]) for the config files of the models. This facilitates the configuration of the path to the input files and other factors (e.g. thresholds for *equivalent* itineraries for clustering).

A.2 Strategic Multimodal Evaluator

A.2.1 Files summary

Table A.1 provides a summary of all the files used by the Strategic Multimodal Evaluator. These are divided between Input, Intermediate Output (generated by some functions and subfunctions within the Strategic Multimodal Evaluator pipeline) and Output.

Usage	Type	Name	Short description
Planned network analsyis	Input	I1. flight_schedules	Flight schedules to be used.
	Input	I2. GTFS rail	Rail data from GTFS.
	Input	I3. rail_stations_considered	The subset of rail stations from GTFS to be used.
	Input	I4. heuristics_precomputed	Precomputed heuristic that as a function of distance (GCD) gives the fastest time to cover that by air and rail. If provided, used to speed up the itineraries path finding.
	Input	I5. regions access	Link between regions and infrastructure reachable from these (to create start and end nodes).

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	Input	I6. airports coordinates	Static information on coordinates airports.
	Input	I7. airports IATA-ICAO	Static information with correlation between IATA and ICAO airports codes
	Input	I8. MCT air	Minimum connecting time required to transfer between flights at an airport.
	Input	I9. MCT rail	Minimum connecting time required to transfer between trains at a train station.
	Input	I10. infrastructure transitions	Time required to transition travel between infrastructure nodes (airports / rail stations) where possible.
	Input	I11. airport pax processes	Time for K2G and G2K for airports
	Input	I12. rail stations pax proceses	Tiem for K2P and P2K for rail stations
	Input	I13. pax demand	Demand between regions per pax archetype.
	Input	I14. logit model sensitivities	Parameters for logit model
	Input	I15. air alliances	Information on which alliances for passengers connections are allowed
	Input	I16. policies	Definition of the multimodality policy packages
	Intermediate Output	IO1. flight_schedules_proc_#.csv	Table with flight services used

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	Intermediate Output	IO2. rail_timetable_proc_#.csv	Table with rail services use
	Intermediate Output	IO3. rail_timetable_proc_gtfs_#.csv	Table with rail services in GTFS format only for stops filtered according to I3. rail_stations_considered
	Intermediate Output	IO4. rail_timetable_all_gtfs_#.csv	Table with rail services in GTFS format but all stops
	Intermediate Output	IO5. transition_layer_connecting_times.csv	Transition times G2P, P2G between layers used.
	Intermediate Output	IO6. potential_paths_#.csv	Potential paths between regions if connecting times between services are not considered.
	Intermediate Output	IO7. possible_itineraries_#.csv	Possible itineraries (succession of services (trains/flights)) to join the different regions.
	Intermediate Output	IO8. possible_paths_avg_#.csv	Possible paths to go between regions considering services schedules and connecting times. Computed from IO7. possible_itineraries_#.csv
	Intermediate Output	IO9. possible_itineraries_clustered_#.csv	Cluster of itineraries (IO7. possible_itineraries_#.csv) considering KPIs describing those itineraries, i.e., *equivalent* itineraries.

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	Intermediate Output	IO10. possible_itineraries_clustered_pareto_#.csv	From IO9. possible_itineraries_clustered_#.csv keep only the ones that dominate the others (Pareto) within some margins and per mode type (rail, air, multimodal).
	Intermediate Output	IO11. possible_itineraries_clustered_pareto_filtered_#.csv	Itineraries from IO7. possible_itineraries_#.csv that are kept one they are clustered and filtered according to IO10. possible_itineraries_clustered_pareto_#.csv
	Intermediate Output	IO12. paths_pivoted_final.csv	Intermediate file used by logit model pivoting the options from IO10. possible_itineraries_clustered_pareto_#.csv
	Intermediate Output	IO13. pax_demand_paths.csv	Output from the logit model with demand per alternative per cluster from IO10. possible_itineraries_clustered_pareto_#.csv
	Intermediate Output	IO14. possible_itineraries_clustered_pareto_w_demand_#.csv	For each cluster from O10. possible_itineraries_clustered_pareto_#.csv the demand of passengers who would like any of the itineraries within that cluster according to IO13. pax_demand_paths
	Intermediate Output	IO15. pax_assigned_seats_max_target_#.csv	For every service maximum number of seats, target load factor and target seats used by pax assigner

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	Intermediate Output	IO16. pax_assigned_to_itineraries_options_#.csv	For each itinerary from IO11 number of passengers assigned
	Output	O1. PIs for the network	KPIs from the network.
	Output	O2. flight_schedules_proc_#.csv	from IO1
	Output	O3. rail_timetable_proc_#.csv	from IO2
	Output	O4. possible_itineraries_clustered_pareto_w_demand_#.csv	from IO14
	Output	O5. passengers_itineraries_#.csv	from IO16
Replanned network analysis	Input	I17. flight_added_schedules_proc_#.csv	Flights added to the planned network if network replanned and additional flight services operated.
	Input	I18. flight_cancelled_#.csv	Flights to be cancelled from the planned network if network replanned and flights cancelled
	Input	I19. flight_replanned_proc_#.csv	Flight to be replanned from the planned network, i.e., original flight replaced by information provided in this file.
	Input	I20. rail_timetable_added_all_gtfs_#.csv	Trains to be added to the network if train services added.
	Input	I21. rail_cancelled_#.csv	Trains to be cancelled in replanned network if train services cancelled.

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	Input	I22. rail_timetable_replanned_all_gtfs_#.csv	Trains to be replanned in the network if train services replanned.
	Intermediate Output	IO17. demand_missing_reaccomodate_#.csv	Origin-destination demand that needs to be reaccomodated as passengers are stranded in the replanned network.
	Intermediate Output	IO18. services_capacities_#.csv	For each service in the replanned network their capacity (number of seats). If flight or rail is cancelled number of seats is set to zero.
	Intermediate Output	IO19. services_w_capacity_#.csv	Samea as IO18 but only for services with spare capactiy left.
	Intermediate Output	IO20. services_wo_capacity_#.csv	Services which do not have capacity available.
	Intermediate Output	IO21. potential_paths_#.csv	Same as IO6 but for replanned network.
	Intermediate Output	IO22. possible_itineraries_#.csv	Samne as IO7 but for replanned network.
	Intermediate Output	IO23. pax_need_replanning_w_it_options#.csv	For each passenger itinerary that needs to be reaccomodated in the replanned network, all the alternatives that would be possible for them.

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	Intermediate Output	IO24. pax_need_replanning_w_it_options_filtered_w_constraints_#.csv	Same as IO23 but fitering alternatives which satisfy the user requirements on which alternatives are valid, e.g. if same mode needs to be respected, if paths can (or not) be changed, etc.
	Intermediate Output	IO25. pax_stranded_#.csv	Itineraries of passengers who end up stranded in replanned network, either because they do not have any alternative or the alternatives do not have enough capacity.
	Intermediate Output	IO26. pax_demand_assigned_#.csv	Summary of demand needed to assign, assigned and unfufilled per passenger itinerary group which needs to be reaccomodated int he replanned network.
	Intermediate Output	IO27. pax_reassigned_results_solver_#.csv	Output of reassigning passengers into alternatives for replanned networks.
	Output	O6. 0.pax_assigned_to_itineraries_options_status_replanned_#.csv	
	Output	O7. 1.pax_assigned_to_itineraries_options_kept_#.csv	
	Output	O8. 1.1.pax_assigned_kept_unnafected_#.csv	
	Output	O9. 1.2.pax_assigned_kept_affected_delayed_or_connections_kept_#.csv	
	Output	O10. 2.pax_assigned_need_replanning_#.csv	

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	Output	O11. 3.pax_reassigned_to_itineraries_#.csv	
	Output	O12. 3.1.pax_affected_all_#.csv	
	Output	O13. 4.pax_assigned_to_itineraries_replanned_stranded_#.csv	
	Output	O14. 5.pax_demand_assigned_summary_#.csv	

Table A.1: *Summary of all input, intermediate output and output files used and generated by the Strategic Multimodality Evaluator*

A.2.2 Files structure

The location of the different input folders and where intermediate and outputs are generated are defined in the configuration.toml file. However, we provide here the structure used for the Case Studies evaluated as it can help to understand the different datasets required.

This folders (in bold) and files structure is therefore per case study:

- **folder per case study**:
  - **v=xx** (version of the dataset for the case study, e.g. v=0.7)
    - configuration.toml (e.g. es_md_baseline.toml) → config file with information on the runs (includes paths to all files below)
    - info.txt → text file with information on the case study.
    - **demand**
      - I13. pax demand (e.g. demand_ES_MD_intra_v0.1.csv)
    - **flights_schedules**
      - I1. flight_schedules (e.g. flight_schedules_oag_es_v0.3.csv)
      - I15. air alliances (e.g. air_alliances_v0.1.csv)
    - **gtfs** (e.g. gtfs_es_UIC_v1.0) – I2. GTFS rail
    - **heuristics** (I4. heuristics_precomputed) – I4. heuristics precomputed
      - air_time_heuristics_v0.1.csv
      - rail_time_heuristics_v0.1.csv
    - **infrastructure**
      - **airports_info**
        - I6. airports coordinates (e.g. airports_coordinates_v1.1.csv)

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        - I7. airports IATA-ICAO (e.g. IATA_ICAO_Airport_codes_v1.3.csv)
    - **infrastructure_transitions**
        - I10. infrastructure transitions (e.g. infrastructure_transitions_v0.1.csv)
    - **mct**
        - I8. MCT air (e.g. mct_air_v0.2.csv)
        - I9. MCT rail (e.g. mct_rail_V0.1.csv)
    - **pax_processes**
        - I11. airport pax processes (e.g. airport_processes_v0.1.csv)
        - I12. rail stations pax processes (e.g. rail_stations_processes_v0.1.csv)
    - **rail_info**
        - I3. rail stations considered (e.g. rail_stations_considered_GTFS_2022.csv)
    - **regions_access**
        - I5. regions access (e.g. regions_access_v0.2.csv)
- **output**
    - **processed** (Processed files (output and intermediate files))
        - IO1.flight_schedules_proc_#.csv
        - IO2. rail_timetable_proc_#.csv
        - IO3. rail_timetable_proc_gtfs_#.csv
        - IO4. rail_timetable_all_gtfs_#.csv
        - IO5. transition_layer_connecting_times.csv
    - **paths_itineraries**
        - IO6. potential_paths_#.csv
        - IO7. possible_itineraries_#.csv
        - IO8. possible_paths_avg_#.csv
        - IO9. possible_itineraries_clustered_#.csv
        - IO10. possible_itineraries_clustered_pareto_#.csv
        - IO11. possible_itineraries_clustered_pareto_filtered_#.csv

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            - IO12. paths_pivoted_final.csv
            - IO13. pax_demand_paths.csv
            - IO14. possible_itineraries_clustered_pareto_w_demand_#.csv
            - IO15. pax_assigned_seats_max_target_#.csv
            - IO16. pax_assigned_to_itienraries_options_#.csv
        - **indicators**
            - O1. Indicators for the network
- **policies**
    - I16. PP#.toml
- **replanned_disruptions**
    - **paths_itineraries**
        - IO17. demand_missing_reaccomodate_#.csv
        - IO18. services_capacities_#.csv
        - IO19. services_w_capacity_#.csv
        - IO20. services_wo_capacity_#.csv
        - IO21. potential_paths_#.csv
        - IO22. possible_itineraries_#.csv
        - IO23. pax_need_replanning_w_it_options#.csv
        - IO24. pax_need_replanning_w_it_options_filtered_w_constraints_#.csv
        - IO25. pax_stranded_#.csv
        - IO26. pax_demand_assigned_#.csv
        - IO27. pax_reassigned_results_solver_#.csv
    - **pax_replanned**
        - O6. 0.pax_assigned_to_itineraries_options_status_replanned_#.csv
        - O7. 1.pax_assigned_to_itineraries_options_kept_#.csv
        - O8. 1.1.pax_assigned_kept_unnafected_#.csv

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        - O9. 1.2.pax_assigned_kept_affected_delayed_or_connections_kept_#.csv
        - O10. 2.pax_assigned_need_replanning_#.csv
        - O11. 3.pax_reassigned_to_itineraries_#.csv
        - O12. 3.1.pax_affected_all_#.csv
        - O13. 4.pax_assigned_to_itineraries_replanned_stranded_#.csv
        - O14. 5.pax_demand_assigned_summary_#.csv
    - **replanned_actions**
        - I17. flight_added_schedules_proc_#.csv
        - I18. flight_cancelled_#.csv
        - I19. flight_replanned_proc_#.csv
        - I20. rail_timetable_added_all_gtfs_#.csv
        - I21. rail_cancelled_#.csv
        - I22. rail_timetable_replanned_all_gtfs_#.csv
- **sensitivities** (e.g. sensitivities_v0.1) – I.14 logit model sensitivities

A.2.3 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 Strategic Multimodal Evaluator. It also provides an example of configuration files for the Strategic Multimodal Evaluator.

A2.3.1 Configuration files

This section presents an example of TOML configuration files for the planning and repanning of a network, with some information.

Configuration planning network

[general]
experiment_path = "version/v=0.15/input/"
output_folder = "../output/processed_cs10.pp00.so00"

[policy_package]
policy_package = 'policies/PP00.toml'

```
[demand]
demand = "demand/demand_ES_MD_intra_v0.4.csv"

[network_definition]
[[network_definition.air_network]]
flight_schedules = "flights_schedules/flight_schedules_oag_intra_es_v0.3.csv"
alliances = "flights_schedules/air_alliances_v0.1.csv"
airports_static = "infrastructure/airports_info/airports_coordinates_v1.1.csv"
mct_air = "infrastructure/mct/mct_air_v0.2.csv"
mct_default = 30
[[network_definition.rail_network]]
gtfs = "gtfs_es_UIC_v2.3"
date_rail = "20230920" # Date to use to filter GTFS
date_to_set_rail = "20190906" # Date from flights to make rail and flights 'compatible'
rail_stations_considered = "infrastructure/rail_info/rail_stations_considered_GTFS_2022v0.1.csv"
mct_rail = "infrastructure/mct/mct_rail_v0.1.csv"
mct_default = 15
create_rail_layer_from = 'services' #gtfs / services
country = "LE"
[[network_definition.processing_time]]
airport_processes = "infrastructure/pax_processes/airport_processes_v0.1.csv"
iata_icao_static = "infrastructure/airports_info/IATA_ICAO_Airport_codes_v1.3.csv"
rail_stations_processes = "infrastructure/pax_processes/rail_stations_processes_v0.1.csv"
default_process_time_k2g = 90 # Default value to be used if not available in previous files
default_process_time_g2k = 30 # Default value to be used if not available in previous files
default_process_time_k2p = 15 # Default value to be used if not available in previous files
default_process_time_p2k = 10 # Default value to be used if not available in previous files
[[network_definition.multimodal]]
air_rail_transitions = "infrastructure/infrastructure_transitions/infrastructure_transitions_v0.1.csv"
[[network_definition.regions_access]]
regions_access = "infrastructure/regions_access/regions_access_v0.4.csv"
iata_icao_static = "infrastructure/airports_info/IATA_ICAO_Airport_codes_v1.3.csv"

[other_param]
[other_param.heuristics_precomputed]
heuristics_precomputed_air = "heuristics/air_time_heuristics_v0.1.csv" # within experiment_path
heuristics_precomputed_rail = "heuristics/rail_time_heuristics_v0.1.csv" # within experiment_path
[other_param.kpi_cluster_itineraries]
# Can define, or not kpis_to_use for the clustering of itineraries
# Then, thresholds can be provided. if category doesn't exit (e.g. no rail, or no some
# kpi for some category), the values from 'all' will be taken (if given)
# if nothing is provided, the threshold will be computed as the std of the kpi for the
# category being clustered
kpis_to_use = ['total_travel_time', 'total_cost', 'total_emissions', 'total_waiting_time', 'nservices']
```


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[other_param.kpi_cluster_itineraries.thresholds.all]
total_cost = 30
total_travel_time = 50
total_emissions = 15
total_waiting_time = 30
nservices = 0
[other_param.kpi_cluster_itineraries.thresholds.air]
total_emissions = 20
[other_param.thresholds_pareto_dominance]
total_travel_time = 15
total_cost = 10
total_emissions = 5
total_waiting_time = 30
[other_param.sensitivities_logit]
sensitivities = "sensitivities_v0.5" # folder within experiment_path
[other_param.pax_assigner]
fillers_in_not_used_flights = 1 #Flights in the schedule but without any pax from the pax itineraries flow also fill with fillers. Otherwise, these flights will be empty.
train_seats_per_segment = 'segment' # 'segment' each train segment is treated independently
type_of_optimisation = 'lexicographic' #Type of optimisation lexicographic (can select solver) or max_assinged_only
[other_param.pax_assigner.max_assinged_only]
problem_file = 'problem' #Save the Gurobi LP problem in a file
compute_leg2_plus_first = 1 # Either 1 or 0 to select if doing 2+ legs assigment first
[other_param.pax_assigner.lexicographic]
solver = 'gurobi'
nprocs = 23 # For parallel computing
objectives = [['total_pax_connecting','maximize'],
['total_pax', 'maximize']]
[other_param.pax_assigner.lexicographic.thresholds]
[other_param.pax_assigner.lexicographic.thresholds.total_pax_connecting]
type = 'relative'
value = 0.05
[other_param.pax_assigner.target_load_factor]
type = 'triangular' # triangular | fix. If something else then flights will be at full capacity
param = [0.75,0.95,1]
[other_param.pax_assigner.target_load_factor.flight]
type = 'triangular' # triangular | fix. If something else then flights will be at full capacity
param = [0.75,0.95,1]
[other_param.pax_assigner.target_load_factor.rail]
type = 'fix' # triangular | fix. If something else then flights will be at full capacity
param = 1
[other_param.pax_assigner.minimum_load_factor]

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```
type = 'triangular' # triangular | fix. If something else then flights will be at full capacity
param = [0.35,0.8,0.8]
[other_param.pax_assigner.minimum_load_factor.flight]
type = 'triangular' # triangular | fix. If something else then flights will be at full capacity
param = [0.35,0.8,0.8]
[other_param.pax_assigner.minimum_load_factor.rail]
type = 'triangular' # triangular | fix. If something else then flights will be at full capacity
param = [0.35,0.8,0.8]
[other_param.tactical_input]
[other_param.tactical_input.aircraft]
ac_type_icao_iata_conversion = "ac_airline_info/ac_type_icao_iata_v0.1.csv"
ac_mtow = "ac_airline_info/mtow_v0.1.csv"
ac_wtc = "ac_airline_info/wtc_v0.1.csv"
[other_param.tactical_input.airlines]
airline_ao_type = "ac_airline_info/airline_icao_ao_type_v1.1.csv"
airline_iata_icao = "ac_airline_info/iata_icao_airlines_codes_v1.1.csv"
```

Configuration replanning network

```
[general]
experiment_path = "../../data/CS10/v=0.16/" # Path to experiment
replanned_input_folder = "replanned_disruptions/DP100/PP20.DM00.PA04" # Path for replanning the network
replanned_actions_folder = "replanned_actions" # Folder where replanning actions (I17-I22 files) are located within replanned_input_folder.

[planned_network_info]
planned_network = 'output/processed_cs10.pp20.nd00.so00.00' # Ouptut of planned network
path_results = 'paths_itineraries' # Folder where paths itineraries of planned network are located
path_processed = 'processed' # Path where processed files of planned network are located
precomputed = 0 # Precomputed version of planned network

[network_definition]
[[network_definition.air_network]]
airports_static = "infrastructure/airports_info/airports_coordinates_v1.1.csv"
mct_air = "infrastructure/mct/mct_air_v0.2.csv"
mct_default = 30
[[network_definition.rail_network]]
gtfs = "gtfs_es_UIC_v2.3"
date_to_set_rail = "20190906" # Date from flights to make rail and flights compatible
rail_stations_considered = "infrastructure/rail_info/rail_stations_considered_GTFS_2022v0.1.csv"
mct_rail = "infrastructure/mct/mct_rail_v0.1.csv"
mct_default = 15
create_rail_layer_from = 'gtfs'
[[network_definition.processing_time]]
```


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airport_processes = "infrastructure/pax_processes/airport_processes_v0.1.csv"
iata_icao_static = "infrastructure/airports_info/IATA_ICAO_Airport_codes_v1.3.csv"
rail_stations_processes = "infrastructure/pax_processes/rail_stations_processes_v0.1.csv"
default_process_time_k2g = 90 # Default value to be used if not available in previous files
default_process_time_g2k = 30 # Default value to be used if not available in previous files
default_process_time_k2p = 15 # Default value to be used if not available in previous files
default_process_time_p2k = 10 # Default value to be used if not available in previous files
[[network_definition.multimodal]]
air_rail_transitions = "infrastructure/infrastructure_transitions/infrastructure_transitions_v0.1.csv"
[[network_definition.regions_access]]
regions_access = "infrastructure/regions_access/regions_access_v0.4.csv"
iata_icao_static = "infrastructure/airports_info/IATA_ICAO_Airport_codes_v1.3.csv"
[replanning_considerations]
[replanning_considerations.constraints]
new_itineraries_respect_alliances = true # true/false -- allow new itineraries accross not within alliance
respect_alliances_pax_it_new_it = false # respect (or not) new itineraries same alliances as planned pax it
respect_path = false # keep only the same paths from planned to actual
respect_modes = false # keep same mode as planned
initial_node_same = false # keep initial node the same
final_node_same = false # keep the final node the same
departure_before_pax_it = false # allow departure (from home)before initial pax planned
[replanning_considerations.optimisation]
solver = 'gurobi'
nprocs = 23 # For parallel computing
# Order of objecteives for lexicographic optimisation to replan passengers impacted
objectives = [['total_pax', 'maximize'],
['arrival_door_difference', 'minimize'],
['same_path', 'maximize'],
['same_starting_node', 'maximize'],
['same_arrival_node', 'maximize']]
Thresholds to be used by lexicographic optimisation to replan passengers impacted
[replanning_considerations.optimisation.thresholds]
[replanning_considerations.optimisation.thresholds.total_pax]
type = 'relative'
value = 0.10
[replanning_considerations.optimisation.thresholds.arrival_door_difference]
type = 'relative'
value = 0.05
[replanning_considerations.optimisation.thresholds.starting_node_different]
type = 'relative'
value = 0.05

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[replanning_considerations.optimisation.thresholds.arrival_node_different]
type = 'relative'
value = 0.05

[other_param]
[other_param.heuristics_precomputed]
heuristics_precomputed_air = "heuristics/air_time_heuristics_v0.1.csv" # within experiment_path
heuristics_precomputed_rail = "heuristics/rail_time_heuristics_v0.1.csv" # within experiment_path
[other_param.tactical_input]
[other_param.tactical_input.aircraft]
ac_type_icao_iata_conversion = "ac_airline_info/ac_type_icao_iata_v0.1.csv"
ac_mtow = "ac_airline_info/mtow_v0.1.csv"
ac_wtc = "ac_airline_info/wtc_v0.1.csv"
[other_param.tactical_input.airlines]
airline_ao_type = "ac_airline_info/airline_icao_ao_type_v1.1.csv"
airline_iata_icao = "ac_airline_info/iata_icao_airlines_codes_v1.1.csv"

A2.3.2 Input files

I1. flight_schedules

- Flight schedules to be used to compute paths and itineraries

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)

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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. rail_stations_considered

- List of rail stations to be used for the search of possible paths

Field	Type	Mandatory	Other info
stop_id	string	yes	should be same format as GTFS rail (I2).

I4. heuristics precomputed

- Heuristic files show how quickly one can reach a given o-d distance by air or rail. Computed from schedules/timetable and used only internally by A* algorithm.
- air_time_heuristics_vxxx.csv and rail_time_heuristics_vxx.csv same format triplets defining from a distance to another distance (in km) what is the minimum time required.

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Field	Type	Mandatory
min_dist	int	yes
max_dist	int	yes
time	float	yes

I5. regions_access

- Information on access/egress times from region to station (airport and rail station). They could be per pax archetype or differential between air/rail. Times from door-to-infrastructure (airport/rail station).
- Note that the station does not necessarily need to be in the same region.

Field	Type	Mandatory	Other info
region	string	yes	usually NUTS region name (should be same as the one used in
station	string	yes	For airports it can be IATA or ICAO code. For rail stations needs to match the stops from the GTFS format.
layer	string	yes	
pax_type	string	yes	
avg_d2i	float	yes	
avg_i2d	float	yes	

Example

region	station	layer	pax_type	avg_d2i	avg_i2d
ES111	SCO	air	all	47	47
ES111	LCG	air	all	31	31

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ES111	007131400	rail	alla	46	46

I6. airports coordinates

- Coordinates of airports (lat, long)

Field	Type	Mandatory
icao_id	string	yes
lat	float	yes
lon	float	yes

I7. airports IATA-ICAO

- Translation between IATA and ICAO airport codes

Field	Type	Mandatory
IATA	string	yes
ICAO	string	yes
Location	string	no
Airport	string	no
Country	string	no

I8. MCT air

- Information on MCT for air-air connections (per airport and with standard, international and domestic connections). A default value to be given in config file.

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

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domestic	int	no	Used for domestic connections
international	int	no	Used for international connections

I9. 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

I10. infrastructure transitions

- Information on transition between air and rail layer (MCT) between layers in minutes (from infrastructure to infrastructure k2k).

Field	**Type**	**Mandatory**	**Other info**
origin_station	string	yes	
destination_station	string	yes	
layer_origin	string	yes	
layer_destination	string	yes	
avg_travel_a_b	float	yes	time it takes to go from infrastructure a to infrastructure b (kerb to kerb)
avg_travel_b_a	float	yes	time it takes to go from infrastructure b to infrastructure a (kerb to kerb)

origin_station	**destination_station**	**layer_origin**	**layer_destination**	**avg_travel_a_b**	**avg_travel_b_a**
7160000	7117000	rail	rail	30	30
LEAL	7160911	air	rail	40	40

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I11. airport pax processes

- Information on time it takes to process passengers through the airport (kerb-to-gate and gate-to-kerb) times. A default value to be given in config file.
- k2g_multimodal and g2k_multimodal, if provided, are used when computing the time it takes to transfer across layers. If not provided then the k2g and g2k are used.

Field	Type	Mandatory	Other info
icao_id	string	yes	
pax_type	string	yes	
k2g	float	yes	
g2k	float	yes	
k2g_multimodal	float	no	If not provided, then k2g is used.
g2k_multimodal	float	no	If not provided, then g2k is used.

I12. rail stations pax processes

- Information on time it takes to process passengers through the rail station (kerb-to-gate and gate-to-kerb) times. A default value to be given in config file.
- k2p_multimodal and p2k_multimodal, if provided, are used when computing the time it takes to transfer across layers. If not provided then the k2p and p2k are used.

Field	Type	Mandatory	Other info
icao_id	string	yes	
pax_type	string	yes	
k2p	float	yes	
p2k	float	yes	
k2p_multimodal	float	no	If not provided, then k2p is used.
p2k_multimodal	float	no	If not provided, then p2k is used.

I13. pax demand

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- Demand between origin-destination regions per pax archetype

Field	Type	Mandatory
date	date (yyymmdd)	no
origin	string	yes
destination	string	yes
archetype	string	yes
trips	float	yes

I14. logit model sensitivities

- pickle files with sensitivities of logit model per passenger archetype

I15. air alliances

- Information on to which alliance an airline belongs to allow connecting pax between different airlines.
- One airline can be in one alliance only.

Field	Type	Mandatory
provider	string	yes
alliance	string	yes

I16. policies

- Definition of a multimodality policy package in TOML format.

Field	Type	Mandatory	Other info
tax_charges.air.co2_cost	int	yes	Eur per kg for air services
tax_charges.rail.co2_cost	int	yes	Eur per kg for rail services
integrated_ticketing.air_air_processing_extra	int	yes	Extra time to go between two airports
integrated_ticketing.rail_rail_processing_extra	int	yes	Extra time to go between two rail stations

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integrated_ticketing.air_rail_processing_extra	int	yes	Extra time to go from airport to rail station
integrated_ticketing.rail_air_processing_extra	int	yes	Extra time to go from rail station to airport

I17. flight_added_schedules_proc_#.csv

same format I1 providing the new flight schedules to be added to the network. The file is not required to replan a network if no flights are added.

I18. flight_cancelled_#.csv

The file is not required to replana network if no flight is cancelled.

Field	Type	Mandatory	Other info
service_id	str	yes	Id of the flight to be cancelled

I19. flight_replanned_proc_#.csv

Same fields as I1 for flights to be replanned in the schedules. The original flight will be replaced by the one provided here. The file is not needed if no flight is replanned in the replanned network.

I20. rail_timetable_added_all_gtfs_#.csv

Same format IO3. The file is not needed to replan the network if no trail service is added.

I21. rail_cancelled_#.csv

Information on which rail services to cancel. The file is not required to replan a network if no train service is cancelled.

Field	Type	Mandatory	Other info
service_id	str	yes	Id of rail service to be cancelled.
from	int	no	If provided trains cancelled from this stop, it not provided train cancelled from the first stop on their trip.
to	int	no	If provided trains cancelled until this stop, if not proviced trains cancelled up to this stop.

I22. rail_timetable_replanned_all_gtfs_#.csv

Same format as IO3. The file is not needed to replan the network if no trail service is replanned.

- **A2.3.3 Output files**

IO1. flight_schedules_proc_#

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- Flight schedules used to compute possible/potential paths compute dfrom I1. flight schedules.

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

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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)

IO2. rail_timetable_proc_#.csv

- Table with rail services use. 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
service_id	string	Id of the service encoded in this way: trip_stoporigin_stop_destination (e.g. 1_3_5) is trip 1 between stops 3 and 5.
origin	string	Id of the stop origin
destination	string	Id of stop destination
departure_time	yyyy-mm-dd hh:mm:ss	Departure datetime from origin (as in GTFS, so by default in local time)
arrival_time	yyyy-mm-dd hh:mm:ss	Arrival datetime to destination (as in GTFS, so by default in local time)
provider	string	
alliance	string	We could have alliance for rail operators too, by default it's jus the same id as the provided. By default also all rail providers can link with any air provider.
cost	float	Expected average cost (EUR)
seats	int	Number of seats of service (note this is for the whole service not between these two stops necessarily)
emission	float	Expected average emissions per pax (CO2) in kg

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country	str	Country of service (this comes from config.toml file)
lat_orig	float	latitude of stop of origin
lon_orig	float	longitude of stop of origin
lat_dest	float	latitude of stop of destination
lon_dest	float	longitude of stop of destination
gcdistance	float	Great circle distance in km from origin to destination

IO3. rail_timetable_proc_gtfs_#.csv

- Table with rail services in GTFS format only for stops filtered according to I3. rail_stations_considered.
- Same format as GTFS stop_times.txt (only added provider, alliance and country)

Field	**Type**	**Other info**
trip_id	string	
arrival_time	hh:mm:ss	In local time
departure_time	hh:mm:ss	In local time
stop_id	string	
stop_sequence	int	Sequence within trip_id
pickup_type		
drop_off_type		
boarder_point		
load_unload		
ckeck_in		
check_out		

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provider	str	
alliance	str	as in IO2. rail_timetable_proc
country	str	as in IO2. rail_timetable_proc (from config toml)

IO4. rail_timetable_all_gtfs_#.csv

- Table with rail services in GTFS format but with all the stops.
- Same format and information as IO3. rail_timetable_proc_gtfs_#.csv

IO5. transition_layer_connecting_times.csv

- Transition times gate-to-platform (G2P), platform-to-gate (P2G) between layers used.
- This is computed internally using the information from I11. airport pax processes, I12. rail stations pax processes and I10. infrastructure transitions to compute the g2k + i2i + k2p, p2k + i2i + k2g, etc. The file is saved only as reference.

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.

IO6. potential_paths_#.csv

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- Potential paths between regions if connecting times between services are not considered.
- The only thing that is considered is if services are compatible (i.e., same airline, alliance and/or rail operator).
- The relevant information is therefore the path (succession of infrastructure nodes), and service providers. The times will be the 'fastest', i.e., fastest service and only using mct.

Field	**Type**	**Other info**
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
option	int	Number of option for that origin-destination
nservices	int	number of services for the path (i.e., number of trains/flights): nservices -1 = number of connections
path	list of infrastructure ids	List of all infrastructures that are in the path, either stop_id for rail stops or ICAO code for airports. For example: ['007131412', '007131400'] ['LEBL', 'LEMD']
total_travel_time	float	estimated door-to-door time of path
total_costs	float	EUR
total_emissions	float	Emisisons in CO2
total_waiting_time	float	Won't have any value as in this output the total_witing_time doesn't matter (should be 0 all the time)
nmode	int	number of differnet modes (1 (air or rail), 2 (multimodal))-- 0 could be access/egress
journey_type	str	air, rail, multimodal or none
acess_time	float	minutes access to first infrastructure d2k
egrees_time	float	minutes egress from final infrastructure k2d

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origin_#	str	id of infratrcutrue of origin for service number # (e.g. origin_0)
destination_#	str	id of infrasture of destination for service nubmer # (e.g. destination_0)
provider_#	str	id of provider for service #
alliance_#	str	id of provider for service #
mode_#	str	mode of service # (air, rail)
travel_time_#	float	travel time (min) of service #
cost_#	float	cost of service # (EUR)
emissions_#	float	emissions of service # per pax (CO2 kg)
mct_time_#_$	float	minimum connecting time between sevice # and service $ (e.g mct_time_0_1)

IO7. possible_itineraries_#.csv

- Possible n fastest itineraries (succession of services (trains/flights)) to join the different regions.

Field	Type	Other info
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
option	int	Number of option for that origin-destination
nservices	int	Number of services in the itinerary
path	list of infrastructure ids (str)	List of all infrastructures that are in the path, either stop_id for rail stops or ICAO code for airports. For example: ['007131412', '007131400'] ['LEBL', 'LEMD']

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total_travel_time	float	estimated door-to-door time of path
total_costs	float	EUR
total_emissions	float	Emisisons in CO2
total_waiting_time	float	Adddition of all waiting times of all the connections. Note waiting time computed as difference between connecting time and minimum connecting time between services
nmode	int	number of differnet modes (1 (air or rail), 2 (multimodal))- - 0 could be access/egress
journey_type	str	air, rail, multimodal, none
acess_time	float	minutes access to first infrastructure d2k
egrees_time	float	minutes egress from final infrastructure k2d
origin_#	str	id of infratrcutrue of origin for service number # (e.g. origin_0)
destination_#	str	id of infrasture of destination for service nubmer # (e.g. destination_0)
provider_#	str	id of provider for service #
alliance_#	str	id of provider for service #
mode_#	str	mode of service # (air, rail)
departure_time_#	datetime with timezone	yyyy-mm-dd hh:mm:ss +00:00. In UTC
arrival_time_#	datetime with timezone	yyyy-mm-dd hh:mm:ss +00:00. In UTC
travel_time_#	float	Travel time in minutes for service_# (arrival_time_# - departure_time_#)
cost_#	float	Cost of service # (EUR)

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emissions_#	float	emissions of service # per pax (CO2 kg)
mct_time_#_$	float	minimum connecting time between sevice # and service $ (e.g mct_time_0_1)
connecting_time_#_$	float	actual connecting time bween service_$ and service_# (departure_time_$ - arrival_time_#)
waiting_time_#_$	float	waiting time as extra time between connecting time and mct time (connectint_time_#_$ - mct_time_#_$)

IO8. possible_paths_avg_#.csv

- Possible paths to go between regions considering services schedules and connecting times. Computed from IO7. possible_itineraries_#.csv
- Group the possible_itinearies by path and compute statistics on them.

Field	Type	Other info
path_id	int	Id of each path
n_itinearies	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-destinatino)
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

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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 with timezone	yyyy-mm-dd hh:mm:ss +00:00. In UTC (even for rail)
latest_arrival_time	datetime with timezone	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 infratrcutrue 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 $

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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 $

IO9. possible_itineraries_clustered_#.csv

- Cluster of itineraries (IO7. possible_itineraries_#.csv) considering KPIs describing those itineraries, i.e., *equivalent* itineraries.
- Cluster done with parameters (KPIs) and thresholds defined in config file (toml)
- Note, by default the number of services difference is set to 0, so if two itineraries have different number of services they are clustered separately. The same applies to journey_type, all journey_types are clustered separatelly.

Field	**Type**	**Other info**
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
journey_type	str	Type of journey: air, rail, multimodal, none
cluster_id	int	Numerical id for cluster for origin-destination (id of first itinerary in cluster)
alternative_id	str	Unique id per cluster formed as origin_destination_cluster_id (e.g. ES111_ES112_0)
options_in_cluster	list of int	List of id of itineraries which belong to this cluster. I.e., list of ids from option from possible_itineraries_#.csv (e.g. [0, 1, 2, 3, 4])
total_travel_time	float	Average total travel time of all itineraries in cluster
total_cost	float	Average total cost (EUR) of all itineraries in cluster
total_emissions	float	Average emissions per pax (CO2) for all itineraries in cluster
total_waiting_time	float	Average total waiting time (min) for itineraries in cluster

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nservcies	int	Average number of services (flights, trains) in itineraries in cluster.

IO10. possible_itineraries_clustered_pareto_#.csv

- From IO9. possible_itineraries_clustered_#.csv keep only the ones that dominate the others (Pareto) within some margins and per mode type (rail, air, multimodal). Thresholds for defining Pareto dominance defined in config file (toml).
- Format is the same as IO9. possible_itineraries_clustered_#.csv. It is just a subset of the clusters.

IO11. possible_itineraries_clustered_pareto_filtered_#.csv

- Itineraries from IO7. possible_itineraries_#.csv that are kept one they are clustered and filtered according to IO10. possible_itineraries_clustered_pareto_#.csv. I.e, only the itineraries that appear in the options_in_cluster of the clusters that are kept.
- Format is the same as IO7. possible_itineraries_#.csv, just addint two extra columns:
    - alternative_id: Unique id of the cluster for which this itinerary belongs (e.g. ES111_ES112_0)
    - cluster_id: Int id of the cluster for the o-d pair of this itinerary (e.g. 0)

IO12. paths_pivoted_final.csv

- Intermediate file used by logit model pivoting the options from IO10. possible_itineraries_clustered_pareto_#.csv
- As we consider that the different itineraries within the cluseter are *equivalent* from a pax perspective the assigment of flows (alternatives for a given o-d pair) are based on the clusters.

Field	**Type**	**Other info**
alterantive_id	string	Id of the clusters (alternatives) (Unique id per cluster formed as origin_destination_cluster_id (e.g. ES111_ES112_0)).
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)

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multimodal_1, multimodal_2, multimodal_3, … plane_1, plane_2, plane_3, plane_4,… train_1, train_2, train_3, train_4… cost_1, cost_2, cost_3,…. emissions_1, emission_2, emissions_3,… travel_time_1, travel_time_2, travel_time_3,…. alternative_id_1, alternative_id_2, alternative_id_3…. observed_choice	enconding of the alternatives	For each alternative put the information from the clusters, for example if the first altenative is mulimiodal and has a cost of 100, emissions of 30, travel_time of 20, the second option is by trrain, has a cost of 40, emissiosn of 10 and travel_time of 90, the encondig would have two rows with: • multimodal_1 = 1 • plane_1 = 0 • train_1 = 0 • cost_1 = 100 • emissions_1 = 30 • travel_time_1 = 20 • alternative_id_1 = xxxx • alternative_id_2 = yyyy • observed_choice = 1 • multimodal_1 = 0 • plane_1 = 0 • train_1 = 1 • cost_1 = 40 • emissions_1 = 10 • travel_time_1 = 90 • alternative_id_1 = xxxx • alternative_id_2 = yyyy • observed_choice = 2
av_1, av_2, av_3…	binary hotencoding of which alternatives are valid per origin-destination	

IO13. pax_demand_paths.csv

- Output from the logit model with demand per alternative per cluster from IO10. possible_itineraries_clustered_pareto_#.csv

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- Number of pax per alternative for origin-destination. It needs to be merged with IO12. paths_pivoted_final.csv to obtain the name of the alternative (cluster) of each alternative_# for each o-d pair.

Field	Type	Other info
date	date	yyyymmdd
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
archetype	string	Archetype of passenger (e.g. archetype_0, archetype_1…)
trips	float	Total volume of pax between origin-destination
alternative_#	float	Number of passengers from the corresponding archetype that want this alternative.
alternativ_prob_#	float	Probability that passenger of that archetype want that alternative for that o-d pair. Note that alternative_prob_# * trips = alternative_#

IO14. possible_itineraries_clustered_pareto_w_demand_#.csv

- For each cluster from IO10. possible_itineraries_clustered_pareto_#.csv the demand of passengers who would like any of the itineraries within that cluster according to IO13. pax_demand_paths.csv.
- First, same information as IO10 and IO9. possible_itineraries_clustered_#.csv. Then information on passengers who want that cluster.

Field	Type	Other info
origin	string	Id of the origin (region, in our case NUTS)
destination	string	Id of the destination (region, in our case NUTS)
journey_type	str	Type of journey: air, rail, multimodal, none
cluster_id	int	Numerical id for cluster for origin-destination (id of first itinerary in cluster)

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alternative_id	str	Unique id per cluster formed as origin_destination_cluster_id (e.g. ES111_ES112_0)
options_in_cluster	list of int	List of id of itineraries which belong to this cluster. I.e., list of ids from option from possible_itineraries_#.csv (e.g. [0, 1, 2, 3, 4])
total_travel_time	float	Average total travel time of all itineraries in cluster
total_cost	float	Average total cost (EUR) of all itineraries in cluster
total_emissions	float	Average emissions per pax (CO2) for all itineraries in cluster
total_waiting_time	float	Average total waiting time (min) for itineraries in cluster
nservcies	int	Average number of services (flights, trains) in itineraries in cluster.
train	boolean	Indicates if itineraries in cluster are by rail (from logit model)
plane	boolean	Indicates if itineraries in cluster are by flight (from logit model)
multimodal	boolean	Indicates if itineraries in cluster are multimodal (from logit model)
option_number	int	option number from options on logit for o-d pair.
num_pax	float	Number of pax who want to do this option (all archetypes from IO13 aggregated together)
prob_of_archetype	dictionary of probabilities	Dictionary of probability that pax is of each archetype. This allows to redesagregate the num_pax into each archetype category if desired to obtain the numbers from IO13. For example: {'archetype_0': 0.7531756963575145, 'archetype_1': 0.016222834404652588, 'archetype_2': 0.02173247627793082, 'archetype_3': 0.10238751147842057, 'archetype_4': 0.05498163452708907, 'archetype_5': 0.05149984695439241}

IO15. pax_assigned_seats_max_target_#.csv

- For every service maximum number of seats, target load factor and target seats used by pax assigner

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Field	Type	Other info
nid	str	Id of the service (e.g. D8_5081)
max_seats	int	Number of seats available in service
target_load_factor	float	Load factor targed as computed wiht information from config toml
target_seats	int	target_load_factor * max_seats rounded to integer. These are the number of seats used by the pax assigner

IO16. pax_assigned_to_itineraries_options_#.csv

- For each itinerary from IO11 number of passengers assigned
- It could be merged back to IO11 by alternative_id and option_number.
- It could be merged back easily to IO9 and IO14 by alternative_id (id of the clusters)

Field	Type	Other info
id	int	Numerical id of cluster (used internally)
option_number	int	Number of option for the origin-destination
alternative_id	str	Unique id of cluster composed of origin_destination_int(of first option incluster) (e.g. ES111_ES112_0)
nid_f#	string	Id of the # service (flight or rail)
total_waiting_time	int	Total waiting time of the itinerary considering all connections (waiting time = connecting time - mct) (min)
total_time	int	Total time of trip (min) (door-to-door estimation)
type	str	Type of itinerary as concatenation of modes used: e.g. rail, flight, flight_flight, rail_flight, rail_rail, rail_flight_rail, etc. Note, it could be empy if no mode is used (only access/egress from infrastructure)
volume	float	Number of pax assigned to the cluster from the logit model. Note this is not the number of pax of this itinerary but of this cluster (i.e., to be shared by all the itineraries in the cluster)

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fare	float	Average fare of the itinerary
volume_ceil	int	Volume applied ceil to transform float to int of pax
pax	int	Number of passengers the passenger assigner (disaggregator) has put in this particular itinerary. Could be 0.

IO17. demand_missing_reaccomodate_#.csv

Same format as I13; genetared automtatically based on passengers needing replanning.

IO18. services_capacities_#.csv

Field	Type	Other info
service_id	str	Service id (flight or rail id)
type	str	‘flight’ or ‘rail’
capacity	int	Number of seats available in the service

IO19. services_w_capacity_#.csv

For services with capacity availabe information on them.

Field	Type	Other info
service_id	str	Service id (flight or rail id)
max_seats_service	int	Maximum number of seats in the service (Regarless of being used)
type	str	flight, rail
max_pax_in_service	int	Maximum number of passengers using the service (for flights it will be number of passengers in the service, for rail it might be higher as some rail services ‘overalp’. For example rail service 123_4_6 is rail service 123 between stops 4 to 6, will have passengers that are also in 123_2_5).
load_factor	float	max_pax_in_service / max_seats_service
pax_between_stops	int	How many passengers are actually going btween the stops of the rail service as in their id (e.g. fro rail service 123_5_7, how many passengers between stops 5 and 7).

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IO20. services_wo_capacity_#.csv

Same format as IO19, but for services which have load_factor=1. These won't be used when looking for alterative itineraries for the passengers.

IO21. potential_paths_#.csv

same format as IO8, but only for the demand neeeding to be reaccomodated using the services with some spare capactiy.

IO22. possible_itineraries_#.csv

same format as IO7, but only for paths required for the demand of passengers needing to be reaccomodated using the services with spare capacity.

IO23. pax_need_replanning_w_it_options1.csv

Similar fields to IO7 representing itineraries with information on alternatives possible per itinerary. In table below key fields charaterising the alternative described.

Field	**Type**	**Other info**
pax_status_replanned	str	Reason for passenger goup needing to be reallocated, e.g., 'cancelled'
modes_it	str	List of modes of services used in alternative, e.g. ['rail', 'air']
alliances_match	bool	If alliances of original itinerary match alternative
same_path	bool	If path of origina itinerary match alternative
delay_departure_home	int	Minutes of delay with respect to departing time from door.
delay_arrival_home	int	Minutes of delay with respect to arrival time to door.
delay_total_travel_time	int	Different on travelling time between alternative and planned itinerary.
extra_services	int	Number of extra services used in alternative with respect to planned itinary.
same_initial_node	bool	If the departing infrastructure node matches the infrastructure node from the original itinerary.
same_final_node	bool	If the arrival infrastructure node is the same as the arrival infrastructure node of the original itinerary.

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journey_type_pax	str	rail, air, multimodal
same_modes	bool	If the modes used in the alternative are used in the original itinerary too.

IO24. pax_need_replanning_w_it_options_filtered_w_constraints_#.csv

Same as IO23 but filtering consdiering the constraints on which type of alternatives are allowed to replan affected itinearies.

IO25 pax_stranded_#.csv

Similar fields to IO11. This file indicates the passengers who are stranded even before assigning them. I.e., passengers which don't have alternatives possible in the replanned network either because their is no alternative itineary or because after filtering the alternatives consdiering the constraints none are left.

IO26. pax_demand_assigned_#.csv

Field	Type	Other info
pax_group_id	int	Id of pax group from passenger itinerary
demand_to_assign	int	Number of passengers that need to be assigned
pax_assigned	int	Number of passenger assigned
unfulfilled	int	Number of passengers stranded (demand_to_assign - pax_assigned)

IO27. pax_reassigned_results_solver_#.csv

same fields as in IO19 but adding the information below

Field	Type	Other info
pax_assigned	int	Number of passengers assigned to this alternative
pax_group_id_new	int	New Id for passenger itinerary group

O1. Indicators for the network

[School of Arch and Cities - General - All Documents]

The output files contain *indicators.csv* file and other files/images for the individual indicators. The specification of the indicators (such as units) can be found in the Digital Catalogue of Indicators: https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY

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O6. 0.pax_assigned_to_itineraries_options_status_replanned_#.csv

Status of passenger itinearies in replanned network. It has the same fields as IO16 but adding:

Field	Type	Other info
pax_status_replanned	str	status of passenger itinerary in replanned newtork: unnafected, cancelled, delayed, replanned_doable, replanned_no_doable.

O7. 1.pax_assigned_to_itineraries_options_kept_#.csv

Same format as O6 but filtering passengers unnafected, delayed or replanned_doable.

O8. 1.1.pax_assigned_kept_unnafected_#.csv

Same format as O6 but only filtering passengers unnafected, i.e. subset of O7.

O9. 1.2.pax_assigned_kept_affected_delayed_or_connections_kept_#.csv

Same format as O6 but only filtering passengers delayed or replanned_doable, i.e. subset of O7 with passenger itineraries affected by the replanning.

O10. 2.pax_assigned_need_replanning_#.csv

Same format as O6, but filtering passengers cancelled or replanned_no_doable.

O11. 3.pax_reassigned_to_itineraries_#.csv

Same format as IO24 but with number of passengers assigned per option for passengers needing to be reaplanned (O10)

Field	Type	Other info
demand_reassigning	int	Number of passengers that need to be reassigned.
option_reassigning	int	Option selected from number of options for itinerary needing to be replanned
pax_assigned	int	Number of passengers assigned into this option
pax_group_id_new	str	New Id of passenger group assigned to this option.
mode_combined_replanned	str	air, multimodal, rail
mode_combined_orig	str	air, multimodal, rail

O12. 3.1.pax_affected_all_#.csv

Same format as O11 but including passengers not needeing to be replanned but affected (O9).

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O12. 4.pax_assigned_to_itineraries_replanned_stranded_#.csv

Same fields as O11 but for passengers that end up stranded either because they don't have any option or because ther is not enought capacity.

Field	Type	Other info
pax_stranded	int	Number of stranded passengers.
stranded_type	str	no_option, no_capacity

O13. 5.pax_demand_assigned_summary_#.csv

Summary of passenger assigment per passenger group.

Field	Type	Other info
pax_group_id	int	Passenger gorup id of passengers that need to be reaccomodated.
origin	str	Origin of itinerary (NUTS3).
destination	str	Destination of itinerary (NUTS3).
demand_to_assign	int	Passengers that need to be reassigned.
pax_assigned	int	Number of passengers reassigned.
unfulfilled	int	Difference between the demand to be assigned (demand_to_assing) and the passengers assigned (pax_assigned).

A.3 Tactical Multimodal Evaluator

The Tactical Muldimodal Evaluator extends Mercury ABM platform developed over several SESAR ER projects from a gate-to-gate simulator to a full multimodal evaluator [1, 5]. Mercury is an open-source model and detailed information on how to execute Mercury can be found in the GitHub repository of the code [3]. Sample data required to run the baseline (gate-to-gate) model is provided in [2]. Therefore this annex describes only the files related to the multimodality aspect and for the generation of the input data for Mercury originating in the Strategic

A.3.1 Files summary

Table A.2 provides a summary of the muldimodality related files used by Tactical Multimodal Evaluator. These are divided between Input Required to Process Strategic Output (related to aircraft performance

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and airline types to be used in the Tactical Evaluator which are not needed Strategically), Input and Output.

Type	Name	Short description
Input Required to Process Strategic Output	IRPSO1. ac type IATA ICAO	Translation between ICAO and IATA ac types. Used to generate input of flight schedules for the Tactical Multimodal Evaluator from the flight schedules of the Strategic Multimodal Evaluator as the aircraft type needs to contain the ICAO code in the Tactical Multimodal Evaluator.
Input Required to Process Strategic Output	IRPSO2. MTOW	MTOW of aircraft types. Used to generate input of flight schedules.
Input Required to Process Strategic Output	IRPSO3. WTC	WTC of aircraft types. Used to generate input of flight schedules.
Input Required to Process Strategic Output	IRPSO4. airline IATA ICAO	Translation between ICAO and IATA for airline codes. Used to generate input of flight schedules.
Input Required to Process Strategic Output	IRPSO5. airline AO type	Aicraft operator type (FSC, CHT, LCC, REG) for each airline. Used to generate input of flight schedules.
Input	I1. flight_schedules	Flight schedules to be used in the format required by the Tactical Multimodality Evaluator. This is the output of the functionality to generate the Tactical Multimodal Evaluator input from the Strategic Multimodal Evaluator.
Input	I2. GTFS rail	Rail data from GTFS.
Input	I3. airport pax processes	Time for K2G and G2K for airports.

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Input	I4. pax.parquet	Passenger itineraries as required by the Tactical Multimodality Evaluator. This is the output of the functionality to generate the Tactical Multimodal Evaluator input from the Strategic Multimodal Evaluator.
Output	O1. PIs for the pax	Realisation of passenger itineraries
Output	O2. Indicators	Tactical indicators

Table A.2: *Summary of multimodal related input and output used and generated by the Tactical Multimodality Evaluator*

A.3.2 Files structure

Data structured as follows (in bold folders)

- **ac_airline_info**
    - IRPSO1. ac type IATA ICAO (e.g. ac_type_icao_iata_v0.1.csv)
    - IRPSO2. MTOW (e.g. mtow_v0.1.csv)
    - IRPSO3. WTC (e.g. wtc_v0.1.csv)
    - IRPSO4. airline IATA ICAO (e.g. iata_icao_airlines_codes_v1.1.csv)
    - IRPSO5. airline AO type (e.g. airline_icao_ao_type_v1.1.csv)
- **indicators**
    - O2. Indicators_tactical.csv
- **folder per case study** :
    - **id=xx** (ID of case study for Mercury)
        - case_study_config.toml → config file with information on the data used in simulation (includes paths to all files below)
        - **pax**
            - I4. pax itineraries
        - **schedules**
            - I1. flight_schedules
        - **gtfs** (e.g. gtfs_es_UIC_v1.0) – I2. GTFS rail
        - **airports**
            - I3. airport pax processes
        - **ground mobility**

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- I5. ground mobility

A.3.3 Files description

A3.3.1 Input Required to Process Strategic Output

IRPSO1. ac type IATA ICAO

- Used to generate input for tactical evaluator for the flight schedules
- Translate ac type form IATA to ICAO

Field	Type	Mandatory	Other info
icao_ac_code	string	yes	
iata_ac_code	string	yes	
model	string	no	Textual description of ac type

IRPSO2. MTOW

- Used to generate input for tactical evaluator for the flight schedules
- Provides MTOW for ac types

Field	Type	Mandatory	Other info
aircraft_type	string	yes	ICAO code
mtow	float	yes	Maximum take-off weight

IRPSO3. WTC

- Used to generate input for tactical evaluator for the flight schedules
- Provides WTC for ac types

Field	Type	Mandatory	Other info
ac_icao	string	yes	ICAO code
ac_eq	string	no	ICAO code (equivalent aircraft performance that could be used instead of ac_icao)
wake	string	yes	Character with wake turbulence category (J, H, M, L)

IRPSO4. airline IATA ICAO

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- Used to generate input for tactical evaluator for the flight schedules
- Translate IATA to ICAO airline operator codes

Field	Type	Mandatory	Other info
IATA_code	string	yes	IATA code of airline (2 letter code)
IACO_code	string	yes	ICAO code of airline (3 letter code)

IRPSO5. airline AO type

- Used to generate input for tactical evaluator for the flight schedules
- Information to AO type (FSC, LLC, REG, CHT) per airline operator

Field	Type	Mandatory	Other info
ICAO	string	yes	ICAO code of airline
AO_type	string	yes	Airline operator type (CHT, REG, FSC, LCC, XXX)

A3.3.2 Input files

I1. schedules.parquet

Field	Type	Mandatory	Other info
nid	int	yes	Unique id per flight
flight_id	int	yes	
callsign	string	yes	
airline	string	yes	
airline_type	string	yes	one of the type: REG, FSC, LCC, CHT
origin	string	yes	ICAO code
destination	string	yes	ICAO code
gcdistance	float	yes	great circle distance between origin and destination (NM)

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long_short_dist	string	yes	D if gcdistance < 810 else I
sobt	datetime	yes	yyyy-mm-dd hh:mm:ss (in UTC time)
sibt	datetime	yes	yyyy-mm-dd hh:mm:ss (in UTC time)
aircraft_type	string	yes	aircraft type
mtow	float	yes	maximum take-off weight (tons)
wk_tbl_cat	string	yes	wake turbulence category
registration	string	yes	aircraft registration
max_seats	int	yes	maximum number seats in aircraft
exclude	int	yes	By default set to 0 to all figths. If set to 1 then the flights are simulated but excluded from the computation of performance indicators (e.g. to exclude cargo flights)

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).
- Besides the standard GTFS files, a list of airport/rail station pairs defining the infrastructure transitions (airport_stations.parquet) is required in the followign format:

Field	Type	Mandatory	Other info
stop_id	string	yes	should be same format as GTFS rail (I2).
icao_id	string	yes	ICAO code for the airport

I3. airport pax processes

- Information on time it takes to process passengers through the airport (kerb-to-gate and gate-to-kerb) times.
- k2g_multimodal and g2k_multimodal, if provided, are used when computing the time it takes to transfer across layers. If not provided then the k2g and g2k are used.

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Field	Type	Mandatory	Other info
icao_id	string	yes	
pax_type	string	yes	
k2g	float	yes	mean value
g2k	float	yes	mean value
k2g_std	float	yes	standard deviation
g2k_std	float	yes	standard deviation
k2g_multimodal	float	no	If not provided, then k2g is used.
g2k_multimodal	float	no	If not provided, then g2k is used.

I4. pax itineraries

Field	Type	Mandatory	Other info
nid	int	yes	ID of pax group
pax	int	yes	number of pax in group
avg_fare	float	yes	average fare
ticket_type	string	yes	economy or flex
leg1	int	yes	Id of flight in leg1
leg2	int	no	Id of flight in leg2
leg3	int	no	Id of flight in leg3
rail_pre	string	no	trip_id of rail before leg1
rail_post	string	no	trip_id of rail after last (air) leg
source	string	no	description of data source (optional)

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gtfs_pre	string	no	filename of gtfs file where rail_pre can be found, e.g. gtfs_es.zip
gtfs_post	string	no	filename of gtfs file where rail_post can be found, e.g. gtfs_es.zip
origin1	string	no	stop_id of origin for pax using rail_pre
destination1	string	no	stop_id of destination for pax using rail_pre
origin2	string	no	stop_id of origin for pax using rail_post
destination2	string	no	stop_id of destination for pax using rail_post
type	string	no	one of flight, flight_flight, rail_flight, flight_rail

I5. ground mobility

Ground mobility specifies connecting times between rail stations and airports in connecting_times.parquet

Field	Type	Mandatory	Other info
origin	string	yes	stop_id/icao_id. Note that connection is unidirectional.
destination	string	yes	stop_id/icao_id
mean	float	yes	mean value
std	float	yes	standard deviation
pax_type	string	no	archetype
estimation_scale	float	yes	noise added to the times estimated using mean/std- representing difference between estimated and 'real' values

A3.3.3 Output files

O1. output_pax.csv

Field	Type	Info
scenario_id	int	

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case_study_id	int	
n_iter	int	
model_version	string	
id	int	
original_id	int	original id before cloning
n_pax	int	number of pax in group
original_n_pax	int	original number of pax in group
pax_type	string	
fare	float	input
origin_uid	int	
destination_uid	int	
time_at_gate	datetime	time of arrival to gate
compensation	float	calculated on pax arrival based on tot_arrival_delay
duty_of_care	float	calculated on pax boarding and arrival based on tot_arrival_delay
initial_sobt	datetime	sobt of leg1
final_sibt	datetime	sibt of last leg
initial_aobt	datetime	aobt of leg1
final_aibt	datetime	aibt of last leg
modified_itinerary	boolean	changed if pax is rebooked
tot_arrival_delay	float	calculated on pax arrival as self.agent.env.now - pax.final_sibt

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connecting_pax	boolean	if length of itinerary >1
final_destination_reached	boolean	calculated on pax arrival
multimodal	boolean	
missed_air2rail	boolean	if current itinerary does not match the original
missed_rail2air	boolean	if current itinerary does not match the original
ground_mobility_time	float	
gate2kerb_time	float	
kerb2gate_time	float	
rail_pre_sobt	datetime	
rail_pre_sibt	datetime	
rail_pre_aobt	datetime	
rail_pre_aibt	datetime	
rail_pre_delay	float	rail_pre_aibt - rail_pre_sibt
rail_post_sobt	datetime	
rail_post_sibt	datetime	
rail_post_aobt	datetime	
rail_post_aibt	datetime	
rail_post_delay	float	rail_post_aibt - rail_post_sibt
tot_journey_time	float	pax.final_aibt - pax.initial_aobt
tot_sch_journey_time	float	pax.final_sibt - pax.initial_sobt
leg1	int	flight id

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airport1	string	
airport2	string	
airline1	string	
leg2	int	
leg1_ct	float	pax.sobts[i+1] - pax.sibts[i]
leg1_sch	int	id of original leg1
airport1_sch	string	original airport
airport2_sch	string	
leg2_sch	int	
leg1_sch_ct	float	
airport3_sch	string	

O2. Indicators

The output files contain *indicators_tactical.csv* file and other files/images for the individual indicators. The specification of the indicators (such as units) can be found in the Digital Catalogue of Indicators: https://nommon.atlassian.net/wiki/external/MzA2ZTJmMjU5MDUyNDNlYzlkNDBmNTMwOTRlMDY4MGY

A.4 References for Annex A

[1] Delgado, L., Gurtner, G., Weiszer, M., Bolic, T. and Cook, A. (2023). Mercury: an open source platform for the evaluation of air transport mobility. SESAR Innovation Days 2023.

[2] Gurtner, G., Delgado, L., Tanner, G., and Bolic, T. (2024). Data sample for Mercury simulator (v3.1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11384379

[3] Mercury GitHub repository – https://github.com/UoW-ATM/Mercury

[4] TOML, Tom's Obvious Minimal Language. A config file format for humans. https://toml.io/en/

[5] Weiszer, M., Delgado, L. and Gurtner, G. (2024). Evaluation of passenger connections in air-rail multimodal operations. SESAR Innovation Days 2024

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