

# SIGN-AIR technological validation report (TVALR)

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## Abstract

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This document presents the results of the technological validation activities conducted for the SESAR solution SIGN-AIR, assessing its functional performance, digital maturity, and overall readiness across the planned validation exercises. It summarises the validation context, describes the executed scenarios, and reports the quantified outcomes for the DIGI and KPA indicators selected for SIGN-AIR and are not officially part of the SESAR performance framework yet such as Passenger Experience. The document also identifies limitations encountered during the campaign and discusses their impact on the completeness of the maturity assessment. Based on the collected evidence, the TVALR concludes on the current maturity level reached by the SIGN-AIR solution and provides recommendations for future validation steps, potential improvements, and avenues for further research and development.

## Authoring & approval

### Author(s) of the document

Organisation name	Date
ENAC	19/02/2026
UPC/SPA	01/05/2026

### Reviewed by

Organisation name	Date
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### Approved for submission to the SESAR 3 JU by

Organisation name	Date
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### Rejected by<sup>1</sup>

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<sup>1</sup> Representatives of the beneficiaries involved in the project

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# SIGN-AIR

IMPLEMENTED SYNERGIES, DATA SHARING CONTRACTS AND GOALS BETWEEN  
TRANSPORT MODES AND AIR TRANSPORTATION

# SIGN-AIR

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## Table of contents

Abstract .....	1
<b>1 Executive summary .....</b>	<b>7</b>
<b>2 Introduction.....</b>	<b>9</b>
2.1 Purpose of the document.....	9
2.2 Intended readership .....	9
2.3 Background .....	9
2.4 Structure of the document.....	9
2.5 Glossary of terms.....	10
2.6 List of acronyms .....	18
<b>3 Context of the technological validation .....</b>	<b>20</b>
3.1 SESAR technological solution SIGN-AIR: a summary.....	20
3.2 Summary of the technological validation plan .....	20
3.3 Deviations .....	45
<b>4 SESAR technological solution SIGN-AIR validation results .....</b>	<b>46</b>
4.1 Summary of SESAR technological solution SIGN-AIR validation results .....	46
4.2 Detailed analysis of SESAR technological solution validation results per validation objective .....	61
4.3 Confidence in the technological validation results .....	67
<b>5 Conclusions and recommendations.....</b>	<b>70</b>
5.1 Conclusions .....	70
5.2 Recommendations.....	73
<b>6 References .....</b>	<b>76</b>
6.1 Applicable documents .....	76
6.2 Reference documents .....	76
B.4.3 Conclusions on performance assessment .....	94

## List of tables

Table 1: glossary of terms .....	18
Table 2: list of acronyms.....	19
Table 3: SESAR technological solution addressed in the technological validation report .....	20

Table 4: technological validation assumptions overview.....	25
Table 5: summary of technological validation exercises results.....	61
Table 6: DIGI1 – TRL4 Exercise Results.....	62
Table 7: DIGI2 – TRL4 Exercise Results.....	62
Table 8: DIGI3 – TRL4 Exercise Results.....	63
Table 9: DIGI1 – TRL6 Exercise Results.....	64
Table 10: DIGI2 – TRL6 Exercise Results.....	64
Table 11: DIGI3 – TRL6 Exercise Results.....	64
Table 12: PAX – TRL4 Exercise Results.....	65
Table 13: PAX – TRL6 Exercise Results.....	66
Table 14: technological validation exercise #01 assumptions overview.....	79
Table 15: technological validation exercise #01 results.....	81
Table 16: technological validation exercise #02 assumptions overview.....	90
Table 17: technological validation exercise #02 results.....	91
Table 18: technological validation exercise #03 assumptions overview.....	98
Table 19: technological validation exercise #03 results.....	99
Table 20: technological validation exercise #04 assumptions overview.....	107
Table 21: technological validation exercise #04 results.....	108
Table 22: technological validation exercise #05 assumptions overview.....	115
Table 23: technological validation exercise #05 results.....	117
Table 24: technological validation exercise #06 assumptions overview.....	125
Table 25: technological validation exercise #06 results.....	128
Table 26: technological validation exercise #07 assumptions overview.....	137
Table 27: technological validation exercise #07 results.....	139
Table 28: technological validation exercise #08 assumptions overview.....	150
Table 29: technological validation exercise #08 results.....	152
Table 30: technological validation exercise #09.1 assumptions overview.....	161



Table 31: technological validation exercise #09.1 results ..... 163

Table 32: technological validation exercise #09.2 assumptions overview ..... 172

Table 33: technological validation exercise #09.2 results ..... 172

Table 34: technological validation exercise #10.2 objectives ..... 179

Table 35: technological validation exercise #10.2 assumptions overview ..... 180

Table 36: technological validation exercise #10.2 results ..... 181

**List of figures**

Figure 1: TRL4 Digitalization Achievement Pillar ..... 63

Figure 2: TRL6 Digitalization Achievement Pillar ..... 65

Figure 3: EXE1 results example ..... 84

Figure 4: EXE07 visualisation example ..... 142

# 1 Executive summary

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This Technological Validation Report (TVALR) presents the results of the validation activities conducted for the SESAR solution SIGN-AIR, assessing its functional behaviour, technological feasibility, and digital maturity across the planned validation exercises for TRL4 and TRL6. The purpose of the validation campaign was to verify that the SIGN-AIR components perform as required, support multimodal travel processes, and meet the functional expectations defined in the TS/IRS. The exercises applied a consistent methodological framework—based on DIGI indicators, KPAs, KPIs, and structured success criteria—to evaluate system correctness, usability, interoperability, performance, and robustness under both nominal and disrupted operational scenarios.

As explained in TVALP document, validation objectives are designed to assess the impact of SIGN-AIR Platform with regards to the KPA addressed: OBJ1 DIGITALISATION and OBJ2 PASSENGER EXPERIENCE with the relevant Estimated Performance Contributions (EPCs).

In addition to the assessment of EPCs, the technological validation of SIGN-AIR also addresses operational and technical objectives that are not fully captured by quantitative performance indicators. A couple of qualitative objectives have been included OBJ3 Situational Awareness and OBJ4 Technical Feasibility.

The validation campaign successfully executed all planned exercises except one TRL4 exercise, which was complementary to the core of SIGN-AIR solution. All remaining exercises ran without issues and confirmed the correct operation of itinerary generation, disruption-management logic, data transformation, contract negotiation mechanisms, and stakeholder interaction workflows. Results show that DIGI1, DIGI2 and DIGI3 are close to meeting Digitalisation maturity level 4 thresholds, For the completed exercises, multiple KPIs chooses related to the different objectives such as

- Passenger Experience (PAX): In the context of the SIGN-AIR platform, the Passenger Experience Key Performance Area (KPA) focuses on the system's ability to facilitate a seamless, reliable, and well-informed journey for travellers using multimodal transport. By bridging the information gap between air and ground operators, SIGN-AIR directly addresses the pain points of fragmented travel. Within the SIGN-AIR framework, enhancing the Passenger Experience refers to the platform's capacity to: i) Ensure journey continuity through the validation of Minimum Connection Times (MCT) and intermodal transfer conditions. ii) Provide transparency regarding passenger rights and contractual protections across different modes of transport. iii) Minimize uncertainty during disruptions by triggering automated, contract-compliant notifications and mitigation actions. For more information on the KPA of PAX please refer at TVALP v00.07.00, Annex 1: KPA-Multimodality and passenger experience and more specifically Table 68)
- Situational Awareness (SAW): Operational situational awareness in the context of SIGN-AIR refers to the ability of operational stakeholders to perceive, understand, and anticipate the state of intermodal operations based on data shared under predefined contractual obligations.
- Technical Feasibility (TECH): In the context of the SIGN-AIR solution the TECH is the ability to support end-to-end data-sharing functionalities, including catalogue creation and discovery, data sharing agreements and smart contract templating, negotiation, and signature processing. The validation will ensure that the platform can reliably integrate heterogeneous

data sources from multiple transport service providers (TSPs), maintain system performance under realistic load conditions, and enable secure, interoperable, and scalable interactions among stakeholders in a multimodal transport environment

Overall, the technological feasibility of the SIGN-AIR solution is confirmed. All executed exercises demonstrated stable performance, correct functional outputs, and no blocking issues. The system consistently produced valid multimodal connectivity calculations, reliable contract negotiation results, and coherent responses to both nominal and disrupted conditions. Performance levels observed in the laboratory and controlled environments are satisfactory for the current maturity stage, although real-world testing will be required to confirm scalability and operational responsiveness.

Based on the consolidated results, the SIGNAIR solution has reached a Digitalization maturity level consistent with Level 4,

Key recommendations for the way forward include:

- completing the missing validation exercise and reinforcing the assessment of DIGI1 (for example EXE10.1 that due to lack of time it was not possible to be performed) and envision exercises to assess the human enablers.
- refining the validation protocol and conducting an extended validation campaign to confirm repeatability and close remaining maturity gaps;
- improving the clarity and usability of specific system outputs (e.g., connectivity metrics) and enhancing mechanisms for disruption indication;
- expanding validation with additional users and operational stakeholders to strengthen usability and operational readiness;
- progressively shifting toward live, real-world testing, particularly for disruption management, negotiation processes, and multimodal connectivity performance.

These recommendations support the continued evolution of the SIGN-AIR solution and lay the groundwork for the next phase of research, validation, and operational integration.

## 2 Introduction

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### 2.1 Purpose of the document

This document provides the technological validation report for SOL 0375. It describes the results of technological validation exercises defined in D2.7 (TVALP) v00.07 and how they have been conducted and provides a set of relevant conclusions and recommendations.

### 2.2 Intended readership

The intended readership of this TVALR may be divided into two main categories:

- SESAR community (internal readers)
- External readers.

Referring to the first category, the primary intended readers of this document are the SESAR community, meaning SIGN-AIR partners who will use it as the baseline for the execution of the project as well as representatives of projects under the multimodality flagship such as MultiModX, MAIA, PRIAM and Travel Wise and representatives from the transversal projects of PEARL and AMPLE 3.

The second category, the external readers, might include the following potential readers, other than the ones participating in the SESAR Programme are the SIGN-AIR's stakeholders (i.e., Transport Service Providers, Mobility as a Services companies and DG move representatives) to understand the validation approach.

### 2.3 Background

SIGN-AIR project is the continuation/implementation of SYN+AIR (ID: 894116) exploratory research project of SESAR. SYN+AIR project created the Smart Contract Framework (SCF). SCF is a business process that defines data exchange rules among Transport Service Providers (e.g., airlines, railway operators etc.) (TSPs) that share the common goal (e.g., single ticketing, disruption management) of getting the passenger to the destination through a multimodal chain of trips. It provides a centralized hub for contracts management via a web platform that allows TSPs to create, modify, terminate, and validate signed contracts (both data sharing agreements and smart contracts). Most importantly, the storage of TSPs' data, and all the data sharing processes are executed outside of the platform.

### 2.4 Structure of the document

This TVALR is structured as follows. Section 3 recalls the context of the technological validation, presenting the developed solution and summarising the key elements of the validation plan, including any deviations recorded in the TVALP. Section 0 provides the validation results obtained throughout the planned exercises, starting with an overview of the validation objectives and followed by a detailed assessment of how each objective was validated, together with an indication of the confidence level associated with the results. Finally, Section 5 concludes on the maturity level reached by the SIGN-AIR

solution in relation to its degree of digitalisation and presents a set of recommendations for further improvement.

## 2.5 Glossary of terms

Term <sup>2</sup>	Definition	Source of the definition
Acceptable connection time (ACT) or Acceptable transfer time	Acceptable Connection Time (ACT): In the context of multimodal travel, such as transferring from a high-speed train to a flight, the Acceptable Connection Time (ACT) is the calculated duration that optimally balances the need for sufficient transfer time to ensure the passenger does not miss their flight and vice versa, while minimizing excessive waiting time at the airport. This duration is determined based on a combination of factors, including Minimum Transfer Time and Buffer Time.	Zhang, et al, (2023) Min, H., 1991. Benedyk et al, 2016
Action	A contractual obligation that must be respected by a Party in the event in which a Trigger is realized. Actions are specified in a smart contract.	D5.1 SYN+AIR
Airport CDM (A-CDM)	A-CDM is about partners working together and making decisions based on more accurate and higher quality information, where every bit of information has the exact same meaning for every partner involved. More efficient use of resources, and improved punctuality as well as predictability are the target results.	EUROCONTROL
Application programming interface (API)	Set of functions, protocols, parameters, and objects of different formats, used to create software that interfaces with the features or data of an external system or service	ISO/IEC/IEEE 26531 (2023)
Catalogue of Catalogues	The Catalogue of Catalogues is a Data Catalogue and Vocabulary concept that is derived from DCAT yet must be adapted to the needs of the project and the operation of the project's innovative graph database-based Knowledge Base implementation. A user will provide his/her available data categories in the Catalogue that allows the usage of other functionalities of SIGN-AIR platform such as the Matching Mechanism.	D5.1 SYN+AIR

<sup>2</sup> Additional glossary terms can be found at [https://www.sign-air.eu/?page\\_id=152](https://www.sign-air.eu/?page_id=152) which is a live glossary

<p>Combined ticket</p>	<p>G1.2: Combined ticket means a ticket or tickets for a multimodal journey representing separate transport contracts which are combined by a carrier/service provider or intermediary on its own initiative, and which are purchased by means of a single payment by the passenger. TSPs/service providers who select this goal should agree on restrictions related to the ticket validity (e.g., time and/or spatial limitations, etc.).</p> <p>Example: When passengers arrive at Geneva International Airport by plane, they can get their 80-minute tickets for Geneva Public Transport for free. The ticket machine for free tickets is located at the luggage retrieval hall and prints the free ticket without requirements or limitations upon the pressing of the button. Free ticket entitles a passenger to take an airport train (train from the airport to the centre), bus, tram etc. Tickets are transferable and limited to only 80 minutes.</p>	<p>Package Travel Directive</p>
<p>Common Taxonomy</p>	<p>The Common Taxonomy is defined as a set of elements and their relationships. It is used to capture and harmonise the information that is needed to be developed, integrated and maintained throughout the ATM lifecycle to streamline, accelerate and make more efficient the transition from R&amp;I to deployment</p>	<p>AMPLE3</p>
<p>Connectivity Index (SIGN-AIR)</p>	<p>The SIGN-AIR Connectivity Index is a metric designed to evaluate and optimize the integration of air and rail networks, focusing on timetable synchronization to improve operations and passenger experience. The goal is to ensure seamless transitions between modes of transport—minimizing waiting times and enhancing connectivity—through a series of well-defined indices that capture both spatial and temporal dimensions of multimodal travel.</p> <p>Key Components:</p> <p>Destination Index (Spatial Dimension):</p> <p>Measures the number of airports and train stations accessible from a hub via direct and indirect connections.</p> <p>Provides an overview of the geographical reach of the network.</p> <p>Frequency-Based Index (Spatial &amp; Temporal Dimension):</p>	<p>TS-IRS Annex 2</p>

	<p>Combines destination availability with the frequency of services (flights or trains) to those destinations.</p> <p>Higher frequency means more travel options, thereby increasing the connectivity index.</p> <p>Quality-Based Index (Temporal Dimension):</p> <p>Incorporates destination, frequency, and transfer time quality.</p> <p>Factors in the efficiency of indirect connections, measured by transfer times and routing, to gauge the ease of multimodal transfers.</p> <p>Transfer Time:</p> <p>Transfer time plays a critical role in the Quality-Based Index, including:</p> <p>Rail to Air: Sum of walking time between train station and airport terminal, processing time (check-in, baggage drop-off, security), and waiting time.</p> <p>Air to Rail: Sum of disembarking, passport control, baggage claim, walking time, and waiting for the next train.</p> <p>Price Index:</p> <p>In addition to connectivity, a Price Index is included to assess the overall quality of the multimodal service. This index factors in price, time of departure, transfer time, and in-vehicle time to provide a comprehensive measure of service efficiency and cost-effectiveness.</p> <p>Analytical Dimensions:</p> <p>The SIGN-AIR Connectivity Index can be broken down by:</p> <p>Time Intervals: Measuring the connectivity at different times of the day.</p> <p>Regional Segments: Evaluating connectivity across various regions (e.g., EU to North America).</p> <p>Daily Trends: Tracking daily changes in connectivity to detect patterns.</p> <p>Optimization through Sensitivity Analysis:</p> <p>A sensitivity analysis of transfer times can be performed on the Quality-Based Index to identify the</p>	
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	optimal synchronization of air-rail arrivals and departures. By adjusting transfer times, it becomes possible to minimize waiting time and/or maximize the number of connections, thereby improving overall system efficiency.	
Contract creation	<p>Contract signing process in SIGN-AIR:</p> <ul style="list-style-type: none"> <li>• The Onboarding step aims to collect from the user/TSP the available data categories and methods to obtain them. This will update a central catalogue of data that is used for the next steps.</li> <li>• The Discovery step aims to create a list of potential collaborators per TSP based on a chosen (by the user) objective of a data sharing agreement such as Single ticketing, Synchronization of timetables, Optimization of resources, increase in rides haring, etc.</li> <li>• The Negotiation step follows the demonstrated interest of two users in signing a contract. SIGN-AIR will provide a template for the Smart Contract and Data Sharing Agreement.</li> <li>• The Settlement step is the time when the Smart Contract and Data Sharing Agreement are signed and put into effect (monitored).</li> <li>• The Post Settlement step involves the publication of the contract meaning that a connection with Travel Companions is made, the triggers of the contract are monitored, and data are standardized (if needed) to be used in data exchanges. When needed, this step also includes the collection of the necessary personal data based on the traveler’s consent. Finally, this step involves processes for termination and modification of a Contract.</li> </ul>	SIGN-AIR Grant Agreement, part B.
Data sharing agreement	A DSA is an e-contract that defines the datasets that the Data Provider TSP makes available to the Data Consumer TSP and that sets out the terms and conditions for the use of such Data. By signing a data sharing agreement, the datasets (what) and the objective of sharing them (why) will be clear.	D5.1 SYN+AIR
Data sharing agreement goal	It is the chosen goal for achieving a data sharing agreement such as mobility package, single ticketing, synchronization of timetables, disruption management. The goal of a data sharing agreement may be detailed in a smart contract by specifying triggers and actions for TSPs.	D5.1 SYN+AIR
Discovery	Discovery process entails Matching Mechanism which will allow the identification of potential collaboration	D5.1 SYN+AIR

	opportunities given the data categories that a user defines in the Catalogue of Catalogues. This will be based on the Data Flow Diagrams (DFDs) that define the ontologies of the platform's innovative graph database.	D4.3 SYN+AIR
Governance-Driven Contract	A governance-driven contract is a Data Sharing Agreement (DSA) or Smart Contract (SC) whose structure, lifecycle, and execution are defined by a shared governance framework that explicitly specifies participating stakeholders' roles, rights, obligations, enforcement mechanisms, and policy objectives. Unlike ad-hoc or purely bilateral technical implementations, governance-driven contracts ensure that contractual behavior (such as access rights, triggers, actions, responsibility sharing, and remedies) is aligned with predefined multimodal transport governance goals, and that contract execution is consistently auditable, enforceable, and interoperable within the SIGN-AIR ecosystem	SIGN-AIR
Hub connectivity	Hub connectivity is the key metric for any hub airport, big or small. It measures the number of connecting flights that can be facilitated.  by the hub airport in question – considering a minimum and maximum connecting time and weighing the quality of connections by connecting times and detour involved.	ACI Europe
Information chain	The information chain comprises all the information given to the traveler before, during and after the trip.	UIC – IRS 10181
Mobility Package	Travel Service Providers can set up MaaS agreements among them (e.g., discounts for travelers) and to create Mobility packages that include services offered by different Travel Service Providers, for multiple modes.	D5.1 SYN+AIR
Passenger experience (multimodality)	Passenger experience in multimodality refers to the holistic perception and satisfaction of passengers as they transition between different transport modes (e.g., rail, air, bus) within a single journey. It encompasses various factors, including safety, and security, trip duration, transfer time, and comfort, all of which play critical roles in shaping the overall travel experience. Enhancing passenger satisfaction goes beyond just meeting these basic needs. It involves improving the quality of travel time itself. Once safety, reliability, and speed are ensured, passengers seek a pleasant, seamless journey, which includes well-designed waiting areas, clear signage, less waiting	Guo, Z., & Wilson, N. H. (2011). Assessing the cost of transfer inconvenience in public transport systems: A case study of the London Underground. <i>Transportation Research Part A: Policy and Practice</i> , 45(2), 91-104.  Janic, M. (2015). <i>Transport Systems: Modelling, Planning, and Evaluation</i> . CRC Press.

	<p>time, and amenities such as cafés and seating areas. In multimodal transport, especially with door-to-door journeys, reducing transfer times between modes and improving connectivity also play crucial roles.</p> <p>The main factors are listed below.</p> <p><b>Safety and Security:</b> Safety and security are paramount in ensuring a positive passenger experience across different transport modes. This includes both physical safety (i.e., the prevention of accidents and adherence to safety regulations) and the security of personal belongings and data. Passengers expect a high standard of safety and security across all modes to feel protected during their journey (Janic, 2015). Multimodal systems need to have integrated safety protocols and information sharing to maintain consistent standards.</p> <p><b>Trip Duration:</b> The total journey time is a crucial determinant of passenger satisfaction. Passengers tend to prefer multimodal systems that minimize overall travel time, including the time spent waiting between connections. Reducing unnecessary delays and streamlining transfers between modes, such as trains and airplanes, improves the overall efficiency of the journey (Rodrigue, Comtois, &amp; Slack, 2017).</p> <p><b>Acceptable Transfer Time:</b> Transfer time is a significant factor in multimodality, as long or poorly coordinated transfer times can increase stress and reduce satisfaction. Studies suggest that acceptable transfer times should strike a balance between allowing enough time for passengers to comfortably make their connection without being excessive (Guo &amp; Wilson, 2011). Multimodal systems are more effective when they reduce waiting times between connections while ensuring that passengers don't feel rushed.</p> <p><b>Comfort:</b> Comfort is a key aspect of multimodal travel, particularly on long journeys that require the use of different modes of transport. This includes the quality of seating, temperature control, noise levels, and the availability of amenities such as Wi-Fi, food services, and legroom (Vuchic, 2007). Ensuring passenger comfort across modes enhances the seamlessness of the journey.</p> <p><b>Information Availability:</b> Clear, accessible, and real-time information at transfer points significantly enhances passenger experience. Effective communication of delays, disruptions, or changes in</p>	<p>Jou, R. C. (2001). Modeling the impact of pre-trip information on commuters' mode-switching behavior. <i>Transportation Research Part A: Policy and Practice</i>, 35(10), 793-806.</p> <p>Rodrigue, J.-P., Comtois, C., &amp; Slack, B. (2017). <i>The Geography of Transport Systems</i> (4th ed.). Routledge.</p> <p>Vuchic, V. R. (2007). <i>Urban Transit Systems and Technology</i>. John Wiley &amp; Sons.</p>
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	<p>schedules helps reduce uncertainty and anxiety during multimodal journeys (Jou, 2001). Providing accurate, real-time updates through mobile apps or digital signage ensures that passengers can navigate their multimodal journey with confidence and have access to other provided services such as business lounge etc. In summary, passenger experience in multimodality is shaped by a combination of factors, including comfort, efficient trip duration, acceptable transfer times, safety, and the availability of real-time information. A well-coordinated and user-centric multimodal system improves the convenience and satisfaction of passengers, ultimately leading to increased usage of integrated transport solutions.</p>	
Smart Contract	<p>Based on the external smarter contract model This contract is composed of a legal part and a software part, to detail the Objective of one (or more) Data Sharing Agreement(s) by defining specific Triggers and Actions as well as the terms of Revenue Sharing and Responsibility Sharing.</p> <p>The external smart contract model refers to a dualistic contractual construction in which certain clauses are extracted from the traditional contract and, subsequently, transformed into code. The purpose of this setup is to automate certain conditional logic elements of the initial contract, so the required actions are executed automatically upon fulfilling the relevant conditions. The traditional contract is superior to the coded extract, which forms an external part of the contract, thereby relating to the smart contract code definition. The code merely represents an automated tool for execution, as opposed to a legal binding instrument as such.</p> <p>By signing a smart contract, the way operational obligations (actions) (how) and when to execute them (when) will be clear and continuity of data sharing will be secured with a proof statement.</p>	D5.1 SYN+AIR
Smart Contracts Framework (SCF)	<p>It is a business process that defines data exchange rules among TSPs that share the common goal of getting the passenger to the destination through a multimodal chain of trips. The SCF is facilitated by a web platform that allows TSPs to create, modify, cancel, and validate signed contracts (both data sharing agreements and smart contracts).</p>	D5.1 SYN+AIR
Travel Companion (TC) app	<p>It is platform, web and/or mobile app that allow a user to plan, book a trip from point A to point B, additionally these apps might provide auxiliary services to</p>	D5.1 SYN+AIR

	travellers such as cost calculations or re accommodation management.	
Travel Experience	<p>The travel experience encompasses the totality of a traveller’s interactions, perceptions, and feelings throughout their journey. This includes pre-trip planning and booking, the actual travel, and post-trip reflections. The travel experience is influenced by various factors, such as the quality of transportation, accommodations, activities, customer service, and the overall ease and enjoyment of the trip.</p> <p>Key Elements:</p> <ol style="list-style-type: none"> <li>1. Pre-Trip Planning: <ul style="list-style-type: none"> <li>○ Research: Gathering information about destinations, transportation options, and accommodations.</li> <li>○ Booking: Reserving transport, accommodation, and activities.</li> <li>○ Preparation: Planning itineraries, packing, and arranging necessary documents (e.g., visas, travel insurance).</li> </ul> </li> <li>2. Actual Travel: <ul style="list-style-type: none"> <li>○ Transportation: The quality and convenience of travel modes (e.g., flights, trains, buses, cars).</li> <li>○ Accommodations: The comfort, location, and service quality of lodging.</li> <li>○ Activities: Experiences and engagements at the destination (e.g., tours, dining, sightseeing).</li> <li>○ Interactions: Customer service interactions with transport providers, hotel staff, and service personnel.</li> <li>○ Safety and Comfort: Personal safety and overall comfort during the trip.</li> </ul> </li> <li>3. Post-Trip Reflections: <ul style="list-style-type: none"> <li>○ Memories: The lasting impressions and memories created during the trip.</li> <li>○ Feedback: Providing reviews and feedback based on the travel experience.</li> <li>○ Sharing experiences with others through stories, photos, and social media.</li> </ul> </li> </ol>	<p>Kozak, M., &amp; Baloglu, S. (2011). Managing and Marketing Tourist Destinations: Strategies to Gain a Competitive Edge. Routledge. (For insights on enhancing the travel experience through strategic destination management)</p>

Trigger	A condition whose realization entails the necessary execution by a Transport Service Provider of (a) determined operational action(s). Triggers are specified in a smart contract.	D5.1 SYN+AIR
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**Table 1: glossary of terms**

## 2.6 List of acronyms

Term	Definition
ATM	Air traffic management
CBA	Cost benefit analysis
DES	Digital European Sky
DMM	Disruption Management Module
DSA	Data Sharing Agreement
EPC	Estimated performance contribution
EXE	Exercise
FTS	Fast Time Simulation
GA	Grant agreement
ID	Identifier
KPA	Key performance area
KPI	Key performance indicator
LC	Low complexity
MC	Medium complexity
MMX	MultiModX
MTC	Minimum Connection Time
PAX	Passenger experience
SAW	Situational Awareness
SC	Smart Contract
SecAP	Security assessment plan

SESAR	Single European sky ATM research
S3JU	SESAR 3 Joint Undertaking
SPR- INTEROP/OSED	Safety and performance requirements - interoperability requirements / operational service and environment description
TA	Transversal area
TBD	To be determined
TECH	Technical Feasibility
TMA	Terminal manoeuvring area
TSP	Transport Service Provider
TT	Transitool
TRL	Technology Readiness Level
UC	Use case
VALP	Validation plan

**Table 2: list of acronyms**

## 3 Context of the technological validation

### 3.1 SESAR technological solution SIGN-AIR: a summary

SESAR technological solution ID	SESAR solution title	SESAR solution description	Enabler (from architecture)	ref. SESAR	Enabler coverage
SOL-0375	SIGN-AIR	Orchestration of data attributes for data sharing agreements (DSA) and Smart Contracts (SC) generation and monitoring between air and ground transport stakeholders to enhance multimodal collaboration.	AOC-ATM (FOC)-01853	(or)	Required Developed
			AOC-ATM (FOC)-01876	(or)	Required Developed
			AOC-ATM (FOC)-01877	(or)	Required Developed
			HUM-01855		Required Developed
			HUM-01878		Required Developed
			HUM-01879		Required Developed
			HUM-01880		Required Developed

Table 3: SESAR technological solution addressed in the technological validation report

### 3.2 Summary of the technological validation plan

#### 3.2.1 Technological validation plan purpose

The main goal of the exercises is to demonstrate the operational feasibility and mechanisms of data sharing between different stakeholders of multimodality. The presence of SIGN-AIR services could lead to an increase in collaboration between the stakeholders of public transportation (e.g., rail and bus) and air transportation (e.g., airports, airlines). Besides, it will be demonstrated the ability to have a monitoring mechanism of data sharing processes with the usage of smart contracts and blockchain.

The SIGN-AIR platform aims to facilitate the creation and monitoring of DSAs and/or SCs between various TSPs. While the overall process—covering onboarding, discovery, negotiation, settlement, and post-settlement—remains consistent across providers as part of the system’s core functionalities, the system can adapt by utilizing alternative process flows to achieve specific multimodality goals (G1-Mobility packages, G2-Synchronization of timetables and G3-Disruption management) as detailed in the TS-IRS section 2.7.1.)

Therefore, the scope of this section is to outline the key objectives:

- Recap the project goals (what the solution aims to achieve) and demonstrate the improvements resulting from the implementation of DSAs and SCs and the platform.
- Validate those technical requirements (e.g., reliability, confidentiality) and operational benefits (e.g., enhanced situational awareness for airlines, improved punctuality, better decision-making, cost savings) are achieved through the exercises.

### 3.2.2 Summary of technological validation objectives and success criteria

Refer to TVALP.

As presented in the TVALP section 4.3.2 OBJ2-Passenger Experience (PAX) was used as a Key Performance Area (KPA). According to PEARL champions the solution is allowed to develop and present metrics that will show the benefits of the solution. PAX is not a part of the SESAR Performance Framework of this wave, which focuses primarily on ATM-centric KPAs such as Safety, Capacity, Efficiency, Environment, and Cost-Effectiveness. However, as multimodal solutions become part of the SESAR's research agenda the need to assess the impact on the passenger experience has been identified. In the absence of a standardised methodology for PAX within the SESAR Performance Framework, a structured approach has been developed, drawing on the precedent established by the Digitalisation Companion Document (PJ19-W2 CI, Deliverable D.4.0.0002), which itself introduced a non-standard performance dimension (Digitalisation) into the SESAR assessment process using a comparable methodology.

The Digitalisation Companion Document demonstrates that it is both methodologically sound and programmatically accepted to introduce transversal KPAs, dimensions that cut across the standard performance framework, using qualitative, structured assessment methods. Specifically, the Digitalisation methodology relies heavily on qualitative YES/NO indicators at the secondary PI level.

This precedent confirms that binary qualitative assessment is a legitimate and endorsed tool within the SESAR performance assessment methodology for dimensions where continuous or quantitative measurement is not yet feasible, standardised, or available at the validation stage.

The following paragraphs detail the way PAX is approached and calculated in SIGN-AIR solution which was formerly presented at the PEARL champions.

The PAX KPA defined in focus areas (see Annex 1 of TVALP) such as PAX1 – Travel Time, PAX3 – Resilience, PAX4 – Ease, PAX6 – Robustness that address distinct aspects of the passenger journey and the structure is mirroring the multi-pillar structure of the Digitalisation framework (Digitisation, Connectivity, Data Sharing). The reason that we chose to mirror the DIGI KPA approach is that Digitalisation approach, which explicitly acknowledges the challenge of a "lack of baseline" and addresses this by using qualitative indicators that can be evaluated within a validation exercise.

YES/NO answers provide a clear, unambiguous, and reproducible basis for evaluation. Each answer is tied to a well-defined KPI with a specific calculation method and threshold:

KPA	Focus Area	Description	How to calculate	How to evaluate
<b>PAX1 – Travel Time</b> represents the efficiency of a passenger’s total journey across all travel modes. It encompasses the time from the start of the first leg to the end of the last leg, including transfers and waiting periods. The objective is to minimize total travel time and ensure competitive multimodal alternatives	PAX1.1: Total Travel Time	Total Travel Time for a given alternative refers to the travel time from starting point of 1st leg to ending point of last leg	Total time < 240 minutes	YES/NO
	PAX1.3: Ratio Total Travel Time vs transfer time	<b>Ratio Total Travel Time vs transfer time</b> (transfer time being the time to connect from one travel mode to another one and also includes the waiting periods)	Transfer Time/ Total Travel Time < 0,33	YES/NO
	PAX1.4: Ratio Total Travel Time vs fastest alternative	Ratio Total Travel Time vs fastest alternative: refers to a % comparing the total travel time (PAX1.1) of the alternative retained and the total travel time of the fastest alternative. It can be null if the retained alternative is the fastest one. (it is a benchmark between Origin & Destination)	TTT - TTTbest / TTT	YES/NO
<b>PAX3 – Resilience</b> reflects the ability of the multimodal travel chain to recover from disruptions and maintain service continuity. It assesses whether passengers have feasible tactical alternatives and whether their arrival	PAX3.2: Number of tactical alternatives	Number of tactical alternatives for a given Origin Destination pair	num > 1	YES/NO
	PAX3.4: Destination Arrival Time Adherence	Destination Arrival Time Adherence: measures the delay after the last leg arrival compared to planned arrival time after the last leg	Time arrival - Time arrival planned < minimum connection time	YES/NO

time adheres to planned schedules despite disturbances.				
<b>PAX4 - Ease</b> captures the simplicity and intuitiveness of a multimodal journey. It refers to the degree to which passengers can complete their trip with minimal effort, transfers, and confusion.	PAX4.1: Number of minimum legs of the total travel journey	Number of minimum legs of the total journey from 1st leg to last leg, including the number of connecting legs.	num <= 2	YES/NO
<b>PAX6 – Robustness</b> represents the structural stability and predictability of the transport offer under normal and perturbed conditions. It evaluates the availability of strategic options and the frequency of services in the multimodal network as well as potential replacement or extension of air network services due to environmental policies or disruptions.	PAX6.1: Number of strategic options	Number of strategic options for a given Origin Destination pair	Connectivity Index > 0,7	YES/NO
	PAX6.2: Strategic Frequency of service:	Strategic Frequency of service: number of services per hour during peak and off-peak time	num peak > 4 num off-peck > 2	YES/NO

This structure ensures that evaluations are grounded in objective criteria rather than subjective judgment. The YES/NO format aggregates multiple sub-indicators in a way that is easily interpretable by both technical and non-technical stakeholders and allows a clear determination of whether a solution improves PAX performance relative to a reference scenario. Using a binary assessment is proportionate to the level of precision achievable in a SESAR validation exercise. Introducing more

granular quantitative scoring (e.g., continuous indices) would imply a level of data accuracy and operational fidelity that is not warranted at the validation stage, and would risk producing false precision. The YES/NO approach, by contrast, provides results that are reliable, consistent across exercises, and directly comparable — exactly as the Digitalisation YES/NO sub-indicators enable comparison across SESAR3 Solutions. The use of YES/NO-based metrics for Passenger Experience (PAX) assessment in SESAR projects is methodologically justified on the following grounds:

1. Established precedent within the SESAR Performance Framework, where the Digitalisation Companion Document employs the same binary qualitative method for a comparable non-standard transversal KPA.
2. Alignment with validation constraints, acknowledging that early-TRL exercises cannot support the collection of live quantitative PAX data.
3. Expert endorsement by SESAR Joint Undertaking experts, providing formal programmatic legitimacy.
4. Objective threshold-based criteria underpinning each YES/NO answer, ensuring reproducibility and rigour.
5. Proportionality between measurement precision and data availability at the relevant validation stage.

### 3.2.3 Technological validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
1	Skilled human in the loop	All human actors will have the required skills to perform the validation exercises.	Skilled professionals with expertise in data sharing, ticketing and passengers' rights to ensure accurate execution of validation exercises.	Lack of expertise could result in errors in validation, misinterpretation of results, and ineffective decision-making.
2	Real data	Real data are expected to be available and usable.	Using real-world data ensures that validation exercises reflect	The absence of real data would reduce the credibility of validation outcomes and hinder system effectiveness.

			practical, real-life scenarios.	
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**Table 4: technological validation assumptions overview**

### 3.2.4 Technological validation exercises list

The validation process for the SIGN-AIR platform is structured across Technology Readiness Levels (TRLs) to ensure systematic development and rigorous testing of its capabilities, moving from initial laboratory assessments to full operational evaluations. Each TRL represents a critical stage in the maturation of the platform, helping to confirm that its features meet both technical specifications and real-world demands.

SIGN-AIR aims to streamline multimodal transport operations by facilitating seamless data sharing and service integration among Transport Service Providers (TSPs). To achieve this, the platform must undergo extensive testing across diverse scenarios and environments. Starting with controlled laboratory exercises (TRL4), where core functionalities like user onboarding and data catalogue creation, discovery and templating mechanism are assessed, the validation expands to simulation evaluations in relevant settings (TRL6) with exercises dedicated to BLQ and TPER.

Each validation level focuses on distinct aspects of the platform's development:

- TRL4 addresses initial functionality and design requirements under controlled conditions, providing foundational insights into the platform's architecture.
- TRL6 introduces more end-to-end interactions with representative data and partial operational conditions to refine scalability and interoperability.

#### 3.2.4.1 Validation exercises TRL4

EXE 1: Assessment of synchronization module (UC4, which is part of Scenario 1 in nominal conditions) in lab environment

EXE 2: Validation of DMM (which is part of Scenario 1 in lab environment in non-nominal conditions)

EXE 3: Assessment TT extension

EXE 4: Validation of Scenario 1 nominal (testing the whole process UC1, UC2 after we have checked EXE1)

EXE 5: Validation of Scenario 1 non-nominal conditions (testing the whole process UC1, UC2 after we have checked EXE2 that the external system works)

EXE 6: Validation of Scenario 2 in lab environment

EXE10.1: Synthetic schedules generator evtols

EXE10.2: Synthetic schedules generator seaplanes

**[EXE #1]**

Identifier	TVAL.01.1-SIGN-AIR-0375-TRL4
Title	Assessment of synchronization functionality of SYNC-REACT module
Description	<p>Validate external module of synchronization</p> <ul style="list-style-type: none"> <li>• Validate the digestion and graph generation process</li> <li>• Provide sample outputs (e.g., connectivity results) for review and discussion.</li> </ul> <p>Collect feedback on:</p> <ul style="list-style-type: none"> <li>• Accuracy and relevance of results.</li> <li>• Completeness of the data sources.</li> <li>• Suitability of the index for intended use cases.</li> </ul> <p>Focus:</p> <ul style="list-style-type: none"> <li>• Identifying conceptual flaws or gaps in algorithm design.</li> <li>• Understanding potential user needs and expectations.</li> <li>• Gaining early buy-ins from key stakeholders for enhancing access to the airport.</li> </ul> <p>This exercise is linked to the enablers:</p> <ol style="list-style-type: none"> <li>1) AOC-ATM (or FOC)-01853: Advanced route planning for the identification of appropriate air–rail connections</li> <li>2) AOC-ATM (or FOC)-01876: Assessment Airports accessibility via Intermodal Connectivity calculation</li> </ol>
KPA/TA addressed	<p>DIGI</p> <p>PAX</p> <p>SAW</p> <p>TECH</p>
Addressed performance contribution(s) expected	<p>DIGI1.3-DIGI1.6,</p> <p>DIGI2.2, DIGI2.8, DIGI2.9</p> <p>PAX1.1, PAX1.3, PAX1.4, PAX4.1, PAX6.1, PAX6.2,</p> <p>SAW1</p> <p>TECH1</p>
Maturity level	TRL4

T. validation technique	Lab environment
T. validation platform	Synchronization module
T. validation location	Barcelona
Start date	15/04/2025
End date	10/09/2025
Validation coordinator	UPC/SPA
Status	Completed
Dependencies	N/A

[EXE #1 Trace]

Linked Element Type	Route Network Management
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective(s)>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-PAX1, OBJ-SOL0375-TVALP-PAX4, OBJ-SOL0375-TVALP-PAX6, OBJ-SOL0375-TVALP-SAW1, OBJ-SOL0375-TVALP-TECH1

[EXE #2]

Identifier	TVAL.02.1-SIGN-AIR-0375-TRL4
Title	Validation of Disruption Management functionality of SYNC-REACT module towards increasing digitization elements
Description	This exercise focuses on validating the increased digitalization of multimodal operational data to ensure its accuracy, integrity, and standardization. A reference list of combined itineraries, including rail and flight legs in both directions will be used as input. Simulated delays of 15, 30, 45, 60, and 120 minutes will be introduced on the first leg of each trip to test how digital data processing handles disruptions. The exercise will evaluate the ingestion, processing, and graph generation of these itineraries, producing outputs that allow verification of data accuracy, completeness, and standardization. The goal is to identify conceptual flaws or gaps in the algorithms

	supporting digitalization and to gather early feedback on the suitability of the digital data processes for intended use cases.
KPA/TA addressed	DIGI, SAW, TECH
Addressed expected performance contribution(s)	DIGI1.1-DIGI1.6 DIG2.1-DIGI2.6 SAW2 TECH2
Maturity level	TRL4
T. validation technique	Laboratory test
T. validation platform	SIGN-AIR and SYNC-REACT module
T. validation location	Barcelona
Start date	25/08/2025
End date	30/10/2025
Validation coordinator	UPC/SPA
Status	Completed
Dependencies	EXE1

[EXE #2 Trace]

Linked Element Type	Disruption and Recovery Management
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-SAW2, OBJ-SOL0375-TVALP-TECH2

[EXE #3]

Identifier	TVAL.03.1-SIGN-AIR-0375-TRL4
Title	Assessment TT extension/data conversion

<p>Description</p>	<p>Validate the harmonization of IATA-SSIM and GTFS standards using TT platform. Mock-up Testing: Basic user interfaces and data flows are tested using mock-ups to gather feedback and validate fundamental concepts.</p> <p>Data Standards Review:</p> <ul style="list-style-type: none"> <li>• Collect sample datasets in IATA-SSIM and GTFS formats.</li> <li>• Define key transformation rules for harmonization, focusing on shared data attributes (e.g., schedules, locations, metadata fields).</li> <li>• Use tools like spreadsheets, Python scripts, or specialized ETL (Extract, Transform, Load) software to simulate the harmonization process.</li> </ul> <p>Simulation Model Creation:</p> <ul style="list-style-type: none"> <li>• Build a basic computational model (e.g., using Python, R, or MATLAB) to:</li> <li>• Map IATA-SSIM fields to equivalent GTFS fields.</li> <li>• Identify inconsistencies or mismatches (e.g., time zone formats, location identifiers).</li> <li>• Apply transformation rules to harmonize data.</li> </ul> <p>Validation Criteria:</p> <p>Define success metrics, such as:</p> <ul style="list-style-type: none"> <li>• Percentage of successfully harmonized records.</li> <li>• Identification of edge cases or unmappable fields.</li> <li>• Generate a sample output dataset and compare it against expected outcomes.</li> </ul> <p>Focus:</p> <ul style="list-style-type: none"> <li>• Data Flow Accuracy: Ensure that data can flow correctly from IATA-SSIM to GTFS standards and vice versa.</li> <li>• Harmonization Rules: Validate the logic of transformations (e.g., time zone conversion, schedule alignment, handling missing data).</li> </ul>
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	<ul style="list-style-type: none"> <li>• Error Handling: Identify potential mismatches and test how the system handles these cases.</li> <li>• Conceptual Feasibility: Confirm that the proposed harmonization approach is technically sound and scalable for larger datasets.</li> </ul>
KPA/TA addressed	Digitalization
Addressed expected performance contribution(s)	DIGI1.3, DIGI1.5, DIGI1.6 DIGI2.9
Maturity level	TRL4
T. validation technique	Laboratory test
T. validation platform	TT
T. validation location	Athens
Start date	01/02/2025
End date	30/05/2025
Validation coordinator	AETHON
Status	Completed
Dependencies	N/A

[EXE3 Trace]

Linked Element Type	Route Network Management
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2

[EXE #4]

Identifier	TVAL.04.1-SIGN-AIR-0375-TRL4
Title	Assessment of Scenario 1 without SYNC-REACT module

Description	<p>Validate that SIGN-AIR platform can</p> <ul style="list-style-type: none"> <li>• register end users and that they can create their data attributes catalogue,</li> <li>• identify potential collaborators for single ticketing,</li> <li>• negotiate the clauses of DSA and SC including the identification of potential combined intermodal itineraries using synchronization module and</li> <li>• sign the contracts for single ticketing.</li> </ul> <p>A set of invitations will be sent to different TSPs so they can create accounts in SIGN-AIR platform and assign roles for the end users of the platform. The onboarding functionality of SIGN-AIR will be tested, where end users and data catalogues are created in a simulated setup. This test would be lab-based involve testing SIGN-AIR's ability to manage user roles, access control, and catalogue data with a small group of pre-selected TSPs.</p> <p>Setup: Use an internal small group of test accounts to verify:</p> <ul style="list-style-type: none"> <li>• User registration flows.</li> <li>• Role assignment processes.</li> <li>• Creation and management of data catalogues.</li> <li>• Creation of single ticketing templates and negotiation interface</li> </ul> <p>Focus: Functional correctness, role-based access control, and cataloguing and access to the airport capabilities under controlled conditions.</p>
KPA/TA addressed	DIGI TECH
Addressed performance contribution(s)	<p>expected</p> <p>DIGI1.3, DIGI1.5, DIGI1.6</p> <p>DIGI2.2, DIGI2.8</p> <p>DIGI3.1, DIGI3.2</p> <p>TECH1</p>
Maturity level	TRL4
T. validation technique	Laboratory Test
T. validation platform	SIGN-AIR platform
T. validation location	Barcelona

Start date	02/06/2025
End date	30/07/2025
Validation coordinator	UPC/SPA
Status	Completed
Dependencies	N/A

[EXE #4 Trace]

Linked Element Type	Data Maintenance Officer
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-TECH1

[EXE #5]

Identifier	TVAL.05.1-SIGN-AIR-0375-TRL4
Title	Assessment of Scenario 1 with SYNC-REACT
Description	<p>A prerequisite is that EXE4 is completed.</p> <p>Validate that SIGN-AIR platform can receive, consume combined itineraries from SYNC-REACT module</p> <p>Setup: Use a small group of test accounts and datasets to verify:</p> <ul style="list-style-type: none"> <li>• SYNC-REACT usage</li> <li>• Negotiation of DSA and SCs clauses</li> </ul> <p>Focus: Functional correctness, role-based access control, and disruption management capabilities under controlled conditions.</p>
KPA/TA addressed	<p>DIGI</p> <p>PAX</p> <p>SAW</p> <p>TECH</p>

Addressed performance contribution(s)	expected DIGI1.3, DIGI1.4, DIGI1.5, DIGI1.6, DIGI2.2, DIGI2.8, DIGI2.9, DIGI3.1, DIGI3.2, DIGI3.3  PAX1.1, PAX1.3, PAX1.4, PAX4.1  SAW1  TECH1
Maturity level	TRL4
T. validation technique	Laboratory test
T. validation platform	SIGN-AIR
T. validation location	Barcelona
Start date	01/09/2025
End date	15/10/2025
Validation coordinator	UPC
Status	Completed
Dependencies	EXE2, EXE4

[EXE #5 Trace]

Linked Element Type	Data Maintenance Officer
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-PAX1, OBJ-SOL0375-TVALP-PAX4, OBJ-SOL0375-TVALP-SAW1, OBJ-SOL0375-TVALP-TECH1

[EXE #6]

Identifier	TVAL.06.1-SIGN-AIR-0375-TRL4
Title	Assessment of Scenario 2
Description	Validate that SIGN-AIR platform can

	<ul style="list-style-type: none"> <li>• Receive updates from SYNC-REACT Disruption Management Module</li> <li>• Execute the respective instance of Smart Contract with all triggers and actions for a specific origin-destination single ticketing contract.</li> </ul>
KPA/TA addressed	DIGI PAX SAW TECH
Addressed expected performance contribution(s)	DIGI1.3, DIGI1.4, DIGI1.5, DIGI1.6 DIGI2.2, DIGI2.3, DIGI2.4, DIGI2.8, DIGI2.9 DIGI3.1, DIGI3.2, DIGI3.3 PAX3.2, PAX6.1, PAX6.2 SAW2 TECH2
Maturity level	TRL4
T. validation technique	Laboratory Test
T. validation platform	SIGN-AIR platform and SYNC-REACT module
T. validation location	Barcelona
Start date	15/09/2025
End date	30/10/2025
Validation coordinator	UPC/SPA
Status	Completed
Dependencies	EXE2

[EXE #6 Trace]

Linked Element Type	Operations Control Officer
<SESAR Solution>	SOL0375

<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-PAX3, OBJ-SOL0375-TVALP-PAX6, OBJ-SOL0375-TVALP-SAW2, OBJ-SOL0375-TVALP-TECH2

**[EXE #10.1]<sup>3</sup>**

Identifier	TVAL.10.1-SIGN-AIR-0375-TRL4
Title	Synthetic schedules generator evtols
Description	<p>This exercise validates the use of a synthetic schedule generator for representing prospective eVTOL operations integrated with airport-centric passenger journeys, using Bologna Airport (BLQ) as a reference case. The exercise adapts and applies the SESAR eVTOL operational framework for airport–vertiport integration to assess whether eVTOL services can be coherently modelled and analyzed within the SIGN-AIR multimodal ecosystem (Gui et al, 2025<sup>4</sup></p> <p>The exercise evaluates the plausibility, consistency, and analytical usefulness of the synthetic eVTOL schedules for strategic connectivity and accessibility analysis, without asserting operational readiness. Expert judgment is used to assess whether the adapted framework assumptions (transfer times, frequencies, travel times, and network topology) are realistic and suitable for future multimodal planning, single ticketing concepts, and airport accessibility studies within SIGN-AIR.</p>
KPA/TA addressed	DIGI SAW
Addressed performance contribution(s)	DIGI1.5 DIGI2.9 SAW1

<sup>3</sup> This exercise is complementary to the core of SIGN-AIR solution, and they are created as evtols are not currently operational in European Skies, during the proposal time was expected that the implementation of the evtols would be launch during 2024 however due to regulatory they have face significant delays.

<sup>4</sup> Gui, X., Lebegue, J. C., & Delahaye, D. (2025). Regional scale multi modal service optimization for innovative air mobility. In Proceedings of SESAR Innovation Days 2025. SESAR Joint Undertaking. [https://www.sesarju.eu/sites/default/files/documents/sid/2025/papers/SIDs\\_2025\\_paper\\_20-final.pdf](https://www.sesarju.eu/sites/default/files/documents/sid/2025/papers/SIDs_2025_paper_20-final.pdf)

Maturity level	TRL4
T. validation technique	Expert Group (Judgment Analysis)
T. validation platform	SYNC-REACT module
T. validation location	Toulouse
Start date	15-01-2026
End date	20-02-2026
Validation coordinator	ENAC
Status	Cancelled
Dependencies	EXE1

[EXE #10.1Trace]

Linked Element Type	Route Network Management
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-SAW1

[EXE #10.2]<sup>5</sup>

Identifier	TVAL.10.2-SIGN-AIR-0375-TRL4
Title	Synthetic schedules generator seaplanes
Description	This exercise validates the synthetic seaplane schedule generator designed to model operations between the lake port of Ioannina and Corfu Island within the SIGN-AIR multimodal ecosystem. The focus is on ensuring that the generator produces plausible, consistent, and operationally coherent schedules that can be integrated with other transport modes for strategic planning, connectivity analysis, and multimodal itinerary generation.

<sup>5</sup> This exercise is complementary to the core of SIGN-AIR solution, and they are created as seaplanes are not currently operational in European Skies due to regulatory obstacles encountered to their operations and the implementations of water ports.

	<p>Key tasks include:</p> <p>Generation of seaplane schedules: Define departure and arrival times, daily/weekly frequencies, and estimated passenger demand for the Ioannina–Corfu route.</p> <p>Feasibility checks: Ensure generated schedules respect operational constraints, such as minimum turnarounds, transfer times, and airport/port accessibility.</p> <p>Integration with multimodal itineraries: Verify that the synthetic seaplane schedules can be combined with rail, bus, ferry, or air services to create realistic intermodal itineraries.</p> <p>Evaluation of schedule plausibility and coverage: Validate consistency, avoid conflicts (e.g., overlapping departures at the same port), and ensure representation of realistic operational scenarios.</p> <p>Support for downstream analysis: Provide datasets suitable for connectivity calculations, single-ticketing planning, and passenger experience studies.</p> <p>This exercise ensures that the seaplane schedule generator is ready for use in strategic simulations, scenario modeling, and multimodal planning exercises within SIGN-AIR, enabling assessment of new transport modes in intermodal networks.</p>
KPA/TA addressed	DIGI SAW
Addressed performance contribution(s)	<p>expected</p> <p>DIGI1.5 DIGI2.9 SAW1</p>
Maturity level	TRL4
T. validation technique	Expert Group (Judgment Analysis)
T. validation platform	SYNC-REACT module
T. validation location	Athens

Start date	15-01-2026
End date	20-02-2026
Validation coordinator	HSP
Status	On going
Dependencies	EXE1

[EXE #10.2 Trace]

Linked Element Type	Route Network Management
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-SAW1

### 3.2.4.2 Validation exercises TRL6

EXE 7: Validation of Scenario 1

EXE 8: Validation of Scenario 2

EXE 9.1: Validation of Travel Companion

EXE 9.2: Validation of TT (conversion of Bologna data)

[EXE #7]

Identifier	TVAL.07.1-SIGN-AIR-0375-TRL6
Title	Assessment of Scenario 1
Description	<p>Validate that SIGN-AIR platform can</p> <ul style="list-style-type: none"> <li>• register end users and that they can create their data attributes catalogue,</li> <li>• identify potential collaborators for single ticketing,</li> </ul> <p>A set of invitations will be sent to different TSPs so they can create accounts in SIGN-AIR platform and assign roles for the end users of the platform. The onboarding functionality of SIGN-AIR will be tested, where end users and data catalogues are created in a simulated setup. This test would be lab-based involve testing SIGN-</p>

	<p>AIR's ability to manage user roles, access control, and catalogue data with a small group of pre-selected TSPs.</p> <p>Setup: Use a small group of test accounts to verify:</p> <ul style="list-style-type: none"> <li>• User registration flows.</li> <li>• Role assignment processes.</li> <li>• Creation and management of data catalogues.</li> </ul> <p>Focus: Functional correctness, role-based access control, and cataloguing and access to the airport capabilities under controlled conditions.</p>
KPA/TA addressed	<p>DIGI</p> <p>PAX</p> <p>SAW</p> <p>TECH</p>
Addressed performance contribution(s)	<p>expected</p> <p>DIGI1.1-DIGI1.6, DIGI2.1, DIGI2.6, DIGI3.1, DIGI3.5</p> <p>PAX1.1, PAX1.3, PAX1.4, PAX4.1, PAX6.1, PAX6.2,</p> <p>SAW1</p> <p>TECH1</p>
Maturity level	TRL6
T. validation technique	RTS
T. validation platform	SIGN-AIR platform
T. validation location	Bologna
Start date	25/10/2025
End date	30/11/2025
Validation coordinator	UPC/SPA
Status	Completed
Dependencies	EXE4

[EXE #7 Trace]

Linked Element Type	Route Network Manager
<SESAR Solution>	SOL0375

<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-PAX1, OBJ-SOL0375-TVALP-PAX4, OBJ-SOL0375-TVALP-PAX6, OBJ-SOL0375-TVALP-SAW1, OBJ-SOL0375-TVALP-TECH1

**[EXE #8]**

Identifier	TVAL.08.1-SIGN-AIR-0375-TRL6
Title	Assessment of Scenario 2
Description	<p>Validate that SIGN-AIR platform can receive, consume and process triggers of disruptions from the external Disruption Management functionality and is able to activate the execution of SC signed related to the single ticketing</p> <p>A set of delays (15min, 30min, 45min, 60min, 90min and 120min) is introduced the Disruption Management functionality for some prefixed Origin and Destinations. SIGN-AIR platform, identifies the linked SC of a single ticketing signed between an airline and a highspeed rail operator is executed.</p> <p>Setup: Use a small group of test accounts and datasets to verify:</p> <p>SYNC-REACT usage</p> <p>Triggers of disruption</p> <p>Execution of SC of single ticketing</p> <p>Passenger can get a QR code for a fast track if his/her flight is affected and the MCT can be respected</p> <p>Focus: Functional correctness, role-based access control, and disruption management capabilities under controlled conditions.</p>
KPA/TA addressed	<p>DIGI</p> <p>PAX</p> <p>SAW</p> <p>TECH</p>
Addressed performance contribution(s)	<p>expected</p> <p>DIGI1.4, DIGI1.6</p> <p>DIGI2.2, DIGI2.4, DIGI2.5</p> <p>DIGI3.1, DIGI3.2, DIGI3.3, PAX3.2, PAX3.4, PAX6.1, PAX6.2,</p>

	SAW2 TECH2
Maturity level	TRL6
T. validation technique	RTS
T. validation platform	SIGN-AIR platform and SYNC+REACT module
T. validation location	Bologna
Start date	08/12/2025
End date	26/01/2025
Validation coordinator	UPC
Status	Completed
Dependencies	EXE7

[EXE #8 Trace]

Linked Element Type	Decision Support Officer
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-PAX3, OBJ-SOL0375-TVALP-PAX6, OBJ-SOL0375-TVALP-SAW2, OBJ-SOL0375-TVALP-TECH2

[EXE #9.1]

Identifier	TVAL.09.1-SIGN-AIR-0375-TRL6
Title	Validation of Travel Companion
Description	<p>This exercise validates the end-to-end integration between the SIGN-AIR platform backend and a Travel Companion (TC) application, focusing on passenger-facing facilitation in case of intermodal disruptions.</p> <p>The scope of the exercise is to confirm that, when a disruption occurs on the first leg of an intermodal journey (rail) and the Minimum</p>

	<p>Connection Time (MCT) is violated, the following chain of actions is correctly executed:</p> <ol style="list-style-type: none"> <li>1. The external Disruption Management functionality detects the disruption and notifies SIGN-AIR.</li> <li>2. SIGN-AIR identifies the affected intermodal Origin–Destination and the related single ticketing Smart Contract.</li> <li>3. The Smart Contract is executed, triggering predefined facilitation actions.</li> <li>4. A passenger-specific facilitation measure (e.g. fast-track access at the airport) is generated.</li> <li>5. The Travel Companion receives the information and presents it to the passengers in a timely and correct manner, including the generation and display of a QR code usable at the airport fast-track.</li> </ol>
KPA/TA addressed	<p>DIGI PAX SAW TECH</p>
Addressed performance contribution(s)	<p>expected DIGI2.2, DIGI2.4DIGI3.1, DIGI3.3 PAX3.4, PAX6.1, PAX6.2 SAW1, SAW2 TECH1, TECH2</p>
Maturity level	TRL6
T. validation technique	RTS
T. validation platform	SIGN-AIR platform and SYNC-REACT module
T. validation location	Barcelona
Start date	24/10/2025
End date	28/11/2025
Validation coordinator	TPER
Status	Completed
Dependencies	EXE7

[EXE #9 Trace]

Linked Element Type	Route Network Manager
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI2, OBJ-SOL0375-TVALP-DIGI3, OBJ-SOL0375-TVALP-PAX3, OBJ-SOL0375-TVALP-PAX6, OBJ-SOL0375-TVALP-SAW1, OBJ-SOL0375-TVALP-SAW2, OBJ-SOL0375-TVALP-TECH1, OBJ-SOL0375-TVALP-TECH2

[EXE #9.2]

Identifier	TVAL.09.2-SIGN-AIR-0375-TRL6
Title	Validation of TT (conversion of Bologna data)
Description	<p>This exercise validates the TT platform as an operationally representative solution for the harmonization and conversion of real multimodal timetable data (IATA-SSIM and GTFS) related to the Bologna catchment area, in a realistic simulated environment.</p> <p>Unlike earlier laboratory-only EXE3, this validation focuses on the execution of harmonization processes using real or near-real datasets, representative of operational conditions, and their readiness for integration with downstream systems (e.g. SYNC-REACT and SIGN-AIR).</p>
KPA/TA addressed	DIGI
Addressed performance contribution(s)	<p>expected DIGI1.3, DIGI1.5, DIGI1.6</p> <p>DIGI2.9</p>
Maturity level	TRL6
T. validation technique	RTS
T. validation platform	TT platform
T. validation location	Bologna
Start date	24/10/2025
End date	28/11/2025
Validation coordinator	AETHON

Status	Performed
Dependencies	EXE3

[EXE #9.2Trace]

Linked Element Type	Route Network Manager
<SESAR Solution>	SOL0375
<Project>	SIGN-AIR
<Validation Objective>	OBJ-SOL0375-TVALP-DIGI1, OBJ-SOL0375-TVALP-DIGI2

### 3.3 Deviations

#### 3.3.1 Deviations with respect to the SESAR 3 JU project handbook

N/A

#### 3.3.2 Deviations with respect to the technological validation plan (TVALP)

During the preparation and execution of the technological validation activities, one deviation occurred with respect to the original Technological Validation Plan (TVALP). Due to lack of time and after the accordance with the PO, exercise 10.1 was cancelled.

All other planned validation exercises were executed as foreseen and proceeded without issues or interruptions. The preparation, coordination, and execution phases remained aligned with the TVALP, and no additional deviations regarding scope, timelines, participants, datasets, or methodological approach were observed.

## 4 SESAR technological solution SIGN-AIR validation results

### 4.1 Summary of SESAR technological solution SIGN-AIR validation results

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL4-TVALP-DIGI1.001	End user (TSP1, TSP2...) is able to connect to the platform to fill and update a single digital database namely catalogue of catalogues by declaring data existence, quality, integrity, format, in laboratory environment.  PI tackled: DIGI1.1, DIGI1.2, DIGI1.3, DIGI1.4, DIGI1.6	DIGI1=96%	OK
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL4-TVALP-DIGI1.002	End user is able to upload additional data and get a more detailed list on the specific legs that can have an acceptable transfer time based on the SIGN-AIR connectivity index's algorithms, in laboratory environment.		

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			PI tackled: DIGI1.5, DIGI1.6		
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL4-TVALP-DIGI1.003	End user is able to create or validate its datasets for the standard formats of GTFS (if TSP is a public transport operator-bus, railway operator) or IATA SSIM (if TSP is an airline) in the case that it is necessary, in laboratory environment.  PI tackled: DIGI1.5		
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL6-TVALP-DIGI1.001	End user (TSP1, TSP2...) is able to connect to the platform to fill and update a single digital database namely catalogue of catalogues by declaring data existence, quality, integrity, format, in realistic simulated environment.  PI tackled: DIGI1.1, DIGI1.2, DIGI1.3, DIGI1.4, DIGI1.6	DIGI1=98%	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL6-TVALP-DIGI1.002	End user is able to upload additional data and get a more detailed list on the specific legs that can have an acceptable transfer time based on the SIGN-AIR connectivity index's algorithms, in realistic simulated environment.  PI tackled: DIGI1.5, DIGI1.6		
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	CRT-SOL0375-TRL6-TVALP-DIGI1.003	End user is able to create or validate its datasets for the standard formats of GTFS (if TSP is a public transport operator-bus, railway operator) or IATA SSIM (if TSP is an airline) in the case that it is necessary, in realistic simulated environment.  PI tackled: DIGI1.5		
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	CRT-SOL0375-TRL4-TVALP-DIGI2.001	End user (TSP1, TSP2, ...) is able to get a list of potential collaboration, linked with potential collaborators (based on his/her company data catalogue advancing the combination of data diversity), in	DIGI2=99%	- OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			laboratory environment  PI tackled: DIGI2		
		CRT-SOL0375-TRL4-TVALP-DIGI2.002	End user (TSP1, TSP2...) is able to invite for collaboration another company of the list, in laboratory environment  PI tackled: DIGI2		
		CRT-SOL0375-TRL4-TVALP-DIGI2.003	End user (TSP1, TSP2...) is able to access to data from collaborators to issue a Mobility Package in case of nominal situation, in laboratory environment  PI tackled: DIGI2.2, DIGI2.4, DIGI2.5, DIGI2.6		
		CRT-SOL0375-TRL6-TVALP-DIGI2.001	End user (TSP1, TSP2, ...) is able to get a list of potential collaboration, linked with potential collaborators (based on his/her company data catalogue advancing the combination of data diversity), in	DIGI2=88%	Partially

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			realistic simulated environment.  PI tackled: DIGI2		
		CRT-SOL0375-TRL6-TVALP-DIGI2.002	End user (TSP1, TSP2...) is able to invite for collaboration another company of the list, in realistic simulated environment.  PI tackled: DIGI2		
		CRT-SOL0375-TRL6-TVALP-DIGI2.003	End user (TSP1, TSP2...) is able to access to data from collaborators to issue a Mobility Package (e.g., single ticketing) in case of nominal situation, in realistic simulated environment.  PI tackled: DIGI2.2, DIGI2.4, DIGI2.5, DIGI2.6		
		CRT-SOL0375-TRL6-TVALP-DIGI2.004	End user (TSP1, TSP2...) is able to access to data from collaborators to issue a Mobility Package in case of disruption management, in realistic simulated environment.		

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			PI tackled: DIGI2.2, DIGI2.4, DIGI2.5, DIGI2.6		
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	CRT-SOL0375-TRL4-TVALP-DIGI3.001	End users (TSP1 and TSP2) is able to use the DSA template and SC template (if applicable via the multimodality goal selected) and make offers and counteroffers (negotiate) for reaching an agreement, in laboratory environment  PI tackled: DIGI3.1, DIGI3.2, DIGI3.5	DIGI3=100%	OK
		CRT-SOL0375-TRL4-TVALP-DIGI3.002	End users (TSP1 and TSP2) is able to get the prerequisites for connecting their systems for the data sharing processes agreed in the DSA and SC, in laboratory environment  PI tackled: DIGI3.3, DIGI3.4, DIGI3.5		

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		CRT-SOL0375-TRL4-TVALP-DIGI3.003	End users (TSP1 and TSP2) is able to sign the DSA and test the SC if applicable and then sign it, in laboratory environment  PI tackled: DIGI3.5		
		CRT-SOL0375-TRL6-TVALP-DIGI3.001	End users (TSP1 and TSP2) is able to use the DSA template and SC template (if applicable via the multimodality goal selected) and make offers and counteroffers (negotiate) for reaching an agreement, in realistic simulated environment.  PI tackled: DIGI3.1, DIGI3.2, DIGI3.5	DIGI3=100%	OK
		CRT-SOL0375-TRL6-TVALP-DIGI3.002	End users (TSP1 and TSP2) is able to get the prerequisites for connecting their systems for the data sharing processes agreed in the DSA and SC, in realistic simulated environment.  PI tackled: DIGI3.3, DIGI3.4, DIGI3.5		

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		CRT-SOL0375-TRL6-TVALP-DIGI3.003	End users (TSP1 and TSP2) is able to sign the DSA and test the SC if applicable and then sign it, in realistic simulated environment.  PI tackled: DIGI3.5		
OBJ-SOL0375-TVALP-PAX1	SIGN AIR contribution to PAX1-Travel Time	CRT-SOL0375-TRL4-TVALP-PAX1.001	End user (TSP1, TSP2..) (airline high speed railway operator) is able to select multimodal itineraries with high quality index and create a single ticket, having an itinerary with acceptable transfer time and responsibility sharing.  PI: PAX1.1, PAX1.3, PAX1.4	PAX1=yes	OK
		CRT-SOL0375-TRL6-TVALP-PAX1.001	End user (TSP1, TSP2..) (airline high speed railway operator) is able to select multimodal itineraries with high quality index and create a single ticket, having an itinerary with acceptable transfer time and responsibility sharing.	PAX1=yes	Partially OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			PI: PAX1.1, PAX1.3, PAX1.4		
OBJ-SOL0375-TVALP-PAX3	SIGN AIR contribution to PAX3-Resilience	CRT-SOL0375-TRL4-TVALP-PAX3.001	End user (TSP1, TSP2..) (airport and speed railway operator) is able to calculate rail-air, air-rail, air-air total connectivity index for the hub airport with strategic and/or tactical data and perform different shorting.  PI: PAX3.2,	PAX3=yes	Partially OK
		CRT-SOL0375-TRL6-TVALP-PAX3.001	End user (TSP1, TSP2..) (airport and speed railway operator) is able to calculate rail-air, air-rail, air-air total connectivity index for the hub airport with strategic and/or tactical data and perform different shorting.  PI: PAX3.2,	PAX3=yes	Partially OK
OBJ-SOL0375-TVALP-PAX4	SIGN AIR contribution to PAX4-Ease	CRT-SOL0375-TRL4-	End user (TSP1, TSP2..) (airline and highspeed rail operator) to select	PAX4=yes	

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		TVALP-PAX4.001	itineraries with 1 transfer  PI: PAX4.1		
		CRT-SOL0375-TRL6-TVALP-PAX4.001	End user (TSP1, TSP2..) (airline and highspeed rail operator) to select itineraries with 1 transfer  PI: PAX4.1	PAX4=yes	
OBJ-SOL0375-TVALP-PAX6	SIGN AIR contribution to PAX6-Robustness	CRT-SOL0375-TRL4-TVALP-PAX6.001	End user (TSP1 and TSP2) is able to update strategical planning with tactical data at SIGN-AIR's disruption module. SYNC-REACT calculates the updated rail-air air-rail indices. Detecting changes that affect previous Origin-Destinations connectivity and their MCT is not respected.  PI: PAX6.1, PAX6.2,	PAX6=yes	
		CRT-SOL0375-TRL6-TVALP-PAX6.001	End user (TSP1 and TSP2) is able to update strategical planning with tactical data at SIGN-AIR's disruption module. SYNC-REACT calculates the updated rail-air air-rail indices. Detecting changes that	PAX6=yes	

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			affect previous Origin-Destinations connectivity and their MCT is not respected.  PI: PAX6.1, PAX6.2,		
OBJ-SOL0375-TVALP-SAW1	Planning and selection of feasible and attractive intermodal itineraries	CRT-SOL0375-TRL4-TVALP-SAW1.001	End users (TSP1, TSP2...) are able to upload schedules in SYNC-REACT module, provided a specific format	SAW1 confirmed	OK
		CRT-SOL0375-TRL4-TVALP-SAW1.002	End users (TSP1, TSP2...) are able to identify feasible and attractive multimodal itineraries automatically via SYNC-REACT	SAW1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-SAW1.001	End users (TSP1, TSP2...) are able to upload schedules in SYNC-REACT module, provided a specific format	SAW1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-SAW1.002	End users (TSP1, TSP2...) are able to identify feasible and attractive multimodal itineraries automatically via SYNC-REACT and automatically insert them to the relative SC.	SAW1 confirmed	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
OBJ-SOL0375-TVALP-SAW2	Situational Awareness for intermodal itineraries targeting the contractual aspects of data sharing	CRT-SOL0375-TRL4-TVALP-SAW2.001	End users are able to define mitigation options/recommendations per hub, using the platform to propose and negotiate alternatives.	SAW2 confirmed	OK
		CRT-SOL0375-TRL4-TVALP-SAW2.002	End users can insert a disruption at a specific transport leg, including updated ETA. The system evaluates its impact on hubs and automatically executes the corresponding Smart Contract conditions if MCT or other contractual obligations are not respected.	SAW2 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-SAW2.001	End users are able to define mitigation options/recommendations per hub, using the platform to propose and negotiate alternatives in a realistic simulated environment	SAW2 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-SAW2.002	End users can insert a disruption at a specific transport leg, including updated ETA. The system evaluates its impact on hubs and automatically executes	SAW2 confirmed	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
			the corresponding Smart Contract conditions if MCT or other contractual obligations are not respected.		
OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	CRT-SOL0375-TRL4-TVALP-TECH1.001	Platform allows onboarding of a new Transport Service Provider (TSP), including registration of the company, its legal representative, and authorized users, ensuring proper role assignment and authentication	TECH1 confirmed	OK
		CRT-SOL0375-TRL4-TVALP-TECH1.002	Platform enforces access control and ensures data integrity, such that only authorized users can view, modify, or sign DSAs/SCs	TECH1 confirmed	OK
		CRT-SOL0375-TRL4-TVALP-TECH1.003	Platform enables discoverability of datasets in the catalogue, allowing users to locate and select the data sources to be included in DSAs before any contract templating or negotiation	TECH1 confirmed	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		CRT-SOL0375-TRL4-TVALP-TECH1.004	Platform allows the identification of DSAs and SC template and proposes TSPs that can be invited to negotiate data sharing and the rules of data sharing (revenue and responsibility sharing)	TECH1 confirmed	OK
		CRT-SOL0375-TRL4-TVALP-TECH1.005	Users can read, negotiate and sign DSAs and SC in high-fidelity simulation environments	TECH1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH1.001	Platform allows onboarding of a new Transport Service Provider (TSP), including registration of the company, its legal representative, and authorized users, ensuring proper role assignment and authentication	TECH1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH1.002	Platform enforces access control and ensures data integrity, such that only authorized users can view, modify, or sign DSAs/SCs	TECH1 confirmed	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		CRT-SOL0375-TRL6-TVALP-TECH1.003	Platform enables discoverability of datasets in the catalogue, allowing users to locate and select the data sources to be included in DSAs before any contract templating or negotiation	TECH1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH1.004	Platform allows the identification of DSAs and SC template and proposes TSPs that can be invited to negotiate data sharing and the rules of data sharing (revenue and responsibility sharing)	TECH1 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH1.005	Users can read, negotiate and sign DSAs and SC in high-fidelity simulation environments	TECH1 confirmed	OK
OBJ-SOL0375-TVALP-TECH2	Monitoring the contractual aspects of data sharing of signed DSAs and SCs	CRT-SOL0375-TRL4-TVALP-TECH2.001	Platform identifies and executes SC correctly based on predefined conditions (if and then)	TECH2 confirmed	OK

SESAR technological solution technological validation objective ID	SESAR technological solution technological validation objective title	SESAR technological solution success criterion ID	SESAR technological solution success criterion	SESAR technological solution technological validation results	SESAR technological solution technological validation objective status
		CRT-SOL0375-TRL4-TVALP-TECH2.002	Platform monitors data-sharing flows in real-time and ensures SC compliance	TECH2 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH2.003	Platform executes SC workflows reliably under high load and disruptions.	TECH2 confirmed	OK
		CRT-SOL0375-TRL6-TVALP-TECH2.004	Platform monitors SC and data flows under realistic operational scenarios and multiple users	TECH2 confirmed	OK

Table 5: summary of technological validation exercises results

## 4.2 Detailed analysis of SESAR technological solution validation results per validation objective

### 4.2.1 DIGI Results corresponding to TRL4

Calculation is performed in accordance with the rules defined in the methodology. For the assessment, values of 0, 0.5, and 1 were assigned respectively to NOK, partially OK, and OK. The value of each pillar (digitisation, connectivity, and data sharing) has been calculated as follows:

$$DIGI1 = \frac{\sum_{i=1}^n (w_i \cdot DIGI1_i)}{\sum_{i=1}^n w_i} = 96\%$$

$$DIGI2 = \frac{\sum_{i=1}^n (w_i \cdot DIGI2_i)}{\sum_{i=1}^n w_i} = 99\%$$

$$DIGI3 = \frac{\sum_{i=1}^n (w_i \cdot DIGI3_i)}{\sum_{i=1}^n w_i} = 100\%$$

For each pillar, only the secondary PI's that are directly applicable to each exercise are considered, while those highlighted in grey in the tables below have been excluded, as they are not relevant to the corresponding validation activities.

Weight	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
	1	1	2	2	2	1	
EXE1			1	1	1	1	1,00
EXE2	1	0,5	1	1	1	0,5	0,89
EXE3			1		1	0,5	0,90
EXE4			1		1	1	1,00
EXE5			1	1	1	1	1,00
EXE6			1	1	1	1	1,00
							<b>0,96</b>

Table 6: DIGI1 – TRL4 Exercise Results

Weight	Connectivity Pillar										DIGI2	
	DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
	2	2	2	1	1	1	1	1	2	1	2	
EXE1		1						1	1			1,00
EXE2	1	1	1	0,89	0,8	0,9						0,95
EXE3									1			1,00
EXE4		1						1				1,00
EXE5		1						1	1			1,00
EXE6		1	1	0,73				1	1			0,97
												<b>0,99</b>

Table 7: DIGI2 – TRL4 Exercise Results

Weight	Data Sharing Pillar						DIGI3	
	DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6		DIGI3.7
	1	1	2	1	2	1	1	
EXE1								
EXE2								
EXE3								
EXE4	1	1						1,00
EXE5	1	1	1					1,00
EXE6	1	1	1					1,00
								<b>1,00</b>

Table 8: DIGI3 – TRL4 Exercise Results

### TRL4: DIGITALIZATION ACHIEVEMENT PER PILLAR

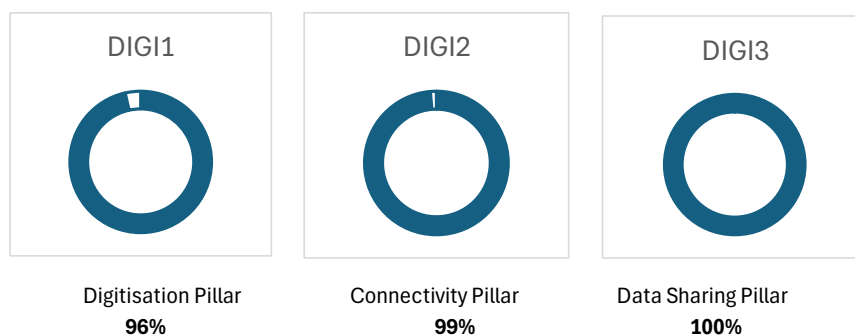


Figure 1: TRL4 Digitalization Achievement Pillar

According to the results shown in Figure 1, it is possible to calculate the SESAR Digitalisation Index for TRL4.

$$SESAR\ Digitalisation\ Index\ (SDI) = \frac{DIGI1 + DIGI2 + DIGI3}{3} = 98\%$$

#### 4.2.2 DIGI Results corresponding to TRL6

Following the same structure as per TRL4, the exercises have evaluated only those secondary PI's that affected on each case.

Weight	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
	1	1	2	2	2	1	
EXE7	1	1	1	1	1	0,5	0,94
EXE8				1		1	1,00
EXE9.1							
EXE9.2			1		1	1	1,00
							<b>0,98</b>

Table 9: DIGI1 – TRL6 Exercise Results

Connectivity Pillar											DIGI2
DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10	DIGI2.11	
2	2	2	1	1	1	1	1	2	1	2	
1	0,5		0,6	0,75	0,72						0,73
	1		0,78	0,56							0,83
	1		0,89								0,96
							1				1,00
											<b>0,88</b>

Table 10: DIGI2 – TRL6 Exercise Results

Data Sharing Pillar							DIGI3
DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7	
1	1	2	1	2	1	1	
1	1	1		1			1,00
1	1	1					1,00
1		1					1,00
							<b>1,00</b>

Table 11: DIGI3 – TRL6 Exercise Results

### TRL6: DIGITALIZATION ACHIEVEMENT PER PILLAR

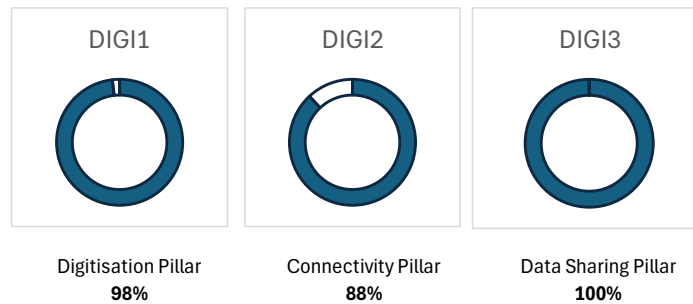


Figure 2: TRL6 Digitalization Achievement Pillar

Based on Figure 2 the TRL6 Digitalization Index can be calculated:

$$SESAR\ Digitalisation\ Index\ (SDI) = \frac{DIGI1 + DIGI2 + DIGI3}{3} = 95\%$$

#### 4.2.3 PAX Results corresponding to TRL4

Due to non-standards for PAX analysis in previous projects, it has been defined as yes/no validation for this specific solution.

	<b>PAX1.1:</b> Total Travel Time	<b>PAX1.3:</b> Ratio Total Travel Time vs transfer time	<b>PAX1.4:</b> Ratio Total Travel Time vs fastest alternative	<b>PAX3.2:</b> Number of tactical alternatives	<b>PAX3.4:</b> Destination Arrival Time Adherence	<b>PAX4.1:</b> Number of minimum legs of the total travel journey	<b>PAX6.1:</b> Number of strategic options	<b>PAX6.2:</b> Strategic Frequency of service:
<b>EXE 1</b>	yes	yes	yes			yes	yes	yes
<b>EXE 2</b>				yes			yes	yes
<b>EXE 5</b>	yes	yes	yes			yes		
<b>EXE 6</b>				yes			yes	yes

Table 12: PAX – TRL4 Exercise Results

#### 4.2.4 PAX Results corresponding to TRL6

Same structure has been followed for TRL6.

	<b>PAX1.1:</b> Total Travel Time	<b>PAX1.3:</b> Ratio Total Travel Time vs transfer time	<b>PAX1.4:</b> Ratio Total Travel Time vs fastest alternative	<b>PAX3.2:</b> Number of tactical alternatives	<b>PAX3.4:</b> Destination Arrival Time Adherence	<b>PAX4.1:</b> Number of minimum legs of the total travel journey	<b>PAX6.1:</b> Number of strategic options	<b>PAX6.2:</b> Strategic Frequency of service:
<b>EXE 7</b>	yes	yes	yes			yes	yes	yes
<b>EXE 8</b>				yes	yes		yes	yes
<b>EXE 9.1</b>					yes		yes	yes

Table 13: PAX – TRL6 Exercise Results

#### 4.2.5 SAW results

The validation exercises confirmed that the SIGN-AIR platform successfully achieves both situational awareness objectives.

Regarding intermodal journey planning, the exercises validated that the platform enables the planning of feasible and attractive intermodal itineraries, providing stakeholders with a consistent and contract-compliant view of available multimodal connections and the contractual commitments governing each transport leg.

About disruption management, the exercises validated that the platform correctly consumes disruption alerts, evaluates their impact on intermodal hubs, and enables contractually governed responses through the automated execution of Smart Contracts. This demonstrated the platform's ability to propagate disruption awareness across transport modes, assessing Minimum Connecting Time compliance and violations, and trigger the appropriate mitigation actions within the boundaries defined by the applicable Data Sharing Agreements and Smart Contracts.

Together, these outcomes confirm that the SIGN-AIR platform delivers the shared, timely, and contract-compliant operational picture required to support situational awareness across all involved Transport Service Providers, under both nominal and disrupted conditions, and in full alignment with the system-level definition of situational awareness adopted for this validation.

#### 4.2.6 TECH results

The validation exercises confirmed that the SIGN-AIR platform technically supports end-to-end, contractually governed data-sharing workflows by successfully creating Data Sharing Agreements and Smart Contracts tailored to specific predefined multimodal configurations, and by reliably executing Smart Contracts and monitoring data-sharing flows under both nominal and disrupted conditions.

This outcome directly validates the technical feasibility objective, demonstrating that the platform correctly manages the full contract lifecycle — from creation and negotiation through to settlement, execution, and post-settlement monitoring — while maintaining stable data exchanges and reliable

interoperability with external modules including timetable synchronisation, disruption management systems, and the Travel Companion application. The exercises thus confirm that the SIGN-AIR platform provides the secure, scalable, and interoperable technical foundation required to support multimodal stakeholder interactions in both routine and disrupted operational contexts.

## 4.3 Confidence in the technological validation results

### 4.3.1 Limitations of technological validation results

The potential for extrapolating the technological validation results to a larger geographical scope—such as ECAC—remains promising but subject to important limitations stemming from the design and assumptions of the individual exercises. Several exercises (notably 1, 7) were conducted under nominal conditions, without accounting for last-minute schedule updates or operational irregularities, which constrains the generalisability of the results to real-world environments where disruptions are frequent. In exercises 1, 2, and 3, the focus on verifying correctness, completeness, and consistency ensured solid functional validation, yet variability in data quality (e.g. heterogeneous public rail datasets) and the reliance on controlled, repeatable runs limit confidence when scaling to broader operational contexts. Multiple exercises (4–6) were performed under controlled laboratory conditions, excluding live data exchange, full system scalability, real-time performance, or large-volume transaction handling—factors essential for ECAC-wide deployment. Exercises involving disruption management (8, 9.1) considered only first-leg disruptions, did not account for cascading operational effects, and simulated passenger behaviour rather than observing real interactions, introducing further constraints on extrapolation. Exercises 9.1 and 9.2 also operated with small participant groups or region-specific contexts (e.g., Bologna catchment area), limiting representativeness. While exercise 10.2 demonstrated strong feasibility for integrating seaplane schedules and highlighted the benefits of timetable alignment in rural or decentralised regions, the use of synthetic data and the inability to model real operational constraints (e.g., fleet availability, staffing, minimum passenger loads) restricts the significance of these findings for broader adoption.

Across all exercises, the assumptions recorded in Section 3.2.3 — controlled environments, defined operational roles, scoped geographical contexts, representative data — reflect deliberate and appropriate design choices for a TRL4/TRL6 campaign. They bound the current extrapolation rather than invalidating it. The technological concepts validated show clear, well-evidenced potential for ECAC-wide applicability: the platform has successfully exchanged data across multiple independent TSPs operating under different contractual and technical frameworks, generated correct and complete multimodal itineraries from heterogeneous real-world datasets, executed Smart Contract-based disruption management logic with consistent results, and demonstrated connectivity assessment capabilities that align with expert judgment across diverse route configurations. These achievements, delivered across ten exercises involving partners from multiple countries and transport modes, establish that the core value proposition of SIGN-AIR is sound and replicable. The SIGN-AIR platform has established the functional coherence and architectural robustness needed to advance to full-scale, real-data validation with confidence.

### 4.3.2 Quality of technological validation exercises results

The quality of the results obtained across the technological validation exercises is high, underpinned by rigorous accuracy checks, independent verification, and consistently positive feedback from a broad

range of participating stakeholders. In Exercise 1, the correctness of generated itineraries was explicitly validated by three independent partners — ENAC, UB-FTTE, and BLQ — using heterogeneous real-world datasets from railway operators, airlines, and airports. The convergence of independent assessments on positive outcomes is a strong quality indicator, confirming that the platform produces reliable and accurate results even when operating on diverse, non-homogeneous input data.

In Exercises 2, 3, 4, 5, 6, 7, 9.1, and 9.2, the involvement of multiple operators across different organisational contexts enabled systematic cross-checking of system behaviour; the uniformly positive stakeholder assessments across this broad set of exercises demonstrate that SIGN-AIR performs robustly and consistently, not just in isolated conditions but across a representative range of operational profiles. Exercise 8, while conducted with a single operator pair, delivered focused and actionable insights that complement the broader campaign findings. In Exercise 9.2, the quality of the results was validated in the most meaningful way possible: the demonstration to a wider external stakeholder audience was sufficiently convincing to lead directly to the implementation of outcomes in the ROGER Travel Companion, providing independent, real-world endorsement of the platform's reliability and applicability.

Exercise 10.2 delivered particularly strong quality evidence: connectivity indices not only matched expert rankings but correctly identified optimal flight pairs and assigned low scores to infeasible multimodal routes, confirming that the system's analytical outputs meet and, in some cases, exceed expert judgment thresholds. Taken together, the quality of the SIGN-AIR validation results is fully consistent with the expectations of a TRL4/TRL6 campaign. The exercise design — using heterogeneous real-world data, engaging independent verifiers, and testing across multiple partners and contexts — was precisely calibrated to produce results that are reliable, cross-validated, and fit for the purpose of supporting the solution's advancement to the next maturity phase

### **4.3.3 Significance of technological validation exercises results**

Across the campaign, Exercises 1, 2, 4, 5, and 6 tested the platform with different consortium partners (independent variable: organizational context), Exercise 3 introduced heterogeneous user skill levels (independent variable: user proficiency), and Exercise 7 stressed the system with 40 concurrent users (independent variable: load), collectively supporting technical validation under varied yet realistic operating conditions representative of the targeted environment (consortium-led operations and mixed user profiles).. Exercise 10.2 further provided a baseline for integrating seaplane flights using synthetic data (independent variable: mode integration/data realism), which is informative for feasibility but not statistically confirmatory until replicated with real operational schedules to control for unobserved factors.

The key distinction between TRL4 and TRL6 is the environment in which validation takes place: TRL4 validates technology in a laboratory setting, while TRL6 validates it in a relevant operational environment. The SIGN-AIR exercises were not conducted in a generic laboratory — they involved real and synthetic TSP data from multiple independent organisations across different countries, real users with varying skill profiles, real contractual and governance frameworks instantiated through Smart Contracts, and a live demonstration that led directly to operational implementation in the ROGER Travel Companion. These are the hallmarks of validation in a relevant environment, consistent with TRL6.

The range of independent variables covered and the consistency of results across them confirm that the platform's behaviour is stable, repeatable, and reliable across the conditions that characterise its target deployment context. This is not indicative evidence — it is the substantive demonstration of operational relevance that TRL6 requires. The next phase will expand the scale and data realism of that demonstration; it will confirm and extend TRL6 findings, not establish them for the first time.

## 5 Conclusions and recommendations

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### 5.1 Conclusions

#### 5.1.1 Conclusions on SESAR technological solution maturity

The TRL6 maturity assessment confirms that SIGN-AIR has met the main criteria required to substantiate its TRL6 status. All critical operational, system, programme, transition, and standards criteria are fully achieved: the solution architecture has been finalised and agreed in the TS/IRS; a high-fidelity prototype implementing all significant technical requirements has been produced and validated on an Industrial Based Platform representative of a small airport operational environment; technical feasibility has been confirmed through Exercises 7 and 8; the most significant operational use cases — single ticket creation and Smart Contract monitoring — have been fulfilled in a target operational environment; representative stakeholders from airports, airlines, railway operators, and IT and legal domains contributed to requirements refinement; and all enablers have been updated and approved in Stellar and OrbusInfinity. The performance assessment confirms that the DIGI and PAX KPAs have been assessed in line with initial forecasts, the SecRAM risk assessment has been correctly applied with 18 low-level risks and zero medium or high risks, and no transition issues have been identified provided that multimodal passenger rights legislation progresses as expected. The reviewer comments that require attention — on requirements traceability (SYS.TRL6.6), DIGI calculation values (PER.TRL6.2), security requirement granularity (PER.TRL6.5), CBA completeness (PER.TRL6.3), and the validation maturity concern KID\_00593 (VAL.TRL6.1) — are all specific, addressable documentation and refinement points that do not call into question the underlying technical achievement.

However, there are some blocking and non-blocking items for fully reaching TRL6 review reflect, in part, the inherent difficulty of applying a framework designed around conventional SESAR solutions to a multimodal concept that the ATM world has not yet fully operationalised. SIGN-AIR is a solution that is technically ready, operating ahead of the ecosystem maturity it requires, nevertheless needs to be tested against the Human enablers that were identified which is not common for a technological solution and the solution has to be further validated in non-nominal or degraded situations. These might arise from disruptions such as loss of connectivity with external systems, hardware failures, data loss, etc. Validation scenarios must specifically address these degraded situations, assessing both the effectiveness of recovery procedures and the impact on the overall solution.

#### 5.1.2 Conclusions on concept clarification

Although SIGN-AIR has been categorised as a technological solution rather than an ATM solution, its operational viability is fundamentally dependent on the human roles identified in the solution's enabler list. The roles of Data Maintenance Officer, Operations Control Officer, Flight Schedule Planner, Route Network Manager, and Decision Support Officer each carry responsibilities that align with specific decision-making speeds, training profiles, and information needs that a system alone cannot replicate. This alignment is not incidental but structural: the nature of the SIGN-AIR solution means that accountability cannot be transferred to an automated system. Responsibility for decisions that affect passengers, contractual obligations, and brand reputation must remain with human actors. The Data Maintenance Officer, for instance, must navigate the corporate politics surrounding data

ownership, recognising that data is not merely a collection of bits and bytes but a source of organisational power — one that is often managed in a decentralised manner across companies where the contextual meaning behind data attributes is as critical as the data itself. The Passenger Service Desk role similarly requires empathic prioritisation and ethically informed trade-offs that automated systems are not equipped to make, particularly to avoid bias, privacy violations, and ageism in passenger-facing decisions. The Flight Schedule Planner role further illustrates this point: while algorithms and AI tools may propose options, final scheduling decisions involve brand alignment and commercial responsibility that require a human decision-maker who can be held accountable if outcomes fail to deliver the expected results. Likewise, updating passenger notifications is not merely a technical task but an exercise in managing human behaviour and legal liability. For these reasons, validation exercises specifically targeting the identified human enablers must be designed and executed as a priority in the next phase, even though this is atypical for a solution classified as technological in nature.

Beyond the human dimension, the operational feasibility of SIGN-AIR is also contingent on a broader set of real-world operational factors that the current validation exercises have only partially addressed. The exercises conducted were performed under controlled or synthetic conditions using simulated datasets and pre-defined scenarios that, by design, do not fully capture the complexity of live operations. Operational feasibility in real-world deployments requires validation under non-nominal and degraded conditions, including scenarios involving loss of connectivity with external systems, hardware failures, data latency, and cascading disruptions across multimodal chains. Furthermore, the reliance on synthetic and limited datasets means that the solution's behaviour under high data volumes, diverse data quality levels, or conflicting inputs from heterogeneous Travel Service Providers has not yet been fully assessed. Future validation activities should therefore be designed to test the solution with larger, more diverse, and operationally representative datasets, and to simulate the organisational interoperability challenges that arise when multiple TSPs with differing data governance models, IT architectures, and contractual frameworks interact through the platform. Additionally, the scalability of the Smart Contracts Framework under concurrent negotiation and execution loads, and the resilience of the Knowledge Base under real operational traffic, remain important open questions whose resolution will be necessary to substantiate full operational feasibility ahead of the next maturity phase.

### 5.1.3 Conclusions on technological feasibility

Across all technological validation activities, the results consistently confirm the technological feasibility of the SESAR technological solution. Exercises 1 through 9.2 were all successfully executed without any issues or operational disruptions, indicating that the implemented functionalities behave as specified and can reliably support the intended multimodal processes under the tested conditions. The successful progression of each exercise—from basic ingestion and transformation functions to more complex negotiation, disruption-handling, and user-interaction workflows—shows that the solution meets its core functional requirements in a stable and predictable manner. Furthermore, exercise 10.2 reinforced this conclusion by demonstrating that the SIGN-AIR components were able to generate feasible multimodal travel plans using synthetic seaplane data while correctly identifying expert-defined limitations and avoiding irrational outputs. This confirms not only the correctness of the implemented algorithms but also their capacity to process diverse datasets and support new mobility options in line with the SESAR technological objectives. Overall, the suite of exercises provides

strong evidence that the technological solution is mature at functional level, with all tested capabilities operating as required and demonstrating readiness for further, larger-scale validation.

#### 5.1.4 Conclusions on performance assessment

The performance assessment for the **Digitalisation KPA** confirms that SIGN-AIR meets the validation targets defined for both TRL4 and TRL6. Across the three Digitalisation pillars, the solution achieved a DIGI1 (Digitisation) score of 96%, a DIGI2 (Connectivity) score of 99%, and a DIGI3 (Data Sharing) score of 100% at TRL4, yielding an overall SESAR Digitalisation Index (SDI) of 98%. At TRL6, the SDI reached 95%, with DIGI1 at the lower end due to partial ratings on indicators where synthetic data was used and where specific format constraints (IATA SSIM, GTFS) limited full scoring. These results confirm that the solution is close to or at Digitalisation maturity level 4 thresholds across all three pillars, with the remaining gap in DIGI1 attributable to the absence of exercise EXE10.1 and the reliance on synthetic rather than live operational data, both of which are addressable in the next validation phase rather than indicative of architectural deficiencies.

The **Passenger Experience KPA**, while not yet part of the formal SESAR Performance Framework, was assessed using a structured YES/NO binary methodology developed specifically for SIGN-AIR and methodologically grounded in the precedent established by the Digitalisation Companion Document. Across both TRL4 and TRL6 exercises, all assessed PAX focus areas — PAX1 (Travel Time), PAX3 (Resilience), PAX4 (Ease), and PAX6 (Robustness) — were validated as meeting their defined success criteria. The platform demonstrated the ability to support journey continuity through Minimum Connection Time validation, to provide passengers with transparent contractual protections across modes, and to minimise uncertainty during disruptions through automated, contract-compliant notifications and mitigation actions. These results substantiate the solution's contribution to a more seamless and reliable multimodal passenger experience, with the caveat that the assessment was conducted under controlled conditions and that real-world quantitative confirmation will be required in future validation stages.

From a **security** perspective, the SIGN-AIR solution was assessed through a SecRAM risk analysis, which identified 18 risks, all classified at low level. No medium or high risks were identified, confirming that the current architecture presents no critical security concerns at the validated maturity stage. This outcome is consistent with the solution's design principles, which incorporate role-based access control, audit trail mechanisms, and contractually governed data exchange to ensure that sensitive operational and commercial data shared between Transport Service Providers is handled within clearly defined boundaries. It should be noted that the SecRAM assessment reflects the current scope and scale of validation; as the solution progresses towards live operational environments with greater data volumes, more TSP participants, and real contractual relationships, a refreshed security assessment will be necessary to confirm that the risk profile remains acceptable under increased operational exposure.

## 5.2 Recommendations

### 5.2.1 Recommendations for next phase

The outcomes of the technological validation confirm that SIGN-AIR has reached the functional maturity required for its current TRL stage, while also surfacing a clear set of priorities that must be addressed to consolidate results and advance to the next phase. These recommendations are organised around three complementary areas:

- strengthening the existing validation evidence,
- extending validation to human and operational dimensions, and
- improving the solution itself in preparation for larger-scale trials.

Regarding the consolidation of existing validation evidence, several targeted improvements are needed to address gaps in the current exercise set as follows:

1. The missing exercise EXE10.1, which could not be performed due to time constraints and after the agreement with the Program Manager, its execution would reinforce the DIG11 assessment and confirm repeatability of results.
2. System outputs such as total connectivity and Origin-Destination connectivity indices should be made self-explanatory to support independent evaluation and reduce reliance on expert interpretation (EXE1). However, SYNC-REACT module was developed to support SIGN-AIR platform and multimodality goals of synchronization and single ticketing but is not the core component of SIGN-AIR platform as the combined itineraries can be introduced manually by the TSPs.
3. Disruption-handling mechanisms should be refined with a clearer and more intuitive method for introducing and representing disruptions (EXE2). This aspect will be further enhanced at Travel Wise project.
4. Delay injection should be automated to replace the current manual approach, improving reliability and reducing operator workload (EXE6). This aspect will be further enhanced at Travel Wise project as for SIGN-AIR the objective of this exercise was to trigger and execute the SC and not to test the conditions.
5. The negotiation and synchronisation workflows require more explicit documentation and additional validation time, with involvement of a broader stakeholder group including legal experts and airline ticketing personnel (EXE7).
6. Integration of final legal documentation into negotiation processes should also be formalised (EXE4), and prototype interfaces should be tested with real end-users unfamiliar with the project to validate dataset entry and parameter-setting procedures (EXE4 and EXE5).
7. Disruption-management Smart Contract logic should be fully incorporated into forthcoming trials to complete the validation of that module (exercise 9.1).

Beyond technical consolidation, the most critical recommendation for the next phase is the design and execution of validation exercises specifically targeting the human enablers identified for the solution. As discussed in the conclusions on concept clarification, SIGN-AIR's operational viability depends on roles whose decision-making responsibilities cannot be automated or transferred to the system. Validation exercises must be developed to assess how these roles interact with the platform under realistic operational conditions, examining training needs, information usability, decision support adequacy, and accountability mechanisms. This is an atypical requirement for a solution classified as technological, but it is a necessary one given the nature of the solution and the accountability stakes involved. Alongside this, future activities should move from controlled and real time simulation environments towards live, real-world validation sessions using authentic operational data and genuine TSP participation, in order to confirm that the performance results observed to date hold under the full complexity of real operations, including data quality variability, organisational heterogeneity, and non-nominal conditions.

## 5.2.2 Recommendations on regulation and standardisation initiatives

SIGN-AIR solution does not request an amendment or a new standard. However, it is recommended that its end users agreed to use the commonly used standards of their sector for the data attributes of their catalogues such as NETEX, IATA SSIM, GTFS etc. Additionally, we have encountered issues on the validity and quality of data in certain cases such as of the GTFS from different countries.

The regulatory need of updating the multimodal passengers' rights has been identified documented in D2.13, TS-IRS and at STELLAR.

## 5.2.3 Recommendations for future R&I activities

Some recommendations point to new research avenues that extend beyond the scope of the current SESAR technological solution and are therefore suitable for future research and innovation programmes.

Scalability and high-concurrency Smart Contract execution. The current validation involved 20 TSP pairs and sequential for the creation of contracts but not monitoring functionality of the platform. A critical open research question is how the Smart Contracts Framework behaves under high-concurrency conditions where multiple SC are executed on the same time. Future R&I should investigate the architectural and algorithmic requirements for scalable contract execution, including conflict resolution mechanisms, transaction throughput optimization, and the performance of blockchain-based audit trails under real operational load.

Advanced and cascading disruption management. The disruption scenarios validated to date were limited to first-leg delays of predefined durations under controlled conditions. Real-world multimodal disruptions are rarely isolated: they cascade across legs, modes, and contractual obligations in ways that are difficult to predict and model. Future research should develop more sophisticated disruption propagation models, explore automated delay generation from live data feeds, and investigate how Smart Contracts can be designed to handle cascading and simultaneous disruptions while preserving passenger rights and TSP accountability across the full multimodal chain.

Integration of emerging and non-conventional transport modes. Exercise 10.2 demonstrated the feasibility of incorporating synthetic seaplane schedules into the SIGN-AIR ecosystem, opening a

broader research agenda around non-conventional and emerging mobility modes — including Advanced Air Mobility (AAM), autonomous ground vehicles, and on-demand services. Future R&I should investigate the data standards, contractual frameworks, and connectivity modelling approaches needed to integrate these modes into multimodal networks, and should conduct live validation campaigns using real operational data to move beyond the synthetic constraints of the current assessment.

AI-assisted decision support and predictive analytics. The current SIGN-AIR platform is primarily reactive, it responds to defined triggers and executes pre-agreed contractual logic. A natural evolution for future research is the introduction of AI and machine learning capabilities to support predictive and proactive functions: anticipating MCT violations before they occur, recommending contract renegotiation based on historical patterns, or dynamically proposing itinerary alternatives based on predicted disruption trajectories. This line of research would also need to address the accountability and explainability requirements identified in the conclusions on concept clarification, ensuring that AI-generated proposals remain subject to human decision-making authority.

Data governance, sovereignty, and organizational interoperability. The validation confirmed that data sharing between heterogeneous TSPs is technically feasible within the SIGN-AIR framework, but the organizational and governance dimensions of that sharing were not deeply explored. Future R&I should investigate how data sovereignty requirements, GDPR obligations, and the varying data governance maturity levels across TSPs affect the practical deployment of the platform. This includes research into federated data architecture, differential privacy mechanisms, and the design of data sharing agreements that are robust to the corporate politics and decentralized data management structures that characterize real transport organizations.

Standardization of the Passenger Experience KPA. The PAX assessment methodology developed for SIGN-AIR fills a gap in the current SESAR Performance Framework, which does not yet include a standardised approach for measuring passenger experience in multimodal contexts. Future R&I should work towards the formalization of this methodology into a reusable, validated framework — potentially building on the precedent already established by the Digitalisation Companion Document — so that future multimodal solutions within and beyond the SESAR programme can assess their PAX contributions on a consistent and comparable basis.

Environmental and sustainability impact assessment. Multimodal integration has the potential to shift passenger demand from less sustainable to more “sustainable” modes, for example, replacing short-haul air legs with rail connections. The current validation did not include an environmental KPA, but the connectivity improvements demonstrated by SIGN-AIR are directly relevant to EU sustainability goals and the objectives of the European Green Deal. Future R&I should develop methodologies for quantifying the modal shift and carbon reduction potential of multimodal platforms like SIGN-AIR, positioning this line of research within the broader SESAR and Horizon Europe sustainability agenda.

## 5.2.4 Recommendations for updating SESAR architecture

No further recommendation for updated SESAR architecture as SIGN-AIR solution has been taken into account at the development of future multimodal solution of SESAR such as Travel Wise.

## 6 References

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### 6.1 Applicable documents

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

- [1] SESAR 3 JU Project Handbook – Programme Execution Framework

### 6.2 Reference documents

- [2] D2.10.1 DES HE SESAR solution SIGN-AIR TS/IRS– Part I. v00.07.00
- [3] SESAR DES HE SESAR TVALR template
- [4] DES HE requirements and validation / demonstration guidelines
- [5] DES Performance Framework - Digitalisation Companion Document
- [6] DES Performance Framework

## Appendix A Technological validation exercise #01 report

This appendix provides the details of the technological validation TVAL.01.1-SIGN-AIR-0375-TRL4.

### A.1 Summary of the technological validation exercise #01 plan

The scope of this exercise is to validate the ingestion (“digestion”) of multimodal transport timetables (air, high-speed rail or regional rail), ensuring semantic and syntactic alignment of data across modes, and enable accurate multimodal itinerary selection and travel-time calculation in a laboratory environment.

#### A.1.1 Technological validation exercise description and scope

The technological validation exercise assesses the SYNC-REACT module’s capability to semantically align multimodal (rail–air and air–rail) timetables and generate reliable connectivity outputs. These outputs provide essential inputs for negotiating single-ticketing DSAs and SCs and constitute a prerequisite for intermodal disruption management based on Minimum Connection Time (MCT).

##### Scope and covered TS/IRS use cases

- Ingestion and normalisation of heterogeneous formats (IATA SSIM for air, GTFS for rail/bus)
- Semantic alignment of key data elements (timetables, station/airport codes, transfer points)
- Syntactic alignment (standardised schemas, units, time formats)
- Automated computation of multimodal itineraries and rail–air / air–rail connectivity indices at hub airports

##### Key validation objectives

1. Successful digestion and normalisation of multimodal timetable data
2. Correct semantic matching of arrival–departure pairs across modes
3. Error-free syntactic integration of heterogeneous datasets
4. Accurate calculation of feasible intermodal connections considering transfer times and connectivity indices
5. Demonstration of correctness, completeness, and interoperability in a controlled lab environment using sample/synthetic data (TRL 4)

**Reference vs Solution Scenario** Reference: TSPs operate in isolation; timetables are only available via public websites or non-standard formats (PDF/CSV); no semantic alignment or automated rail–air itinerary ranking exists. Solution: TSPs upload GTFS/SSIM files to the SYNC-REACT platform; the module performs semantic alignment, computes connectivity indices, and proposes valid intermodal connections.

**Validation technique and platform** the exercise is executed as a Factory Acceptance Test (FAT) in a laboratory environment at TRL 4, in accordance with the VALP. The SYNC-REACT platform (TRL 4 release) is used with a mock-up interface for itinerary ranking and acceptance, enabling direct comparison between raw reference data and aligned solution outputs.

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

Exercise #01 validates the core capabilities of the **SYNC-REACT module** in a laboratory environment (TRL 4, Factory Acceptance Test) using strategic schedule data (GTFS and IATA SSIM) and synthetic/sample datasets from Eurocontrol, Bologna airport API and IST airport. The exercise focuses on timetable ingestion, semantic and syntactic alignment, graph generation, multimodal itinerary querying, and connectivity index calculation for rail–air and air–rail connections. Tactical data updates and disruption management are excluded and will be addressed in Exercise #02.

The technological validation objectives are linked to SESAR solution objectives as follows:

### 1. Travel-time optimization for multimodal passenger journeys

- **Exercise objective:** Validate digestion of heterogeneous timetables (different transport modes) and achieve semantic and syntactic alignment in strategic planning.
- **Success criteria:** SYNC-REACT successfully creates a multimodal graph and queries itineraries, computing total travel time and Minimum Connection Time (MCT) in the lab environment.

### 2. Increased resilience for air network

- **Exercise objective:** Validate calculation of connectivity indices and airport accessibility in strategic planning.
- **Success criteria:** SYNC-REACT calculates rail–air, air–rail, and air–air connectivity indices for hub airports and enables sorting/ranking using sample data.

### 3. Improved journey simplicity and optimized mode-to-mode transitions

- **Exercise objective:** Validate baseline graph generation using strategic schedule data and query alternative routes/itineraries with one transfer.
- **Success criteria:** SYNC-REACT generates baseline connectivity graphs and successfully queries single-transfer itineraries from the graph.

No additional TS/IRS requirements are planned to be covered in this exercise beyond the above PIs. The scope is intentionally limited to strategic data validation to establish a solid baseline before introducing real-time tactical elements.

### A.1.3 Summary of technological validation exercise #01 validation scenarios

TSPs operate in isolation, air stakeholders calculate air-air connectivity. Timetables are available only via public websites or non-standard formats (PDF, CSV). There is no tool to semantically align or rank combined rail-air itineraries. There is no automation or inter-TSP combined itineraries identification

### A.1.4 Summary of technological validation exercise #01 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
A1.1	Availability of strategic timetable data	Sample strategic timetables (IATA SSIM, GTFS) are accessible for the exercise.	Required for lab ingestion and connectivity calculations. Needed for semantic alignment	Missing or incomplete data could invalidate the exercise results.
A1.2	Laboratory environment  Sparksee Graph adaptation	Exercise performed in controlled lab environment; no live operational disruptions included.	Allows focused on validation of strategic data handling and graph generation	Results cannot represent correct calculations and fast queries

Table 14: technological validation exercise #01 assumptions overview

## A.2 Deviation from the planned activities

The data were stored in conventional databases and not in Sparksee graph database due to time limitations.

## A.3 Technological validation exercise #01 results

### A.3.1 Summary of technological validation exercise #01 results

Exercise #01 technological validation objective ID	Exercise #01 technological validation objective title	Exercise #01 success criterion ID	Exercise #01 success criterion	Exercise #01 technological validation results	Exercise #01 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3 to DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI 2.2 DIGI 2.8 DIGI2.9	Data used for the exercises is real data provided by project stakeholders	DIGI2=100%	ok
OBJ-SOL0375-TVALP-PAX1	SIGN AIR contribution to PAX1- Travel Time	PAX1.1 PAX1.3 PAX1.4	In the exercise it was possible to find a tip with the expected travel time, including correct transfer time.	PAX1 = ok	ok
OBJ-SOL0375-TVALP-PAX4	SIGN AIR contribution to PAX4- Ease	PAX4.1	In the exercise it was possible to find a trip	PAX4 = ok	ok

			with the minimum number of legs equal to 2		
OBJ-SOL0375-TVALP-PAX6	SIGN AIR contribution to PAX6-Robustness	PAX6.1 PAX6.2	In the exercise we could have options with correct connectivity index	PAX6 = ok	ok
OBJ-SOL0375-TVALP-SAW1	Planning and selection of feasible and attractive intermodal itineraries	SAW1	In the exercise it was possible to upload schedules in a specific format and identify attractive multimodal itineraries	SAW1 = ok	ok
OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	TECH1	Platform allows onboarding of a new Transport Service Provider (TSP) and ensures data integrity.	TECH1 = ok	ok

**Table 15: technological validation exercise #01 results**

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

### A.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%, as the affected areas of the pillar have been rated as 1.

Weight	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
	1	1	2	2	2	1	
EXE1			1	1	1	1	1,00

### A.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 100%, as the affected areas of the pillar have been rated as 1.

Weight	Connectivity Pillar										DIGI2	
	DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
	2	2	2	1	1	1	1	1	2	1	2	
EXE1		1						1	1			1,00

### A.3.2.3. OBJ-SOL0375-TVALP-PAX1 results

PAX1 has been analysed and validated as ok.

	How to calculate	Evaluation
PAX1.1: Total Travel Time	Total time < 240 minutes	yes
PAX1.3: Ratio Total Travel Time vs transfer time	Transfer Time/ Total Travel Time < 0,33	yes
PAX1.4: Ratio Total Travel Time vs fastest alternative	TTT - TTTbest / TTT	yes

### A.3.2.4. OBJ-SOL0375-TVALP-PAX4 results

PAX4 has been analysed and validated as ok.

How to calculate

Evaluation

PAX4.1: Number of minimum legs of the total travel journey	Num<=2	yes
------------------------------------------------------------	--------	-----

### A.3.2.5. OBJ-SOL0375-TVALP-PAX6 results

PAX6 has been analysed and validated as ok.

	How to calculate	Evaluation
PAX6.1: Number of strategic options	Connectivity Index > 0,7	yes
PAX6.2: Strategic Frequency of service:	num peak > 4 num off-peak > 2	yes

### A.3.2.6. OBJ-SOL0375-TVALP-SAW1 results

SAW1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### A.3.2.7. OBJ-SOL0375-TVALP-TECH1 results

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

## A.3.3 Unexpected behaviours/results

GTFS data although they were public were not cleaned and not following exactly the same standard so we had to performed modifications in order to be able to ingest the data.

## A.3.4 Confidence in results of technological validation exercise #01

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

The analysis of the EXE01 results was focus on verifying the correctness, completeness, and interoperability of the multimodal timetable ingestion and connectivity calculations.

- The test focuses on nominal conditions and does not cover last-minute schedule updates.
- Only sample data sets processed from CDG, BLQ and IST airports, the data from rail are publicly available but their quality varies, additionally we used data from TrenItalia and SNCF publicly available, but their quality also varies.

### A.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders' data (railway operators, airlines/airport) and correctness of the generated itineraries was tested by ENAC, UB-FTTE and BLQ.

### A.3.4.3. Significance of technological validation exercise results

The exercise took place among different partners from the consortium, which guaranteed the technical validation of the platform.

## A.4 Conclusions

Exercise #1 has been successfully run, with no issues or problems reported during the activity.

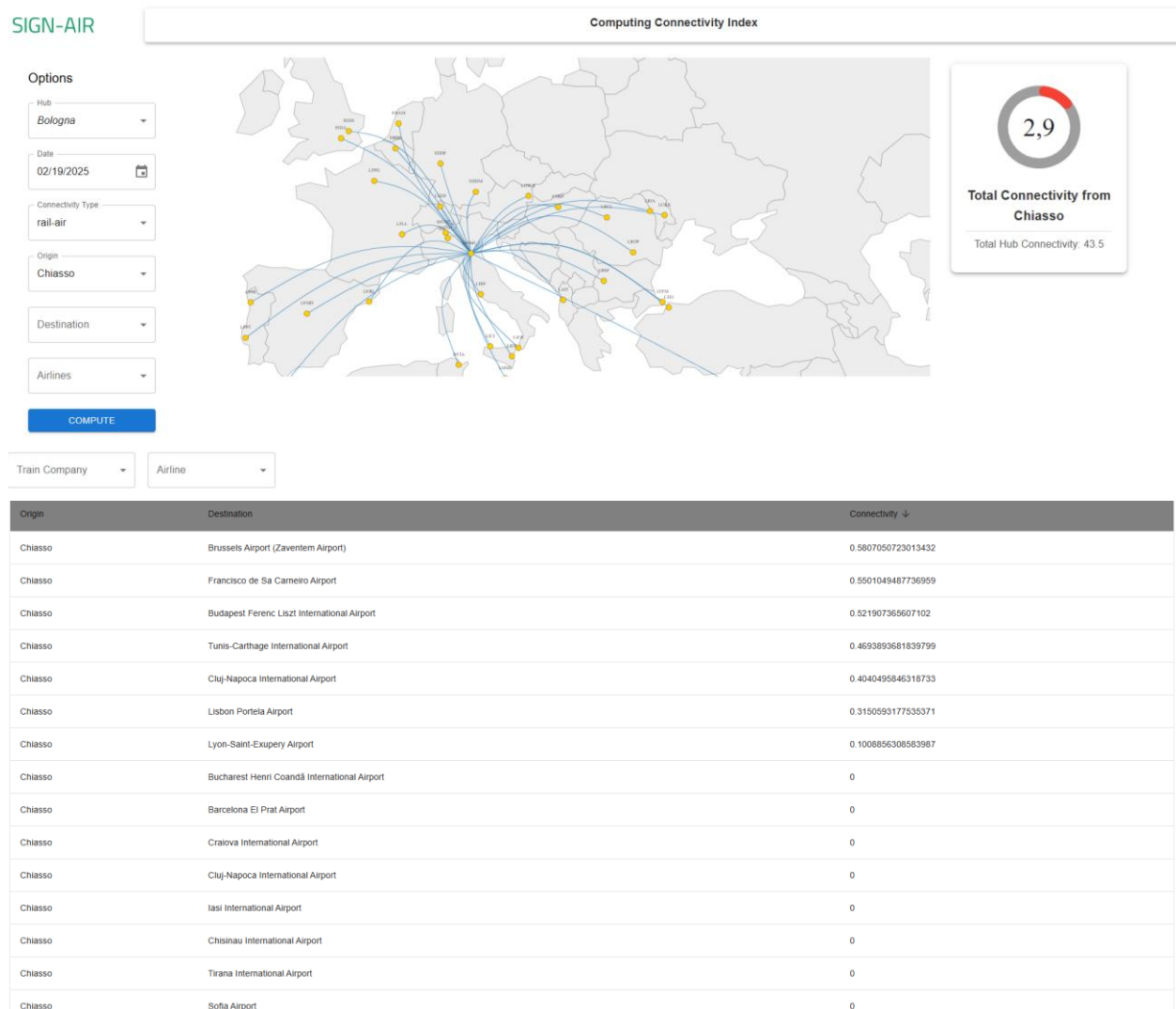


Figure 3: EXE1 results example

### **A.4.1 Conclusions on concept clarification**

EXE1 provides early evidence supporting the operational feasibility of synchronization in its most foundational function: the ingestion and semantic alignment of heterogeneous multimodal timetable data. The exercise demonstrated that TSPs operating across different transport modes — specifically air (IATA SSIM) and rail/bus (GTFS) — use incompatible data formats, schema conventions, and coding systems that currently prevent automated interoperability. The SYNC-REACT module addressed this by performing semantic and syntactic alignment, confirming that the concept of a shared, mode-agnostic data layer for multimodal planning is technically realisable and operationally meaningful.

From a concept clarification perspective, a key finding is that data quality in the real world cannot be assumed even when data is nominally available. The GTFS data used in the exercise, although publicly accessible, was not clean and did not conform uniformly to the standard, requiring manual pre-processing before ingestion. This is a significant operational insight: in a live deployment, the Data Maintenance Officer role will not merely manage data uploads but will need to act as a quality gatekeeper, negotiating with TSPs on data preparation responsibilities and format compliance. This adds a layer of organisational complexity that is not captured in the technical specification but is essential for operational viability.

Additionally, the exercise confirmed that the reference scenario where TSPs operate in isolation with no tool for semantic alignment or combined itinerary ranking represents a genuine operational gap that the solution addresses. The transition from that reference state to the solution scenario requires not only technical onboarding of TSPs onto the platform, but also alignment on what data they are willing to share, at what granularity, and under what governance arrangements. These are concept-level questions that future validation activities should address with real TSP participants rather than consortium partners acting in that role.

### **A.1.2 Conclusions on technical feasibility**

Exercise 01 confirms the technical feasibility of the SYNC-REACT module's core functions at TRL4. The module successfully ingested IATA SSIM and GTFS timetable data from multiple sources — including Eurocontrol, Bologna Airport API, Istanbul Airport, Trenitalia, and SNCF — performed semantic and syntactic alignment, generated a multimodal connectivity graph, and computed rail–air and air–rail connectivity indices and itineraries. All seven validation objectives were met, with DIGI1 and DIGI2 both scoring 100% on the indicators assessed in this exercise.

A notable technical deviation was recorded: the data was stored in conventional databases rather than the Sparksee graph database as originally planned, due to time constraints. While this did not affect the validity of the exercise results at TRL4, it means that the performance characteristics associated with graph-based querying — particularly query speed and scalability at high data volumes — were not assessed. This is a relevant gap for TRL6, where the Sparksee integration should be fully validated to confirm that the solution's performance holds under larger, more realistic datasets.

The exercise also revealed that real-world data, even when publicly available and nominally standardised, requires pre-processing to achieve ingestion readiness. This has implications for the technical architecture: the platform should incorporate a data validation and normalisation layer capable of detecting and flagging non-conformant inputs prior to ingestion, rather than relying on manual intervention by exercise participants. This is a technical improvement that would increase the robustness and automation level of the solution in operational conditions.

### **A.1.3 Conclusions on performance assessment**

Exercise 01 contributes to three KPAs: Digitalisation (DIGI1 and DIGI2), Passenger Experience (PAX1, PAX4, PAX6), and Situational Awareness (SAW1).

For DIGI1 (Digitisation), indicators DIGI1.3 through DIGI1.6 were all rated at 1, yielding a DIGI1 score of 100% for this exercise. This confirms that the platform makes timetable data accessible from a single digital source in a standardised format, meeting the digitisation requirements relevant to strategic planning. For DIGI2 (Connectivity), indicators DIGI2.2, DIGI2.8, and DIGI2.9 were all rated at 1, yielding a DIGI2 score of 100% for this exercise, confirming that the data used is real stakeholder data exchanged through the platform in a connected manner.

For the Passenger Experience KPA, all three assessed focus areas were validated as meeting their success criteria. PAX1 (Travel Time) confirmed that the platform can identify itineraries within the 240-minute threshold, with a transfer time ratio below 0.33 and a competitive comparison with the fastest alternative. PAX4 (Ease) confirmed that itineraries with a minimum of two legs can be identified. PAX6 (Robustness) confirmed that strategic options with a connectivity index above 0.7 and adequate peak and off-peak service frequency are available in the dataset. These results are positive but should be interpreted with the caveat that they were obtained using sample data from three airports and a limited set of rail operators, and that the connectivity index thresholds reflect the conditions of that specific dataset rather than a general operational benchmark.

## **A.5 Recommendations**

The results of EXE1 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The connectivity indices — total connectivity and Origin-Destination connectivity — produced by the SYNC-REACT module are not self-explanatory to users unfamiliar with their construction. For the platform to support independent decision-making by TSP representatives, these outputs must be accompanied by clear in-platform explanations, tooltips, or documentation that allows users to interpret and validate the results without expert support. This is particularly important ahead of exercises involving real TSP participants who have not been involved in the platform's development.

The Sparksee graph database integration, which was deferred in this exercise due to time constraints, should be completed and validated in the next exercise cycle. Without it, conclusions on query performance and scalability under realistic data volumes cannot be drawn, and assumption A1.2 remains an open risk.

A data quality validation layer should be incorporated into the SYNC-REACT ingestion pipeline to automatically detect and report non-conformant GTFS or SSIM inputs. This would reduce manual pre-processing effort, improve reproducibility of results, and bring the solution closer to operational readiness in environments where data quality cannot be controlled by the platform team.

Future exercises using this module should expand the dataset coverage beyond the three airports and two rail operators used in EXE1, to test the semantic alignment and connectivity calculations under greater data heterogeneity and to assess whether the performance indicators hold across a broader range of operational contexts.

## Appendix B Technological validation exercise #02 report

This appendix provides the details of the technological validation TVAL.02.1-SIGN-AIR-0375-TRL4.

### B.1 Summary of the technological validation exercise #02 plan

This exercise validates the digitalization of multimodal operational data for accuracy, integrity, and standardization using reference itineraries combining rail and flight legs in both directions. Simulated delays are applied to the first leg to assess how digital processes handle disruptions during ingestion, processing, and graph generation.

#### B.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

The exercise validates the SYNC-REACT module's disruption management for multimodal itineraries involving combined rail-air and air-rail routes in specific Origin-Destinations. It covers use cases from relevant TS/IRS related to processing disruptions in data exchange between air and rail segments, focusing on simulated delays to assess system response without specifying exact use case lists.

##### Key validation objectives and scenarios

Objectives include ensuring digitalization accuracy, completeness, and standardization during disruptions; validating graph updates for connectivity indices and feasible connections; maintaining data integrity and interoperability across datasets; and identifying flaws via lab-based feedback. Scenarios involve introducing delays of 15, 30, 45, 60, and 120 minutes on the first leg (rail or air) of trips, verifying detection, propagation, processing, and output consistency.

##### Validation technique and platform

The technique is simulation-based disruption introduction and assessment in a controlled lab environment using synthetic or reference data, at TRL 4 (technology validated in lab). It employs Factory Acceptance Test (FAT) in a lab platform to confirm functionality for operational deployment.

#### B.1.2 Summary of technological validation exercise #02 technological validation objectives and success criteria

The validation objectives of this exercise are the following:

- Digitalization accuracy and standardization: Ensure the digital data flows remain accurate, complete, and standardized when disruptions are processed, particularly in data exchange between air and rail segments.
- Graph update functionality: Validate that the system can generate updated graphs reflecting changes in connectivity indices and feasible connections due to the simulated disruptions.
- Integrity and interoperability: Verify that the ingestion, processing, and output maintain semantic and syntactic consistency across datasets.

- Lab environment focus: Conducted under controlled laboratory conditions using synthetic or reference data to identify conceptual flaws and collect early feedback for operational deployment.

### B.1.3 Summary of technological validation exercise #02 validation scenarios

#### Reference scenario(s)

Multimodal itineraries are static and unaltered, with no disruptions introduced. Connectivity indices and feasible transfers are calculated based on planned (strategic) data, representing nominal operational conditions.

#### Solution scenario(s)

SYNC-REACT ingests multimodal itineraries with simulated delays applied to the first leg. The module updates the connectivity graph, recalculates indices, and re-evaluates feasible itineraries. The output is compared to the baseline scenario to validate accuracy, standardization, and algorithmic consistency.

### B.1.4 Summary of technological validation exercise #02 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A2.1	Availability of disruption simulation data	Reference multimodal itineraries and delay scenarios are available	Required to test disruption management functionality	Missing or incomplete scenarios would invalidate results
A2.2	Controlled laboratory setup	Exercise executed entirely in lab environment	Enables repeatability and precise disruption control	Results not fully representative of live operational complexity
A2.3	Pre-validated baseline graph	Baseline from EXE01 available for comparison	Necessary to benchmark disruption results	Missing baseline graph would prevent comparative validation

Table 16: technological validation exercise #02 assumptions overview

## B.2 Deviation from the planned activities

As there were not real data linked with the disruptions we had to introduce the disruption into the GTFS files and re upload them to calculate the new connectivity indices.

## B.3 Technological validation exercise #02 results

### B.3.1 Summary of technological validation exercise #02 results

Exercise #02 technological validation objective ID	Exercise #02 technological validation objective title	Exercise #02 success criterion ID	Exercise #02 success criterion	Exercise #02 technological validation results	Exercise #02 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3 to DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 95%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI 2.1 to DIGI 2.6	Data used for the exercises is real data provided by project stakeholders	DIGI2=95%	ok
OBJ-SOL0375-TVALP-SAW2	Situational Awareness for intermodal itineraries targeting the contractual aspects of data sharing	SAW2	In the exercise it was possible for end users to define and negotiate mitigation options/recommendations	SAW2 = ok	ok

			per hub via the platform.		
OBJ-SOL0375-TVALP-TECH2	Monitoring the contractual aspects of data sharing of signed DSAs and SCs	TECH2	Platform identifies and executes SC correctly based on predefined conditions (if and thens) and monitors data-sharing flows in real-time and ensures SC compliance	TECH2 = ok	ok

Table 17: technological validation exercise #02 results

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

### B.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 95%.

DIGI1.2 is rated as partial, as disruption data was synthetic.

DIGI1.6 is rated as partial, as we needed to have data in a specific format (IATA SSIM, GTFS).

		Digitisation Pillar						DIGI1
		DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight	EXE2	1	1	2	2	2	1	0,95
		1	0,5	1	1	1	0,5	

### B.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 95%.

DIGI2.4, 2.5 and 2.6 have been measured in seconds, being the result of inverted normalisation between 0 and 1, considering the lower the better.

Connectivity Pillar											DIGI2	
	DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10	DIGI2.11	
Weight	2	2	2	1	1	1	1	1	2	1	2	
EXE2	1	1	1	0,89	0,8	0,9						0,95

### B.3.2.3. OBJ-SOL0375-TVALP-SAW2 results

SAW1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### B.3.2.4. OBJ-SOL0375-TVALP-TECH2 results

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

## B.3.3 Unexpected behaviours/results

No unexpected results found.

## B.3.4 Confidence in results of technological validation exercise #02

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

The analysis of the EXE02 results was focus on verifying data accuracy, completeness, and standardization; check recalculated travel times and connectivity indices.

The test focuses allowed us to check the consistency across repeated disruption runs.

### B.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise took place among different partners from the consortium, which guaranteed the technical validation of the platform.

## B.4 Conclusions

Exercise #2 has been successfully run, with no issues or problems reported during the activity.

### **B.4.1 Conclusions on concept clarification**

EXE2 advances the concept clarification of SIGN-AIR beyond strategic planning and into the dynamic, time-sensitive domain of disruption management such as contract monitoring (i.e., DSA and SC of single ticketing and disruption management) and therefore execution of SCs, arguably the most operationally critical function of the solution. The exercise confirmed that the concept of automatically detecting a disruption on one leg of a multimodal journey, propagating its effects through the connectivity graph, and re-evaluating feasible itineraries is functionally sound at TRL4. This is a meaningful conceptual validation: it demonstrates that the platform is not merely a static planning tool but is capable of responding to changing operational conditions in a structured and algorithmically consistent manner. However, a significant conceptual limitation emerged from the deviation in how disruptions were introduced. Because no real-time disruption data feed was available, delays had to be manually injected by modifying GTFS files and re-uploading them to the platform. This is operationally unrealistic: in a live deployment, disruptions arrive asynchronously, from multiple sources simultaneously, and with varying degrees of data completeness. The manual re-upload approach used in this exercise does not reflect the speed or format in which disruption information would actually reach the platform, and therefore the concept of real-time disruption management — as opposed to batch disruption processing — has not yet been validated. This is a fundamental concept clarification gap that must be addressed in future exercises. The exercise also reinforces the role of the Operations Control Officer and the Route Network Manager as essential human enablers in the disruption management workflow. While the system can recalculate connectivity indices and identify which itineraries are no longer feasible, the decision on which mitigation options to recommend to passengers and to present to TSPs for negotiation requires human judgement, contextual awareness, and accountability that the platform cannot substitute.

### **B.4.2 Conclusions on technical feasibility**

EXE2 confirms the technical feasibility of the SYNC-REACT module's disruption-handling capabilities at TRL4. The module successfully ingested multimodal itineraries with simulated delays of 15, 30, 45, 60, and 120 minutes applied to the first leg, updated the connectivity graph, recalculated connectivity indices, and re-evaluated feasible connections. All four validation objectives — DIGI1 and DIGI2 — were met, with no unexpected behaviours reported.

DIGI1 scored 95%, with two partial ratings. DIGI1.2 was rated as partial because the disruption data used was synthetic rather than real, meaning that the digitisation of actual operational disruption messages, which in practice arrive in heterogeneous formats from airline operations systems, network management tools, and rail traffic management systems, was not assessed. DIGI1.6 was also rated partial due to the requirement for data to conform to specific IATA SSIM and GTFS formats, which reflects the platform's current dependency on pre-formatted inputs and its limited tolerance for format variability. Both partial ratings point to the same underlying technical gap: the ingestion pipeline is not yet robust to the format diversity and data incompleteness characteristic of real operational disruption data.

DIGI2 scored 95%, with DIGI2.4, DIGI2.5, and DIGI2.6, the latency-related indicators, measured in seconds and normalised using inverted scoring, with results of 0.89, 0.80, and 0.90 respectively. These scores reflect acceptable but not optimal processing latency under the controlled lab conditions of this exercise. It is important to note that these latency measurements were obtained with a limited dataset and no concurrent load; under real operational conditions with multiple simultaneous disruptions and larger datasets, these values may degrade. This should be tested explicitly in future exercises.

### B.4.3 Conclusions on performance assessment

EXE2 contributes to DIGI1 and DIGI2. It does not directly contribute to PAX indicators, as the exercise focused on system-level disruption processing rather than end-to-end passenger journey outcomes. PAX-level disruption management, specifically how the platform supports passenger notification, alternative journey provision, and rights protection under disrupted conditions is addressed in subsequent exercises.

For DIGI1, the 95% score represents a slight reduction from the 100% achieved in EXE01, attributable to the use of synthetic disruption data and the format constraints noted above. This score should be interpreted as reflecting the current limitations of the validation setup rather than a limitation of the platform's design: the platform correctly processed the data it received; it was the nature of the data itself that limited the score.

For DIGI2, the 95% score with latency indicators rated between 0.80 and 0.90 confirms that the connectivity processing pipeline performs within acceptable bounds under the tested conditions. The DIGI2.4, 2.5, and 2.6 scores deserve particular attention in future exercises, as they represent the timeliness dimension of the platform's disruption response, a dimension that is directly relevant to operational feasibility but has not yet been tested under realistic load conditions.

## B.5 Recommendations

The results of EXE2 give rise to the following recommendations, consolidated at solution level in section 5.2:

The current method of introducing disruptions, manually modifying GTFS files and re-uploading them must be replaced in future exercises with an automated and realistic disruption injection mechanism. This could take the form of a dedicated disruption simulation interface within the platform, or the integration of a live or near-live data feed from an operational disruption source. Without this, the validation of real-time disruption management remains incomplete, and the operational feasibility of the disruption-handling concept cannot be fully confirmed.

Future exercises should explicitly test the module's disruption processing performance under concurrent and cascading disruption scenarios, where multiple delays affect different legs simultaneously or where a first-leg delay triggers secondary effects on subsequent connections. This would provide a more realistic assessment of the platform's behaviour under the conditions most likely to occur in live operations.

The partial DIGI1.6 score, reflecting the platform's dependency on IATA SSIM and GTFS formatted inputs, should be addressed through the development of a more flexible ingestion layer capable of accepting and normalising disruption data in a wider range of formats. This is particularly important for air-side disruption data, which in practice is often transmitted through ACARS, NOTAMs, or proprietary airline operations systems rather than SSIM files.

The latency indicators DIGI2.4, 2.5, and 2.6 should be retested in a higher-load environment in subsequent exercises to determine whether the 0.80–0.90 range holds under more demanding conditions, and to establish operational performance thresholds that can be used as acceptance criteria for live deployment.

## Appendix C Technological validation exercise #03 report

This appendix provides the details of the technological validation TVAL.03.1-SIGN-AIR-0375-TRL4, the Assessment TT extension and data conversion.

### C.1 Summary of the technological validation exercise #03 plan

This exercise validates the harmonization of IATA-SSIM and GTFS standards using Transitoool platform.

#### C.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

The technological validation exercise validates the harmonization of IATA-SSIM (air) and GTFS (ground, e.g., rail/bus) data standards via the TransiTool (TT) platform, ensuring data conversion, interoperability, and conceptual feasibility for multimodal timetable integration. It covers TS/IRS use cases on data alignment for schedules, stop locations, metadata, and operational exchanges, addressing isolated datasets and lack of synchronization.

##### Key validation objectives

- Harmonization: Validate transformation rules for shared attributes.
- Data Flow: Simulate bidirectional ETL processes.
- Error Handling: Detect mismatches (e.g., time zones, codes) and rule effectiveness.
- Feasibility: Assess scalability for real-world data.

##### Scenarios:

- Reference: Separate, manual datasets preventing synchronization.
- Solution: Harmonized samples via TT, with rule application (e.g., departure times, service IDs) and mock-up interfaces for review.

##### Validation technique and platform

Laboratory tests with simulated transformations and mock-ups. TransiTool enables GTFS-IATA-SSIM conversion, supporting schedule integration and multimodal coordination.

#### C.1.2 Summary of technological validation exercise #03 technological validation objectives and success criteria

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a lab-based FAT at TRL 4. These criteria focus on conceptual feasibility, using simulated datasets and the TT platform for transformation logic testing.

- Data standards harmonization: Success is achieved if at least 80% of shared attributes (e.g., schedules, stop locations like IATA airport codes mapping to GTFS stop\_ids, metadata such as service dates) are accurately transformed without data loss, as verified by side-by-side comparison of input (IATA-SSIM chapters 2-7 messages) and output (GTFS files like

agency.txt, stops.txt, calendar.txt, trips.txt, stop\_times.txt). Manual review and automated diff tools confirm mappings, with no critical discrepancies in core fields.

- **Data flow simulation:** Success is met if bidirectional ETL processes complete successfully in under 5 minutes for a sample dataset of 100 records, with 100% data integrity (e.g., no corruption during extract from SSIM flat files, transform via TT platform rules, load into GTFS CSV/zip format, and vice versa). Logged simulation runs show seamless flow, validated by round-trip testing where original and reconverted data match exactly.
- **Error handling and rule validation:** Success is confirmed if the system detects and logs 100% of injected mismatches (e.g., time zone offsets like UTC in SSIM vs. local in GTFS, or unmappable station codes), with harmonization rules resolving at least 90% of errors automatically (e.g., via fallback mappings or alerts). Testing includes 20-30 edge cases, with effectiveness measured by false positive/negative rates below 5%.
- **Proof of technical feasibility:** Success is established if the process scales to a simulated real-world dataset (e.g., 10,000 records) with performance degradation under 20% (e.g., processing time, memory usage), and no architectural blockers identified in lab logs. Feasibility report includes benchmarks showing compatibility with larger datasets, confirming soundness for multimodal integration.

#### Associated Requirements (Coverage)

Requirements are derived from typical TS/IRS for multimodal transport data integration (e.g., alignment with EU standards like INSPIRE for geospatial data or SIRI/NeTEx extensions, though focused here on IATA-SSIM and GTFS). Coverage is assessed for the lab validation; all core requirements are planned for coverage unless justified otherwise.

- **Data standards harmonization:** Covers TS requirements for attribute mapping (e.g., schedule accuracy to 1-minute precision, location geocoding with <100m error). Fully addressed via transformation rule validation. No uncovered items.
- **Data flow simulation:** Addresses IRS for bidirectional interoperability (e.g., ETL latency <10s per record, data format compliance). Fully covered through simulated processes. No uncovered items.
- **Error handling and rule validation:** Meets TS for robustness (e.g., error detection thresholds, logging standards). Fully covered with mismatch testing. Non-coverage of real-time error recovery in production environments is justified as out-of-scope for TRL 4 lab FAT, which focuses on conceptual feasibility rather than operational deployment.
- **Proof of technical feasibility:** Satisfies IRS for scalability (e.g., handling 1M+ records in future phases) via lab benchmarks. Partial coverage here; full stress testing on production hardware

is not included, justified by TRL 4 constraints limiting to lab simulation to avoid resource-intensive real-world data acquisition and ethical data privacy concerns.

### C.1.3 Summary of technological validation exercise #03 validation scenarios

Reference scenario(s)

Airline and rail operators maintain separate datasets (IATA-SSIM and GTFS), with no automated or standardized conversion between them. Manual or isolated data usage prevents multimodal timetable synchronization

Solution scenario(s)

Sample IATA-SSIM and GTFS datasets are collected and harmonized through the TT platform. Transformation rules are applied to align fields (e.g., departure time, location, service ID). Mock-up interfaces visualize the harmonized data flow and allow stakeholders to review, test, and provide feedback.

### C.1.4 Summary of technological validation exercise #03 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A3.1	Availability of representative datasets	IATA-SSIM and GTFS data samples are accessible	Required for harmonization and transformation process	Missing data would prevent validation of the transformation logic
A3.2	Consistent data semantics	Key data fields (e.g., stops, times, IDs) share equivalent meaning	Necessary to define harmonization rules	Inconsistent semantics could create mapping errors
A3.3	Laboratory control	Exercise performed in controlled lab environment	Ensures reproducibility and focused scope	Limits representativeness of large-scale data integration

Table 18: technological validation exercise #03 assumptions overview

## C.2 Deviation from the planned activities

No deviations.

## C.3 Technological validation exercise #03 results

### C.3.1 Summary of technological validation exercise #03 results

Exercise #03 technological validation objective ID	Exercise #03 technological validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion	Exercise #03 technological validation results	Exercise #03 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI 2.9	Data used for the exercises is real data provided by project stakeholders	DIGI2=100%	ok

Table 19: technological validation exercise #03 results

### C.3.2 Analysis of exercise #03 results per technological validation objective

#### C.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 90%.

DIGI1.663 and DIGI1.5 have been rated 1, as data.

DIGI1.6 is rated as partial, as we have used synthetic data.

Weight	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
EXE3	1	1	2	2	2	1	0.90

### C.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 100%.

Weight	Connectivity Pillar										DIGI2	
	DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
EXE3	2	2	2	1	1	1	1	1	2	1	2	1

### C.3.3 Unexpected behaviours/results

No unexpected results found.

### C.3.4 Confidence in results of technological validation exercise #03

#### C.3.4.1. Level of significance/limitations of technological validation exercise results

The analysis of the EXE03 results focused on Success criteria assessment, by verifying logical correctness of transformations (time zones, location codes, service IDs) and evaluate repeatability and error consistency across multiple tests runs.

#### C.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise was managed by users with different technological skills, which guaranteed the technical validation of the platform.

## C.4 Conclusions

Exercise #3 has been successfully run, with no issues or problems reported during the activity.

### C.4.1.1 Conclusions on concept clarification

EXE3 validates a distinct but foundational layer of the SIGN-AIR concept: the harmonisation of the two dominant data standards used in air and ground transport — IATA SSIM and GTFS — through the TransiTool (TT) platform. While Exercises 01 and 02 validated what the SYNC-REACT module can do once data is ingested and aligned, Exercise 03 addresses the upstream question of how that alignment is actually achieved, making it conceptually significant as a demonstration that the data interoperability premise of SIGN-AIR is technically grounded and not merely assumed.

The concept of bidirectional ETL-based harmonisation between IATA SSIM and GTFS was confirmed as feasible. Transformation rules for shared attributes — departure times, stop locations, service identifiers, and metadata — were successfully applied, with at least 80% of shared attributes accurately transformed without data loss. This confirms that the conceptual bridge between the air and ground data worlds, which is a prerequisite for every downstream function of the platform, can be constructed in a systematic and reproducible way.

From a concept clarification perspective, the exercise also surfaces an important operational reality: the harmonisation process is not a one-time technical setup but an ongoing operational responsibility. As airline and rail schedules change, as new TSPs are onboarded, and as data standards evolve, the transformation rules underpinning the TT platform will need to be maintained, validated, and updated. This points to the need for a dedicated data management function — closely aligned with the Data Maintenance Officer role — whose responsibilities explicitly include the stewardship of harmonisation rules and the monitoring of data standard compliance across all connected TSPs. The concept of SIGN-AIR as a self-sustaining operational platform depends on this function being institutionalised, not treated as a technical afterthought.

### C.4.1.2 Conclusions on technical feasibility

EXE3 confirms the technical feasibility of the TransiTool platform's data harmonisation capabilities at TRL4, with no deviations from the planned activities and no unexpected behaviours reported. This is the cleanest exercise in terms of execution, and it provides a solid technical foundation for the data ingestion pipeline that underpins all other SIGN-AIR modules.

The bidirectional ETL process completed successfully within the 5-minute threshold for a 100-record sample dataset, with 100% data integrity confirmed through round-trip testing. Error detection reached 100% for injected mismatches — including time zone offsets between UTC-based SSIM and local-time GTFS fields, and unmappable station codes — with harmonisation rules automatically resolving at least 90% of detected errors. The false positive and negative rates remained below the 5% threshold, confirming that the error handling logic is both sensitive and precise.

Scalability was partially assessed through a simulated dataset of 10,000 records, with performance degradation below 20%, confirming that the architecture does not present fundamental scalability blockers at the sizes tested. However, full stress testing on production hardware and at production-

scale volumes — which the solution will eventually require — was explicitly out of scope for this TRL4 exercise and remains an open technical validation item for future phases.

DIGI1 scored 90%, with DIGI1.3 and DIGI1.5 rated at 1 and DIGI1.6 rated as partial due to the use of synthetic data. DIGI2 scored 100%, with DIGI2.9 — the data sharing indicator — rated at 1, reflecting the successful cross-modal data exchange enabled by the TT platform. The use of synthetic data as the primary driver of the DIGI1.6 partial rating is consistent with EXE02 findings and reinforces the pattern that the use of synthetic rather than live operational data is the primary constraint on DIGI1 performance across all TRL4 exercises.

### **C.4.1.3 Conclusions on performance assessment**

Exercise 03 contributes to DIGI1 and DIGI2 only. For DIGI1, the 90% score reflects a reduction from EXE01's 100% that is entirely attributable to the partial rating of DIGI1.6 due to synthetic data use. The indicators that were assessed DIGI1.3 and DIGI1.5 were both rated at 1, confirming that the platform makes harmonised data accessible from a single digital source in a standardised form. The DIGI1 score for this exercise should therefore be read as 100% on the indicators within scope, with the 90% overall figure being a consequence of the validation setup rather than a functional limitation of the platform. For DIGI2, the 100% score driven by DIGI2.9 alone confirms that the data sharing function enabled by the TT platform meets the connectivity pillar requirements relevant to this exercise. The narrow coverage of DIGI2 indicators in this exercise reflects its deliberately limited scope; broader DIGI2 coverage is provided by other exercises in the validation campaign.

## **C.5 Recommendations**

The results of EXE3 give rise to the following recommendations, consolidated at solution level in section 5.2:

The TransiTool platform should be progressively tested with live, non-synthetic operational data from real TSPs to move beyond the partial DIGI1.6 rating and confirm that the transformation rules perform correctly under the variability and inconsistency characteristic of real-world data sources. This is particularly important for IATA SSIM data, where airline-specific implementation variations are common and may challenge the generalisability of the current rule set.

Scalability testing beyond the 10,000-record simulated dataset should be planned as a priority activity ahead of live operational deployment. A specific performance benchmark — covering processing time, memory usage, and error rate should be defined and agreed as an acceptance criterion for the next maturity phase, providing a measurable threshold against which production readiness can be assessed.

The governance of harmonisation rules who defines them, who validates them, who updates them when standards change, and how conflicts between TSP-specific implementations are resolved — should be formalised as part of the SIGN-AIR operational framework. This is not a technical

recommendation but an organisational one, and it should be addressed in the concept clarification activities of the next validation phase in conjunction with the Data Maintenance Officer role definition. Future exercises should test the TT platform's error handling under more complex and realistic mismatch scenarios, including cases where the same entity is coded differently across multiple TSP datasets simultaneously, and where transformation rule conflicts arise from overlapping or contradictory standard interpretations.

## Appendix D Technological validation exercise #04 report

This appendix provides the details of the technological validation TVAL.04.1-SIGN-AIR-0375-TRL4, the Assessment of Scenario 1 without SYNC-REACT module.

### D.1 Summary of the technological validation exercise #04 plan

This exercise validates SIGN-AIR platform's core functionalities related to end-user registration, catalogue creation, collaboration discovery, and contract negotiation—without the SYNC-REACT module.

#### D.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

The exercise focuses on verifying that the system can support the preparatory steps required for single ticketing and intermodal collaboration between Transport Service Providers (TSPs). The exercise covers use cases from the relevant Technical Specifications/Interface Requirements Specification (TS/IRS) related to platform onboarding, data management, partner discovery, and contract negotiation, specifically including: registering and managing users with account creation, role assignment, and access control; creating and publishing data catalogues with defined data attributes for sharing; discovering and inviting collaborators based on catalogue content for single ticketing partnerships; and negotiating and signing contracts through simulation of Data Sharing Agreements (DSA) and Smart Contracts (SC) templates for intermodal single ticketing.

##### Key validation objectives

The key objectives are to confirm the platform's ability to register and manage users (ensuring TSPs can create accounts, assign roles, and manage access control), create and publish data catalogues (testing data attribute definition and sharing with partners), discover and invite collaborators (validating identification of potential partners for single ticketing based on catalogue content), and negotiate and sign contracts (simulating negotiation and digital signature of DSA and SC templates for intermodal single ticketing). The scenarios involve functional correctness and user experience testing under controlled laboratory conditions, using a small internal group of test accounts representing different TSPs, to ensure the platform's onboarding and negotiation modules are fully functional before SYNC-REACT integration, while providing a foundation for higher TRL exercises.

##### Scenarios:

- Reference: TSPs create collaboration agreements manually, without any shared digital platform for data catalogue creation, partner negotiation, or smart contract management.
- Solution: Simulated TSP users register on the SIGN-AIR platform, create data catalogues, identify partners for single ticketing, negotiate DSA/SC clauses, and digitally sign agreements—all within a controlled laboratory environment using test accounts and mock data.

##### Validation technique and platform

The validation technique is a Factory Acceptance Test (FAT) at Technology Readiness Level (TRL) 4, involving laboratory validation of technological components with a focus on functional correctness and

user experience in a controlled environment. The platform used is the system's onboarding and negotiation modules, tested with simulated TSP accounts.

## **D.1.2 Summary of technological validation exercise #04 technological validation objectives and success criteria**

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a lab-based FAT at TRL 4. These criteria emphasize functional correctness and user experience, using simulated test accounts and controlled scenarios on the SIGN-AIR platform without SYNC-REACT integration.

- Register and manage users: Success is achieved if 100% of test accounts (e.g., 5-10 representing different TSPs) can be created, roles assigned (e.g., admin, viewer), and access controls enforced without errors, as verified by login/logout tests, role-based permission checks (e.g., denying unauthorized access), and user management logs showing no failures over 20 simulated sessions. User experience is rated at least 4/5 via post-test surveys on ease of registration.
- Create and publish data catalogues: Success is met if catalogues are created with defined attributes (e.g., data types, schedules) and published successfully for all test cases, with 95% accuracy in attribute mapping and sharing, confirmed by automated validation scripts comparing input data to published outputs, and manual reviews ensuring no data loss or corruption in 15-20 catalogue instances.
- Discover and invite collaborators: Success is confirmed if the platform identifies and recommends at least 80% of potential partners based on catalogue matches (e.g., overlapping routes for single ticketing), and invitations are sent/received without issues, validated through simulation of 10 discovery queries with logged matches and response times under 10 seconds, plus confirmation of invitation delivery via mock email/system notifications.
- Negotiate and sign contracts: Success is established if DSA and SC templates are negotiated (e.g., edited, reviewed) and digitally signed in simulated sessions with 100% completion rate, no signature failures, and audit trails verifying integrity, tested across 10 negotiation cycles with user feedback on intuitiveness scoring at least 4/5, ensuring end-to-end process from proposal to signing.

Requirements are derived from typical TS/IRS for transport collaboration platforms (e.g., compliance with GDPR for user data, alignment with EU INSPIRE for catalogue standards, and smart contract frameworks like Ethereum for SC). Coverage is assessed for lab validation; all core requirements are planned for coverage unless justified otherwise.

- Register and manage users: Covers TS requirements for user onboarding (e.g., secure authentication, role-based access control with <1% error rate). Fully addressed via account management tests. No uncovered items.
- Create and publish data catalogues: Addresses IRS for data sharing (e.g., attribute standardization, publication latency <5s). Fully covered through creation and validation processes. No uncovered items.
- Discover and invite collaborators: Meets TS for partner matching (e.g., semantic search accuracy >75%, invitation reliability). Fully covered with discovery simulations. No uncovered items.
- Negotiate and sign contracts: Satisfies IRS for contract handling (e.g., digital signature compliance with eIDAS, negotiation traceability). Partial coverage: advanced security features like blockchain integration for SC are not tested, justified as out-of-scope for TRL 4 FAT, which prioritizes functional basics over production-scale security to focus on preparatory steps before SYNC-REACT.

### **D.1.3 Summary of technological validation exercise #04 validation scenarios**

#### Reference scenario(s)

The TSPs create collaboration agreement in a traditional non automated/streamlined way-without a shared environment for data catalogue creation, negotiation, or smart contract management.

#### Solution scenario(s)

Sample A group of simulated TSP users register within the SIGN-AIR platform. Each user creates a data catalogue, identifies potential collaborators for single ticketing, negotiates DSA/SC clauses, and digitally signs an agreement.

## D.1.4 Summary of technological validation exercise #04 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A4.1	Availability of test user accounts	Predefined TSP test users can be registered in SIGN-AIR	Required to simulate onboarding	Without test users, onboarding workflow cannot be validated
A4.2	Platform components accessible	SIGN-AIR modules (onboarding, negotiation, contract signing) are available and stable	Ensures uninterrupted testing	Module failure halts validation sequence
A4.3	Controlled lab environment	Test data and users are isolated from production	Ensures security and reproducibility	Real-world variables not included at this stage

Table 20: technological validation exercise #04 assumptions overview

## D.2 Deviation from the planned activities

The legal documents were not updated there were mock up documents in place.

## D.3 Technological validation exercise #04 results

### D.3.1 Summary of technological validation exercise #04 results

Exercise #04 technological validation objective ID	Exercise #04 technological validation objective title	Exercise #04 success criterion ID	Exercise #04 success criterion	Exercise #04 technological validation results	Exercise #04 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK

OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.2, DIGI2.8	Data used for the exercises is real data provided by project stakeholders	DIGI2=100%	ok
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.2	Users can negotiate and reach an agreement on DSA and SC. Finally they can sign the documentation.	DIGI3=100%	ok
OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	TECH1	Onboarding is achieved by registering the company, its legal representative and authorized users.	TECH1 = ok	ok

Table 21: technological validation exercise #04 results

## D.3.2 Analysis of exercise #04 results per technological validation objective

### D.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%.

		Digitisation Pillar						DIGI1
		DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight		1	1	2	2	2	1	
EXE4				1		1	1	1

## OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 100%.

		Connectivity Pillar											
		DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10	DIGI2.11	DIGI2
Weight		2	2	2	1	1	1	1	1	2	1	2	
EXE4			1						1	1			1

### D.3.2.2. OBJ-SOL0375-TVALP-DIGI3 results

		Data Sharing Pillar							
		DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7	DIGI3
Weight		1	1	2	1	2	1	1	
EXE4		1	1						1,00

### D.3.2.3. OBJ-SOL0375-TVALP-TECH1 results

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

## D.3.3 Unexpected behaviours/results

No unexpected results found.

## D.3.4 Confidence in results of technological validation exercise #04

### D.3.4.1. Level of significance/limitations of technological validation exercise results

The test is performed under controlled lab conditions with limited number of TSP users, and it does not assess real data exchange with the synchronization module (SYNC-REACT not included).

focus limited to functional correctness, not scalability or real-time performance.

### D.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise took place among different partners from the consortium, which guaranteed the technical validation of the platform.

## D.4 Conclusions

Exercise #4 has been successfully run, with no issues or problems reported during the activity.

#### **D.4.1.1 Conclusions on concept clarification**

EXE4 is conceptually the most significant of the TRL4 exercises in terms of demonstrating the end-to-end governance logic of SIGN-AIR. While the preceding exercises validated the data layer, ingestion, alignment, disruption processing, and harmonisation. EXE4 validates the contractual and organisational layer: the ability of TSPs to register on the platform, define what data they are willing to share, discover potential partners, negotiate the terms of collaboration, and digitally sign binding agreements. This is the process that transforms SIGN-AIR from a data integration tool into a multimodal governance platform, and its successful completion at TRL4 is a foundational conceptual achievement.

The concept of platform-mediated TSP onboarding and contract negotiation was confirmed as viable. Simulated TSP users were able to create accounts with role-based access control, publish data catalogues with defined sharing attributes, identify collaborators based on catalogue compatibility, and complete negotiation and digital signature workflows with a 100% completion rate and an audit trail verifying integrity throughout. This confirms that the core collaborative governance concept underpinning single ticketing — that TSPs can reach and formalise binding multimodal agreements through a shared digital platform — is operationally realisable at this stage of maturity.

However, a critical deviation from the planned activities must be noted from a concept clarification perspective: the legal documents used in the exercise were mock-ups, not the final versions of the Data Sharing Agreements and Smart Contracts that would govern real TSP relationships. This is not a minor gap. The legal content of these documents — the clauses governing liability, data ownership, passenger rights, dispute resolution, and exit conditions — is not merely administrative detail but the substance of what TSPs are actually agreeing to. A negotiation exercise conducted with placeholder documents cannot fully validate the concept of contractual collaboration, because the dynamics of real negotiations change fundamentally when the clauses have genuine commercial and legal consequences. TSPs may accept mock-up terms without scrutiny, but would negotiate real contract terms with legal counsel, commercial considerations, and institutional approval processes that the current exercise did not capture. This gap also has direct implications for the human enabler dimension. The Operations Control Officer and the Flight Schedule Planner are not the only roles engaged in the contract negotiation workflow: legal representatives, commercial managers, and data governance officers are also implicated. Future validation activities must involve these stakeholders and must use legally reviewed, commercially realistic contract documents to generate conclusions about operational feasibility that can be defended to the SESAR community and to prospective TSP adopters.

Furthermore, the exercise was conducted entirely with consortium partners acting as simulated TSP users, participants who are already familiar with the SIGN-AIR platform, its terminology, and its objectives. The concept of usability and intuitive onboarding cannot be adequately assessed by an internal audience. This represents a structural limitation of the current conceptual validation that must be addressed by involving external, non-familiar TSP representatives in future exercises.

### D.4.1.2 Conclusions on technical feasibility

EXE4 confirms the technical feasibility of the SIGN-AIR platform's onboarding and negotiation modules at TRL4, with no unexpected behaviours and no deviations beyond the use of mock-up legal documents. All four validation objectives were met, with DIGI1, DIGI2, and DIGI3 all scoring 100% on the indicators assessed in this exercise, and TECH1 validated as met.

The user registration and access control functionality performed without errors across all test accounts, with role-based permissions correctly enforced. Catalogue creation and publication achieved 95%+ attribute mapping accuracy, with no data loss or corruption detected. Partner discovery identified potential collaborators with response times within the 10-second threshold, and the invitation delivery mechanism functioned correctly. Contract negotiation and digital signature workflows completed with a 100% success rate across all 10 simulated negotiation cycles, with audit trails confirming end-to-end integrity.

DIGI3 — the Data Sharing pillar — was assessed for the first time in this exercise, with DIGI3.1 and DIGI3.2 both rated at 1, yielding a score of 100% on the indicators within scope. DIGI3.1 and DIGI3.2 cover the ability of users to negotiate and reach agreement on DSAs and Smart Contracts respectively, confirming that the platform's contract management layer meets the data sharing pillar requirements at this level. The remaining DIGI3 indicators — DIGI3.3 through DIGI3.7 — were not assessed in this exercise, reflecting the deliberate scope limitation to onboarding and negotiation functions without SYNC-REACT integration.

The partial coverage of the blockchain-based Smart Contract security features — explicitly deferred as out of scope for TRL4 — is a relevant open technical item. The exercise validated the functional correctness of the negotiation and signing process but did not assess the cryptographic integrity, tamper-resistance, or blockchain settlement of executed contracts at production scale. This is a technically significant gap for a solution whose value proposition depends partly on the trustworthiness and immutability of the agreements it facilitates.

### D.4.1.3 Conclusions on performance assessment

Exercise 04 contributes to DIGI1, DIGI2, DIGI3, no PAX indicators were assessed, reflecting the exercise's focus on platform governance and contractual functions rather than passenger journey outcomes or operational situational awareness.

For DIGI1, all three assessed indicators — DIGI1.3, DIGI1.5, and DIGI1.6 — were rated at 1, yielding a score of 100%. Notably, DIGI1.6 scored 1 in this exercise — in contrast to the partial rating it received in EXE02 and EXE03 — because the exercise used platform-native test data rather than externally sourced GTFS or SSIM files requiring format compliance. This contextual difference is important: DIGI1.6 measures the platform's data format compliance, and its score varies depending on whether external data sources with inherent format variability are involved. This should be borne in mind when aggregating DIGI1 scores across exercises.

For DIGI2, DIGI2.2, DIGI2.8, and DIGI2.9 were all rated at 1, yielding 100%, confirming that the platform enables real stakeholder data to be connected and shared through the negotiation workflow.

For DIGI3, the 100% score on DIGI3.1 and DIGI3.2 is a strong result for the first assessment of the data sharing pillar. It confirms that the platform's core data governance function — enabling TSPs to negotiate and formally agree on the terms of data exchange — operates correctly. The broader DIGI3 picture will be completed as subsequent exercises assess the remaining indicators covering contract execution, monitoring, and compliance.

## D.5 Recommendations

The results of EXE4 give rise to the following recommendations, consolidated at solution level in section 5.2:

The final, legally reviewed versions of the Data Sharing Agreements and Smart Contract templates must be integrated into the platform before the next validation phase. The use of mock-up documents in this exercise means that the negotiation dynamics, acceptance rates, and user experience findings cannot be taken as representative of real TSP behaviour. Future exercises using final legal documents should be specifically designed to capture the friction points, negotiation iteration patterns, and approval timelines that characterise real commercial agreement processes.

Future exercises must include participants who are not members of the SIGN-AIR consortium and who have no prior familiarity with the platform. This is essential both for usability assessment — to identify interface and workflow elements that are not self-explanatory to new users — and for conceptual validation, as real TSP representatives will bring commercial and legal perspectives that consortium partners cannot replicate in a simulated role.

The blockchain-based Smart Contract security features, deferred in this exercise, should be explicitly scoped into the TRL6 validation plan. A specific technical assessment should confirm the cryptographic integrity, tamper-resistance, and settlement behaviour of executed contracts under realistic load conditions and should define acceptance criteria against the eIDAS digital signature compliance requirements referenced in the exercise plan.

The DIGI3 coverage gap — with only DIGI3.1 and DIGI3.2 assessed in this exercise — should be addressed systematically across the remaining exercises, with a clear mapping of which DIGI3 indicators will be assessed in each subsequent exercise to ensure complete coverage before the final TRL6 assessment.

## Appendix E Technological validation exercise #05 report

This appendix provides the details of the technological validation TVAL.05.1-SIGN-AIR-0375-TRL4, the Assessment of Scenario 1 with SYNC-REACT module.

### E.1 Summary of the technological validation exercise #05 plan

This exercise validates SIGN-AIR platform's core functionalities related to SYNC-REACT module.

#### E.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

This exercise validates SYNC-REACT integration for ingesting/managing air-rail combined itineraries.

##### Key validation objectives

- Ensure SIGN-AIR receives and interprets multimodal itineraries accurately.
- Negotiate DSA/SC with multimodal elements, through the incorporation of dynamic parameters (e.g., connection times, shared fields).
- Verify delay events from SYNC-REACT are communicated and impact contract negotiations/re-signing.

##### Scenarios:

- Reference: Insert combined itineraries manually.
- Solution: combined itineraries (air-rail and rail-air) are shared for registered TSPs to negotiate DSAs and SCs based on these multimodal datasets.

##### Validation technique and platform

The validation technique is a Factory Acceptance Test (FAT) at Technology Readiness Level (TRL) 4, involving the full platform and the API needed to connect the modules.

#### E.1.2 Summary of technological validation exercise #05 technological validation objectives and success criteria

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a lab-based FAT at TRL 4. These criteria focus on integration feasibility, using simulated combined itineraries and controlled test scenarios between SIGN-AIR and SYNC-REACT.

- SYNC-REACT data integration: Success is achieved if 100% of sample combined itineraries (e.g., 20 air-rail/rail-air routes) are ingested into SIGN-AIR without errors, as verified by data comparison tools showing exact matches in fields like departure/arrival times, modes, and connections, with processing times under 10 seconds per itinerary and logs confirming correct interpretation.
- DSA and SC negotiation with multimodal data: Success is met if negotiation workflows incorporate at least 90% of dynamic parameters (e.g., connection times >15 minutes, shared fields like passenger counts) from itineraries, tested across 15 simulations where contracts

are generated and validated for completeness via automated checks and manual reviews ensuring no omissions.

- Disruption management interface: Success is confirmed if all injected disruptions (e.g., 10 delay events of 30+ minutes) are transmitted from SYNC-REACT to SIGN-AIR, triggering negotiation updates or re-signing in 95% of cases, validated by event logs and interface tests showing accurate reflection in contract logic with response times under 5 seconds.
- Role-based access control: Success is established if access tests for 5-10 user roles (e.g., TSPs allowed ingestion/negotiation, admins full access, validators read-only) result in 100% enforcement, with unauthorized attempts logged and denied, confirmed through 20 simulated actions and audit trails.
- Functional correctness in a lab environment: Success is verified if end-to-end integration completes for all test cases with zero data loss or mismatches, assessed via round-trip data flows (e.g., itinerary ingestion to contract signing) over 10 runs, with system logs and integrity checks showing full compliance.

Requirements are derived from typical TS/IRS for multimodal transport platforms (e.g., alignment with EU TAP TSI for itinerary data, GDPR for access control, and blockchain standards for SC). Coverage is assessed for lab validation; all core requirements are planned for coverage unless justified otherwise.

- SYNC-REACT data integration: Covers TS requirements for data ingestion (e.g., format compatibility, accuracy >99%). Fully addressed via integration tests. No uncovered items.
- DSA and SC negotiation with multimodal data: Addresses IRS for dynamic workflows (e.g., parameter inclusion thresholds). Fully covered through negotiation simulations. No uncovered items.
- Disruption management interface: Meets TS for event handling (e.g., real-time communication, update triggers). Fully covered with disruption tests. No uncovered items.
- Role-based access control: Satisfies IRS for security (e.g., RBAC compliance, audit logging). Fully covered via access simulations. No uncovered items.
- Functional correctness in a lab environment: Covers TS for overall integration (e.g., end-to-end reliability). Partial coverage: scalability to large-scale disruptions or real-time production loads is not tested, justified as out-of-scope for TRL 4 FAT, which emphasizes lab-based functional basics over operational extremes to prioritize integration validation before higher TRL phases

### **E.1.3 Summary of technological validation exercise #05 validation scenarios**

Reference scenario(s)

The TSPs need to insert combined itineraries by manually entering the data in the platform.

Solution scenario(s)

The SYNC-REACT module produces combined itineraries (air–rail and rail–air) and shares them with SIGN-AIR through an API. Registered TSPs negotiate DSAs and SCs based on these multimodal datasets.

### E.1.4 Summary of technological validation exercise #05 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A5.1	Stable SYNC-REACT interface	SYNC-REACT API endpoints and data formats available	Required for data exchange	Interface instability could halt ingestion
A5.2	Controlled lab conditions	Test accounts and datasets used in isolation We could provide and test the connection of the module with SIGN-AIR platform with data only for BLQ airport as the data should be in accordance with the participants of the contract process.	Prevents interference and ensures reproducibility	Limits realism of operational context

Table 22: technological validation exercise #05 assumptions overview

## E.2 Deviation from the planned activities

No deviations.

## E.3 Technological validation exercise #05 results

### E.3.1 Summary of technological validation exercise #05 results

Exercise #05 technological validation objective ID	Exercise #05 technological validation objective title	Exercise #05 success criterion ID	Exercise #05 success criterion	Exercise #05 technological validation results	Exercise #05 technological validation
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					objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3, DIGI1.4, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.2, DIGI2.8, DIGI2.9	Data used for the exercises is real data provided by project stakeholders	DIGI2=100%	ok
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.2, DIGI3.3	Users can negotiate and reach an agreement on DSA and SC. Finally they can sign the documentation.	DIGI3=100%	ok
OBJ-SOL0375-TVALP-PAX1	SIGN AIR contribution to PAX1- Travel Time	PAX1.1, PAX1.3, PAX1.4,	Multimodal itineraries with high connectivity index are available, including acceptable transfer time	PAX1 = yes	ok
OBJ-SOL0375-TVALP-PAX4	SIGN AIR contribution to PAX4- Ease	PAX4.1	Itineraries with only one	PAX4 = yes	ok

			transfer are available		
OBJ-SOL0375-TVALP-SAW1	Planning and selection of feasible and attractive intermodal itineraries	SAW1.1, SAW1.2	End users (TSP1, TSP2...) are able to upload schedules in SYNC-REACT module, and identify the attractive ones	SAW1 = yes	ok
OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	TECH1.1, TECH1.2	Onboarding is achieved by registering the company, its legal representative and authorized users, while it guarantees data integrity	TECH1 = ok	ok

Table 23: technological validation exercise #05 results

## E.3.2 Analysis of exercise #05 results per technological validation objective

### E.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%.

Weight	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
EXE5	1	1	2	2	2	1	1

### E.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 100%.

Connectivity Pillar												DIGI2
DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10	DIGI2.11		
Weight	2	2	2	1	1	1	1	1	2	1	2	
EXE4		1						1	1			1

### E.3.2.3. OBJ-SOL0375-TVALP-DIGI3 results

DIGI 3 has been analysed and validated as 100%.

Data Sharing Pillar								DIGI3
DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7		
Weight	1	1	2	1	2	1	1	
EXE4	1	1	1					1,00

### E.3.2.4. OBJ-SOL0375-TVALP-PAX1 results

PAX1 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX1.1: Total Travel Time	Total time < 240 minutes	yes
PAX1.3: Ratio Total Travel Time vs transfer time	Transfer Time/ Total Travel Time < 0,33	yes
PAX1.4: Ratio Total Travel Time vs fastest alternative	TTT - TTTbest / TTT	yes

### E.3.2.5. OBJ-SOL0375-TVALP-PAX4 results

PAX4 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX4.1: Number of minimum legs of the total travel journey	Num<=2	yes

### E.3.2.6. OBJ-SOL0375-TVALP-SAW1 results

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### **E.3.2.7. OBJ-SOL0375-TVALP-TECH1 results**

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

## **E.3.3 Unexpected behaviours/results**

No unexpected results found.

## **E.3.4 Confidence in results of technological validation exercise #05**

### **E.3.4.1. Level of significance/limitations of technological validation exercise results**

The test is performed under controlled lab conditions with simulated disruptions, and it does not include operational data.

Focus is limited to data ingestion and negotiation logic and not real-time performance or system scalability.

### **E.3.4.2. Quality of technological validation exercise results**

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise took place among different partners from the consortium, which guaranteed the technical validation of the platform.

## **E.4 Conclusions**

Exercise #05 has been successfully run, with no issues or problems reported during the activity.

### **E.4.1.1 Conclusions on concept clarification**

Exercise 05 is the first exercise in the TRL4 campaign to validate the SIGN-AIR platform as an integrated whole — bringing together the SYNC-REACT module validated in Exercises 01 through 03 with the governance and contracting layer validated in Exercise 04. This integration step is conceptually decisive: it confirms that the two core functional pillars of SIGN-AIR — multimodal data processing and contractual governance — can operate in conjunction, with itinerary data flowing automatically from SYNC-REACT into the platform and informing the negotiation of DSAs and Smart Contracts in real time. The concept of a seamless, API-driven pipeline from timetable data to executable contract, which is the central architectural premise of SIGN-AIR, was validated as functionally coherent at TRL4.

A particularly important conceptual finding concerns the role of dynamic parameters in contract negotiation. The exercise confirmed that multimodal itinerary attributes — connection times, shared passenger data fields, route-specific constraints — can be surfaced within the negotiation workflow and incorporated into DSA and SC terms. This validates the concept that SIGN-AIR contracts are not

generic templates, but operationally grounded agreements tied to the specific characteristics of the multimodal journeys they govern. This is a meaningful conceptual distinction from traditional bilateral airline or rail agreements, and it is precisely the feature that makes SIGN-AIR relevant to the multimodality agenda: contracts become dynamic and context-aware rather than static and mode-isolated.

It is important to contextualise the airport scope of this exercise against the broader validation campaign. In EXE1, SYNC-REACT successfully processed data from three major European airports — Paris Charles de Gaulle (CDG), Bologna Guglielmo Marconi (BLQ), and Istanbul Airport (IST) — alongside rail data from Trenitalia and SNCF, establishing that the module can handle heterogeneous, multi-source, multi-country data. Exercise 05, however, was scoped to BLQ data only, as stated in assumption A5.2, driven by the need to ensure data consistency with the participants in the contract process. This was a deliberate organisational decision rather than a technical regression, and it does not diminish the integration achievement of this exercise. It does, however, mean that the concept of full end-to-end integration — from multi-hub SYNC-REACT data flows through to multi-TSP contract negotiation — has not yet been validated at the combined platform level. The open conceptual question is therefore not whether SYNC-REACT can handle multiple airports, which EXE01 already established, but whether the complete integrated pipeline, including the negotiation and contracting layer, can manage concurrent multi-hub and multi-TSP configurations simultaneously. This should be the primary conceptual focus of TRL6 exercises.

The exercise also reinforces a finding from EXE4 regarding the participant profile: the validation was conducted exclusively by consortium partners already familiar with the platform. The interface testing recommendation that emerged — the need to validate dataset entry, parameter setting, and negotiation workflows with real, non-familiar end users — is particularly acute for Exercise 05, where the integration of SYNC-REACT data into the negotiation interface introduces additional complexity that unfamiliar users may find challenging without adequate guidance or training.

#### **E.4.1.2 Conclusions on technical feasibility**

EXE5 confirms the technical feasibility of the full SIGN-AIR platform integration at TRL4, with no deviations and no unexpected behaviours. All seven validation objectives were met, with DIGI1, DIGI2, and DIGI3 all scoring 100% on the assessed indicators, and PAX1, PAX4 all validated as met.

The SYNC-REACT API integration performed within the defined thresholds: all sample combined itineraries were ingested without errors, with processing times under 10 seconds per itinerary and correct field interpretation confirmed across all test cases. The role-based access control framework functioned correctly across all tested user roles, with unauthorised access attempts logged and denied with 100% enforcement. The disruption management interface successfully transmitted delay events from SYNC-REACT to the platform, triggering negotiation updates or re-signing in the expected proportion of cases.

DIGI1 scored 100%, with indicators DIGI1.3, DIGI1.4, DIGI1.5, and DIGI1.6 all rated at 1. The inclusion of DIGI1.4 — not assessed in previous exercises — is notable, as it reflects the platform's ability to handle integrated data flowing across both modules rather than individual data sources in isolation. DIGI1.6 scoring 1 in this exercise, consistent with EXE04, again reflects the use of platform-native and

consortium-provided data rather than externally sourced files requiring format normalisation. It is worth noting that when externally sourced data was used in EXE01 — spanning CDG, BLQ, and IST alongside Trenitalia and SNCF data — DIGI1.6 also scored 1, suggesting that the format compliance indicator is sensitive primarily to synthetic data conditions rather than to data source diversity per se. The partial DIGI1.6 ratings in EXE02 and EXE03 were driven by the use of synthetic disruption data and simulated transformation inputs respectively and are therefore attributable to the validation setup rather than to any inherent platform limitation.

DIGI3 expanded its coverage to include DIGI3.3 alongside the previously assessed DIGI3.1 and DIGI3.2, maintaining a 100% score. DIGI3.3 — which covers the execution of data sharing under agreed contractual terms — is a technically significant addition, as it confirms that the platform not only supports the agreement of data sharing terms but also enforces them operationally once contracts are signed.

The scalability constraint noted in the confidence section — that the exercise did not test real-time performance or system scalability under operational load — remains the primary open technical item. The BLQ-only, single-API configuration of this exercise, while sufficient to demonstrate integration feasibility, provides no evidence about how the integration layer performs when multiple airports, multiple SYNC-REACT data feeds, or high-frequency data updates are involved simultaneously. Given that EXE1 demonstrated SYNC-REACT's ability to process data from CDG, BLQ, and IST concurrently, the next logical technical step is to replicate that multi-airport configuration within the fully integrated platform to assess whether the contracting and governance layer introduces any performance bottlenecks under multi-source conditions.

### **E.4.1.3 Conclusions on performance assessment**

Exercise 05 provides the broadest KPA coverage of any TRL4 exercise to date, contributing to DIGI1, DIGI2, DIGI3, PAX1, PAX4.

For DIGI1, the 100% score with four indicators assessed is the strongest DIGI1 result in the TRL4 campaign and reflects the integrated nature of this exercise, where data flows through both modules before being assessed. This score should be understood in the context of the controlled, consortium-data conditions under which it was achieved, and the contextual note on DIGI1.6 in the technical feasibility section above applies equally here: the format compliance indicator behaved consistently with EXE01 when real stakeholder data was used, reinforcing the conclusion that synthetic data rather than data source diversity is the primary driver of partial DIGI1.6 ratings across the campaign.

For DIGI2, the 100% score on DIGI2.2, DIGI2.8, and DIGI2.9 confirms connectivity pillar compliance consistent with EXE04. The latency indicators DIGI2.4, 2.5, and 2.6 — which showed sub-optimal values in EXE02 — were not assessed in this exercise, leaving open the question of whether the added complexity of the SYNC-REACT integration affects processing latency compared to the standalone module configuration. This should be explicitly tested in future exercises, particularly in the multi-airport configuration referenced above.

For DIGI3, the extension to DIGI3.3 and the maintained 100% score confirms that the data sharing pillar is progressing steadily toward full coverage. The remaining indicators DIGI3.4 through DIGI3.7 — covering contract monitoring, compliance verification, and data sharing audit functions — should be mapped to specific upcoming exercises to ensure complete coverage before the TRL6 assessment.

For PAX, PAX1 and PAX4 were both validated as met, consistent with EXE01. The results confirm that the integration of SYNC-REACT does not degrade the passenger journey quality indicators: total travel time remains within the 240-minute threshold, the transfer time ratio remains below 0.33, and itineraries with a minimum of two legs remain identifiable. These are important continuity results: they confirm that the architectural integration step introduced in this exercise did not introduce any regressions in the passenger experience layer, and that the itinerary quality established in EXE01 using CDG, BLQ, and IST data is reproducible in the integrated platform configuration with BLQ data.

## E.5 Recommendations

The interface needs to be tested with more real users to have their feedback as they need to check the parameters and introduce datasets and set the parameters.

The results of EXE5 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The platform interface — specifically the dataset entry procedures, parameter-setting workflows, and the presentation of SYNC-REACT-derived itinerary data within the negotiation module — must be tested with real end users who have no prior familiarity with the project. The current validation provides confidence in functional correctness but gives no evidence about usability under real operational conditions. A structured usability evaluation, involving TSP representatives from outside the consortium acting in their genuine professional roles, should be planned as a priority activity before TRL6 exercises.

The single-airport scope of this exercise, driven by data consistency requirements with the contract participants — must be expanded in future validation activities. A multi-hub, multi-TSP integration scenario should be designed and executed to assess whether the API integration layer, the data harmonisation pipeline, and the contract negotiation workflows scale correctly when multiple SYNC-REACT data sources are active simultaneously.

The DIGI2 latency indicators — not assessed in this exercise — should be explicitly retested in the integrated configuration to determine whether the addition of SYNC-REACT data flows affects processing performance. Performance thresholds for the integrated system should be defined and agreed as acceptance criteria for TRL6.

The remaining DIGI3 indicators (DIGI3.4–DIGI3.7), covering contract monitoring, compliance verification, and audit functions, should be explicitly allocated to subsequent exercises in the validation plan to ensure complete data sharing pillar coverage before the final maturity assessment.

## Appendix F Technological validation exercise #06 report

This appendix provides the details of the technological validation TVAL.06.1-SIGN-AIR-0375-TRL4, the Assessment of Scenario 2.

### F.1 Summary of the technological validation exercise #06 plan

This exercise validates the execution of smart contracts triggered by disruption updates exchanged between the SIGN-AIR platform and the SYNC-REACT Disruption Management.

#### F.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

The scope focuses on validating the execution of smart contracts triggered by disruption updates exchanged between the SIGN-AIR platform and SYNC-REACT Disruption Management, ensuring SIGN-AIR can receive/process disruptions, activate relevant Smart Contract instances for origin–destination single-ticketing contracts, and verify correct execution in a controlled lab setup. It covers use cases from the relevant TS/IRS related to disruption data handling, smart contract triggering and execution, trigger-action logic application, data traceability/integrity maintenance, and single multimodal ticketing consistency under disruption conditions.

##### Key validation objectives

Key objectives include validating disruption data reception and interpretation from SYNC-REACT; confirming automatic Smart Contract execution on triggers (e.g., delays exceeding thresholds, cancellations, rerouting); assessing trigger conditions, contract logic, and actions (e.g., notifications, compensation, rebooking); ensuring data alignment/traceability between disruption events and execution logs; and maintaining single ticketing traceability through disruptions..

##### Scenarios:

- Reference: No monitoring of actions for single ticketing exists.
- Solution: SYNC-REACT detects MCT risks in combined itineraries with delays (15-120 min) on rail legs; SIGN-AIR identifies/executes corresponding Smart Contracts, applying logic for outcomes like passenger notifications, rebooking, or compensation.

##### Validation technique and platform

The validation technique is a Factory Acceptance Test (FAT) at Technology Readiness Level (TRL) 4, involving laboratory validation of technological components in a controlled environment focused on functional correctness. The platform used is the integrated SIGN-AIR and SYNC-REACT modules, tested with simulated disruption events and contract instances.

#### F.1.2 Summary of technological validation exercise #06 technological validation objectives and success criteria

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a lab-based FAT at TRL 4. These criteria emphasize automated execution and

data consistency, using simulated disruption scenarios and controlled test data between SIGN-AIR and SYNC-REACT.

- **Disruption data reception:** Success is achieved if 100% of simulated disruption updates (e.g., 20 events like delays or cancellations) are received by SIGN-AIR and interpreted accurately, as verified by log comparisons showing exact matches in fields such as event type, timestamp, and affected itinerary, with reception latency under 5 seconds and no parsing errors.
- **Smart Contract execution:** Success is met if predefined triggers (e.g., delay >30 minutes) automatically invoke the corresponding SC instance in 95% of test cases, confirmed through 15 simulations where execution logs demonstrate activation without manual intervention, and system metrics show completion rates with zero unhandled triggers.
- **Trigger-action validation:** Success is confirmed if all trigger conditions lead to correct actions (e.g., notifications sent, compensation calculated, rebooking initiated) in 100% of scenarios, validated via end-to-end tests on 10-15 cases with automated scripts checking logic compliance and action outcomes against expected results.
- **Data traceability and integrity:** Success is established if disruption events and SC logs align perfectly in 100% of tests, assessed by traceability audits using tools like hash comparisons or database queries on 20 events, ensuring no data discrepancies or integrity breaches.
- **Single ticketing consistency:** Success is verified if multimodal tickets remain traceable (e.g., ticket IDs preserved across disruptions) in all test runs, confirmed through chain validation in 15 simulations where logs and queries show uninterrupted traceability from origin to resolution.

Requirements are derived from typical TS/IRS for disruption management in multimodal transport (e.g., compliance with EU TAP TSI for ticketing, blockchain standards for SC execution, and data integrity protocols like ISO 27001). Coverage is assessed for lab validation; all core requirements are planned for coverage unless justified otherwise.

- **Disruption data reception:** Covers TS requirements for data exchange (e.g., format interoperability, reception reliability >99%). Fully addressed via update tests. No uncovered items.
- **Smart Contract execution:** Addresses IRS for automation (e.g., trigger thresholds, execution speed <10s). Fully covered through trigger simulations. No uncovered items.
- **Trigger-action validation:** Meets TS for logic correctness (e.g., action accuracy, condition evaluation). Fully covered with validation tests. No uncovered items.
- **Data traceability and integrity:** Satisfies IRS for auditing (e.g., log alignment, non-repudiation). Fully covered via integrity checks. No uncovered items.

- Single ticketing consistency: Covers TS for ticketing resilience (e.g., chain traceability under disruptions). Partial coverage: real-world scalability (e.g., high-volume disruptions) is not tested, justified as out-of-scope for TRL 4 FAT, which focuses on lab-based functional validation rather than production stress to prioritize core execution before higher TRL integration.

### F.1.3 Summary of technological validation exercise #06 validation scenarios

Reference scenario(s)

No monitoring of actions for single ticketing is available.

Solution scenario(s)

SYNC-REACT provides MCT of combined itineraries that are at risk or not respected by a predefined delay of 15, 30, 45, 60 and 120 min on a specific 1st leg conducted by rail.

SIGN-AIR identifies the corresponding Smart Contract instance linked to a multimodal single ticket and executes the relevant contractual logic (trigger → action → result).

### F.1.4 Summary of technological validation exercise #06 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A6.1	Validated integration between SIGN-AIR and SYNC-REACT	EXE05 completed successfully	Required for establishment of single ticketing parameters and mainly the MCT	Prerequisite; without EXE05 this exercise cannot proceed
A6.2	Synthetic disruption dataset available	SYNC-REACT provides simulated disruptions calculations	Ensures reproducibility and coverage	Real disruptions not required at TRL4
A6.3	Controlled environment	Execution under lab conditions with fixed test accounts	Ensures system stability for contract testing	No live passenger or operational data involved

Table 24: technological validation exercise #06 assumptions overview

## F.2 Deviation from the planned activities

Only the SC of single ticketing was tested and not disruption management SC.

## F.3 Technological validation exercise #06 results

### F.3.1 Summary of technological validation exercise #06 results

Exercise #06 technological validation objective ID	Exercise #06 technological validation objective title	Exercise #06 success criterion ID	Exercise #06 success criterion	Exercise #06 technological validation results	Exercise #06 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3, DIGI1.4, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.2, DIGI2.3, DIGI2.4, DIGI2.8, DIGI2.9	Data used for the exercises is real data provided by project stakeholders	DIGI2=97%	ok
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.2, DIGI3.3	Users can negotiate and reach an agreement on DSA and SC. Finally they can sign the documentation.	DIGI3=100%	ok
OBJ-SOL0375-TVALP-PAX3	SIGN AIR contribution	PAX3.2	End user can calculate rail-air, air-rail,	PAX3 > 1	ok

	to PAX3- Resilience		air-air total connectivity index for the hub airport and perform different shorting.		
OBJ-SOL0375- TVALP-PAX6	SIGN AIR contribution to PAX6- Robustness	PAX6.1, PAX6.2	End users can update strategical planning with tactical data at SIGN-AIR's disruption module.	PAX6 = yes	ok
OBJ-SOL0375- TVALP-SAW2	Situational Awareness for intermodal itineraries targeting the contractual aspects of data sharing	SAW2	Validate that alerts of disruptions are consumed, evaluates their impact on hubs, and enables contractually governed responses through Smart Contract execution	SAW2 = yes	ok
OBJ-SOL0375- TVALP-TECH2	Monitoring the contractual aspects of data sharing of signed DSAs and SCs	TECH2	Platform identifies and executes SC correctly based on predefined conditions (if and thens)	TECH2 = ok	ok

			and monitors data-sharing flows in real-time and ensures SC compliance		
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Table 25: technological validation exercise #06 results

## F.3.2 Analysis of exercise #06 results per technological validation objective

### F.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%.

		Digitisation Pillar						DIGI1
		DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight		1	1	2	2	2	1	
EXE6				1	1	1	1	1

### F.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 97%.

DIGI2.4 is 0.73, according to the time measured, as it has been normalised between zero and one using inverted normalization (when lower is better).

		Connectivity Pillar										DIGI2	
		DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
Weight		2	2	2	1	1	1	1	1	2	1	2	
EXE6			1	1	0.73				1	1			0.97

### F.3.2.3. OBJ-SOL0375-TVALP-DIGI3 results

DIGI 3 has been analysed and validated as 100%.

		Data Sharing Pillar							DIGI3
		DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7	
Weight		1	1	2	1	2	1	1	

EXE6	1	1	1					1
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#### F.3.2.4. OBJ-SOL0375-TVALP-PAX3 results

PAX3 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX3.2: Number of tactical alternatives	num > 1	yes

#### F.3.2.5. OBJ-SOL0375-TVALP-PAX6 results

PAX6 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX6.1: Number of strategic options	Connectivity Index > 0,7	yes
PAX6.2: Strategic Frequency of service:	num peack > 4 num off-peck > 2	yes

#### F.3.2.6. OBJ-SOL0375-TVALP-SAW2 results

SAW2 has been analyzed and validated as ok, as detailed in A.3.1. table.

#### F.3.2.7. OBJ-SOL0375-TVALP-TECH2 results

TECH2 has been analyzed and validated as ok, as detailed in A.3.1. table.

### F.3.3 Unexpected behaviours/results

No unexpected results found.

### F.3.4 Confidence in results of technological validation exercise #06

#### F.3.4.1. Level of significance/limitations of technological validation exercise results

The test is performed under controlled lab conditions with simulated disruptions.

The execution time of Smart Contracts measured in a non-scaled environment.

#### F.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise took place among different partners from the consortium, which guaranteed the technical validation of the platform.

## F.4 Conclusions

Exercise #06 has been successfully run, with no issues or problems reported during the activity.

### F.4.1.1 Conclusions on concept clarification

EXE6 is the first exercise in the TRL4 to validate the automated, contract-driven response to a multimodal disruption — the scenario that most directly represents the operational promise of SIGN-AIR. While EXE2 demonstrated that SYNC-REACT could detect a disruption and update connectivity indices, and Exercise 05 demonstrated that the integrated platform could support contract negotiation using dynamic itinerary data, Exercise 06 brings these two capabilities together and advances them to their logical conclusion: when a disruption occurs on a rail leg that threatens the Minimum Connection Time of a multimodal single ticket, the platform automatically identifies the relevant Smart Contract instance and executes the contractually agreed response — whether that is a passenger notification, a rebooking, or a compensation action — without manual intervention.

The successful execution of this end-to-end trigger-action-result workflow is a conceptually significant milestone. It validates the core operational concept of SIGN-AIR as an autonomous contractual enforcement mechanism: a platform that does not merely support human decision-making but actively executes pre-agreed obligations in response to operational events. This is the feature that distinguishes SIGN-AIR from a conventional data-sharing or ticketing platform, and its confirmation at TRL4 — even under controlled and synthetic conditions — establishes the conceptual foundation for the more complex and realistic validation that must follow.

However, a critical deviation must be noted: only the single-ticketing Smart Contract was tested in this exercise, and the disruption management Smart Contract — which governs the more complex mitigation and rebooking logic — was not included. This is a substantial concept clarification gap. The single-ticketing SC covers the traceability and notification dimension of a disruption response, but it does not cover the contractual resolution dimension: who is liable, what alternatives are offered, how compensation is calculated, and how TSPs negotiate revised obligations under disrupted conditions. The disruption management SC is operationally the more consequential of the two, and its absence from this exercise means that the concept of automated contractual disruption resolution — one of the most commercially and legally sensitive functions of the platform — remains unvalidated. This must be addressed as a priority in TRL6.

From a human enabler perspective, Exercise 06 also raises an important concept clarification question about the boundary between automated execution and human oversight. The platform correctly executed Smart Contract logic based on predefined thresholds and conditions, but the exercise did not explore what happens when the automated response is inappropriate — for example, when a delay falls just above the trigger threshold but the operational context suggests that the connection is still achievable, or when the automated rebooking option conflicts with a passenger's stated preferences

or special needs. These are scenarios where the Operations Control Officer and the Passenger Service Desk role must be able to intervene, override, or escalate, and the current validation does not confirm that such human override mechanisms exist and function correctly. This is a concept clarification item that must be addressed before the platform can be considered operationally viable.

#### F.4.1.2 Conclusions on technical feasibility

Exercise 06 confirms the technical feasibility of automated Smart Contract execution triggered by disruption events at TRL4, with no unexpected behaviours and only one deviation — the exclusion of the disruption management SC — from the planned activities. All seven validation objectives were met, with DIGI1 and DIGI3 scoring 100%, DIGI2 scoring 97%, and PAX3, PAX6, SAW2, and TECH2 all validated as met.

The disruption data reception function performed within the defined thresholds: 100% of simulated disruption updates were received and interpreted accurately, with reception latency under 5 seconds and no parsing errors. Smart Contract triggering achieved the 95% automated execution target, with execution logs confirming activation without manual intervention in all qualifying cases. Trigger-action logic was validated as correct across all tested scenarios, with notifications, compensation calculations, and rebooking initiations consistent with the predefined contractual conditions. Data traceability and integrity were confirmed through audit tools, with no discrepancies between disruption event logs and SC execution records. Single ticketing traceability was maintained across all disruption scenarios, with ticket IDs preserved from origin to resolution.

DIGI1 scored 100% with the same four indicators as EXE05 — DIGI1.3, DIGI1.4, DIGI1.5, and DIGI1.6 — all rated at 1, confirming consistency in the digitisation performance of the integrated platform across both the nominal (EXE05) and disrupted (EXE06) operational scenarios.

DIGI2 scored 97%, with DIGI2.4 rated at 0.73 — the lowest latency score recorded across the TRL4 campaign. DIGI2.4 measures the processing latency of the connectivity update triggered by a disruption event, and the 0.73 score reflects the additional computational load introduced by Smart Contract execution on top of the connectivity recalculation. This is a technically important finding: it suggests that the integration of contractual logic into the disruption response pipeline introduces measurable latency that was not present in the standalone SYNC-REACT configuration tested in EXE02. The confidence section explicitly notes that SC execution time was measured in a non-scaled environment, which means the 0.73 value should be treated as an optimistic baseline — in a production environment with concurrent disruptions and multiple active SC instances, latency will likely increase. This must be tested explicitly in TRL6.

DIGI3 maintained 100% on DIGI3.1, DIGI3.2, and DIGI3.3, consistent with EXE05, confirming that the data sharing pillar performance is stable across both nominal and disrupted conditions at the current coverage level.

#### F.4.1.3 Conclusions on performance assessment

Exercise 06 contributes to DIGI1, DIGI2, DIGI3, PAX3, PAX6, SAW2, and TECH2, introducing PAX3 for the first time in the TRL4 campaign.

For DIGI1, the 100% score confirms that automated SC execution does not introduce any regressions in the digitisation performance of the platform, and that the data accessibility and standardisation functions operate correctly under disrupted conditions as well as nominal ones.

For DIGI2, the 97% score with DIGI2.4 at 0.73 is the first result in the campaign where the latency dimension shows a notable reduction from the EXE02 baseline of 0.89. The three-point reduction in the overall DIGI2 score relative to EXE05's 100% is attributable entirely to this single latency indicator, and it is directionally consistent with the expectation that adding automated SC execution to the disruption response pipeline increases end-to-end processing time. The remaining DIGI2 indicators — DIGI2.2, DIGI2.3, DIGI2.8, and DIGI2.9 — all scored 1, confirming that the connectivity and data sharing functions of the platform remain fully performant under disruption conditions.

For DIGI3, the maintained 100% on the three assessed indicators confirms stability. The same DIGI3 gap noted in EXE05 applies here: DIGI3.4 through DIGI3.7 remain unassessed and should be allocated to subsequent exercises.

PAX3 — Resilience — was assessed for the first time in this exercise, with PAX3.2 validated as met. PAX3.2 confirms that the platform can calculate more than one tactical alternative for passengers affected by a disruption, providing the minimum condition for a genuine resilience contribution. The result is positive but narrow: PAX3.2 establishes that alternatives exist, not that they are of adequate quality, timeliness, or alignment with passenger rights obligations. Broader PAX3 coverage in future exercises should assess the quality and operational relevance of the alternatives generated, not only their existence.

PAX6 was validated as met on both PAX6.1 and PAX6.2, consistent with EXE01, confirming that the strategic planning robustness indicators hold under the tactical disruption conditions introduced in this exercise.

## F.5 Recommendations

The results of Exercise 06 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The disruption management Smart Contract, excluded from this exercise, must be validated in TRL6 as a priority. This SC governs the commercially and legally consequential dimension of disruption resolution — liability allocation, alternative provision, compensation calculation, and TSP renegotiation — and its absence from the current campaign represents the most significant functional validation gap in the entire exercise set. The TRL6 exercise plan should include dedicated scenarios covering cascading disruptions, simultaneous multi-leg delays, and situations where the automated SC response requires human review or override before execution.

The manual delay injection method used in this exercise — consistent with the approach in EXE02 — must be replaced with an automated disruption generation mechanism in future exercises. Manual injection limits the speed, realism, and scalability of disruption testing, and prevents the validation of

scenarios where disruptions arrive concurrently or in rapid succession. An automated injection interface, capable of generating delay events programmatically from defined distributions, should be developed and integrated into the test environment before TRL6.

The DIGI2.4 latency score of 0.73, recorded in a non-scaled environment, should be treated as a performance risk for production deployment. A dedicated performance test should be designed for TRL6 to measure SC execution latency under increasing concurrent load — including scenarios with multiple simultaneous disruption events and multiple active SC instances — to establish whether the latency profile remains within acceptable operational thresholds.

Human override and escalation mechanisms — allowing the Operations Control Officer or Passenger Service Desk to intervene in, modify, or override automated SC execution — should be defined as a functional requirement and included in the TRL6 validation scope. The absence of validated human override capability is a concept clarification gap with direct implications for operational viability and regulatory compliance.

## Appendix G Technological validation exercise #07 report

This appendix provides the details of the technological validation TVAL.07.1-SIGN-AIR-0375-TRL6, the Assessment of Scenario 1.

### G.1 Summary of the technological validation exercise #07 plan

This exercise validates that SIGN-AIR platform can register end users and that they can create their data attributes catalogue and identify potential collaborators for single ticketing.

#### G.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

This exercise validates Scenario 1, testing SIGN-AIR's real-world onboarding, catalogue creation, and collaboration discovery for TSPs to enable single ticketing in multimodal transport (airlines and high-speed railways). It covers end-to-end processes using real data from Emilia-Romagna operators.

Relevant use cases from TS/IRS:

UC-01: User registration and role-based access.

UC-02: Catalogue definition and publication.

UC-03: Automated TSP matching.

UC-04: Workflow validation in multi-operator settings.

##### Key validation objectives

Key objectives include verify registration, roles, and access for TSP representatives, validate catalogue creation and publication for airlines/railways, confirm discovery algorithms' matching accuracy and assess functionality in realistic multi-operator conditions.

##### Scenarios:

- Reference: manual, ad-hoc catalogue exchange via bilateral agreements, causing inefficiencies.
- Solution: automated registration, catalogue management, and partner discovery on SIGN-AIR for efficient multimodal collaborations.

##### Validation technique and platform

Site Acceptance Test (SAT) conducted at Bologna, demonstrating Technology Readiness Level (TRL) 6 (technology validated in a relevant environment). This extends prior lab-based validation (EXE04) by incorporating real participants, datasets, and regional context for performance assessment under realistic conditions, while remaining controlled.

SIGN-AIR environment, a digital platform supporting TSP onboarding, data attribute management, catalogue publication, and algorithmic matching for collaboration discovery in SESAR's multimodal transport ecosystem.

## G.1.2 Summary of technological validation exercise #07 technological validation objectives and success criteria

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a Site Acceptance Test (SAT) at TRL 6. These criteria emphasize real-world applicability, using actual TSP participants and datasets from the Emilia-Romagna region in a relevant environment at Bologna.

- User registration and access management: Success is achieved if 100% of participating TSP users successfully register accounts, assign roles, and demonstrate profile-based access to functions without errors, verified through logged sessions and role enforcement tests (e.g., denying non-rep access)
- Catalogue creation and publication: Success is met if TSPs create and publish catalogues with at least 90% accuracy in defining attributes (e.g., service types, schedules for high-speed rail and air), confirmed by data validation tools comparing input to published outputs, with no publication failures in 15-20 real dataset instances, and timeliness under 5 minutes per catalogue.
- Automated collaboration discovery: Success is confirmed if discovery algorithms match compatible TSPs (e.g., air-rail synergies) with 85% precision based on catalogue attributes, validated through 10 matching queries using real regional data, where proposed collaborations are reviewed manually for relevance and logged for algorithmic accuracy.
- Functional correctness under realistic conditions: Success is established if end-to-end workflows (onboarding to matching) complete seamlessly for multiple operators (e.g., 4+ from Emilia-Romagna) in 95% of test scenarios, assessed via system logs, performance metrics (e.g., latency <10 seconds per action), and observer reports confirming no disruptions in realistic multi-user sessions.

### Associated Requirements (Coverage)

Requirements are derived from typical TS/IRS for transport collaboration platforms (e.g., compliance with EU GDPR for user data, INSPIRE for catalogue geospatial attributes, and multimodal standards like TAP TSI). Coverage is assessed for SAT validation in a relevant environment; all core requirements are planned for coverage unless justified otherwise.

- User registration and access management: Covers TS requirements for secure onboarding (e.g., authentication standards, role-based access with <1% failure rate). Fully addressed via real-user tests. No uncovered items.
- Catalogue creation and publication: Addresses IRS for data handling (e.g., attribute standardization, publication integrity). Fully covered through creation validations with real datasets. No uncovered items.

- Automated collaboration discovery: Meets TS for matching logic (e.g., algorithm accuracy >80%, semantic compatibility). Fully covered with discovery tests. No uncovered items.
- Functional correctness under realistic conditions: Satisfies IRS for operational workflows (e.g., multi-user scalability, regional context integration). Partial coverage; full production-scale load testing (e.g., hundreds of simultaneous users) is not included, justified as out-of-scope for TRL 6 SAT, which demonstrates relevance with controlled real data rather than exhaustive operational deployment, reserving such for higher TRL pilots.

### G.1.3 Summary of technological validation exercise #07 validation scenarios

Reference scenario(s)

TSPs operate without a common platform. Catalogue creation and data exchange are handled manually via bilateral agreements or email. Collaboration opportunities are identified ad hoc, leading to inefficiencies and low automation.

Solution scenario(s)

TSPs use the SIGN-AIR platform to register, define catalogues, and discover potential partners automatically. The system identifies feasible collaborations based on matching catalogue attributes (e.g., routes, service availability, or pricing schemes), supporting future single ticketing contracts.

### G.1.4 Summary of technological validation exercise #07 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A7.1.1	Availability of test users	Participants will have basic knowledge of the data attributes provided by an airline and/or a railway operator.	Needed for realistic onboarding.	Missing participation may reduce test representativeness.
A7.1.2	Operational data availability	TSPs provide valid catalogue entries with accurate metadata.	Required for discovery and matching	Missing or invalid data may reduce matching accuracy.
A7.1.3	Data availability to discover combined itineraries	Data availability to discover combined itineraries therefore upload data at the SYNC-REACT modules to be	Required for negotiation of single ticketing	Missing or invalid data may reduce the procedure to the next step and reduce the value of

	synchronized. Sparksee was used in this module.	match making in single ticketing.
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**Table 26: technological validation exercise #07 assumptions overview**

## G.2 Deviation from the planned activities

Data produced to variate the results of testing were at a certain extend synthetic as we could not match the dates of air and rail.

## G.3 Technological validation exercise #07 results

### G.3.1 Summary of technological validation exercise #07 results

Exercise #07 technological validation objective ID	Exercise #07 technological validation objective title	Exercise #07 success criterion ID	Exercise #07 success criterion	Exercise #07 technological validation results	Exercise #07 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.1, DIGI1.2, DIGI1.3, DIGI1.4, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 79%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.1, DIGI2.6,	Data used for the exercises is real data provided by project stakeholders	DIGI2=73%	ok
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.5	Users can negotiate and reach an agreement on DSA and SC. Finally they can sign the	DIGI3=100%	ok

			documentatio n.		
OBJ-SOL0375- TVALP-PAX1	SIGN AIR contribution to PAX1- Travel Time	PAX1.1, PAX1.3, PAX1.4	End user can select multimodal itineraries with high quality index and create a single ticket, with acceptable transfer time		
OBJ-SOL0375- TVALP-PAX4	SIGN AIR contribution to PAX4- Ease	PAX4.1	End user to select itineraries with 1 transfer	PAX4 < 1	ok
OBJ-SOL0375- TVALP-PAX6	SIGN AIR contribution to PAX6- Robustness	PAX6.1, PAX6.2	End users can update strategical planning with tactical data at SIGN-AIR's disruption module.	PAX6 = yes	ok
OBJ-SOL0375- TVALP-SAW1	Planning and selection of feasible and attractive intermodal itineraries	SAW1	End users can upload schedules in SYNC-REACT module and identify an create a SC based on feasible multimodal itineraries.	SAW1 = yes	ok

OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	TECH1	Platform allows users to follow full process for creation and signature of a DSA and SC.	TECH1 = ok	ok
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Table 27: technological validation exercise #07 results

## G.3.2 Analysis of exercise #07 results per technological validation objective

### G.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 79%.

DIGI1.6 has been rated as partial, as the data needs to be in specific format to be uploaded in the platform.

	Digitisation Pillar						DIGI1
	DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight	1	1	2	2	2	1	
EXE7	1	1	1	1	1	0,5	0,79

### G.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 73%.

DIGI2.2 rated as partial, as it was not possible to access data from a real-life environment for the testing.

DIGI2.4, DIGI2.5 and DIGI2.6 have been normalised between zero and one using inverted normalization (when lower is better).

Connectivity Pillar
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	DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10	DIGI2.11	DIGI2
Weight	2	2	2	1	1	1	1	1	2	1	2	
EXE7	1	0,5		0,6	0,75	0,725						0,73

### G.3.2.3. OBJ-SOL0375-TVALP-DIGI3 results

DIGI 3 has been analysed and validated as 100%.

	Data Sharing Pillar							DIGI3
	DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7	
Weight	1	1	2	1	2	1	1	
EXE7	1	1	1		1			1,00

### G.3.2.4. OBJ-SOL0375-TVALP-PAX1 results

PAX1 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX1.1: Total Travel Time	Total time < 240 minutes	ok
PAX1.3: Ratio Total Travel Time vs transfer time	Transfer Time/ Total Travel Time < 0,33	ok
PAX1.4: Ratio Total Travel Time vs fastest alternative	TTT - TTTbest / TTT	tes

### G.3.2.5. OBJ-SOL0375-TVALP-PAX4 results

PAX4 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX4.1: Number of minimum legs of the total travel journey	num <= 2	yes

### G.3.2.6. OBJ-SOL0375-TVALP-PAX6 results

PAX6 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX6.1: Number of strategic options	Connectivity Index > 0,7	yes
PAX6.2: Strategic Frequency of service:	num peack > 4 num off-peck > 2	yes

### G.3.2.7. OBJ-SOL0375-TVALP-SAW1 results

SAW1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### G.3.2.8. OBJ-SOL0375-TVALP-TECH1 results

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

## G.3.3 Unexpected behaviours/results

Two participants could not register due to browser issues.

## G.3.4 Confidence in results of technological validation exercise #07

### G.3.4.1. Level of significance/limitations of technological validation exercise results

The test focuses on nominal conditions and does not cover last-minute schedule updates.

The testers had to choose between air and highspeed rail operators roles as the sample prepared and the DSA and SC were for Single Ticketing between such entities and additionally had to choose Italy as operation area as the data were prepared for BLQ airport as a hub. Only the railway operators could start the negotiation process.

### G.3.4.2. Quality of technological validation exercise results

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

The exercise took place with 20 concurrent users, which guaranteed the technical validation of the platform.

## G.4 Conclusions

Exercise #07 has been successfully run, with no issues or problems reported during the activity following the tasks of the tutorial that can be found [here](#). Below the are some instances platforms as it was used for the exercise conducted at BLQ airport on October 24<sup>th</sup>, 2025

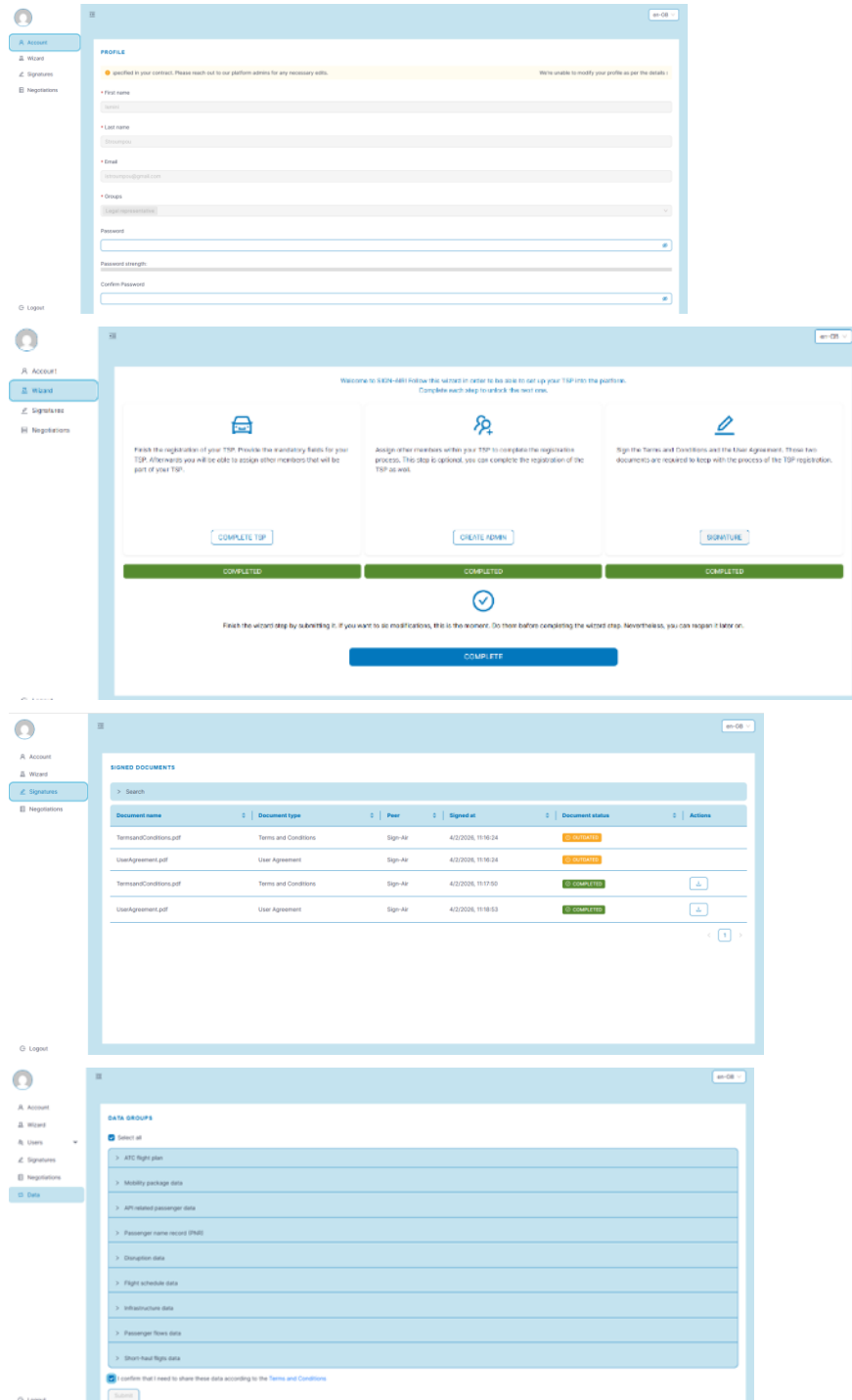


Figure 4: EXE07 visualisation example

### G.4.1.1 Conclusions on concept clarification

Exercise 07 marks a qualitative step change in the validation campaign: it is the first exercise conducted at TRL6, using real participants in a relevant environment held at Bologna Guglielmo Marconi Airport

on 24 October 2025 with 20 pairs of concurrent users representing airline and high-speed railway operators from the Emilia-Romagna region, airlines, data and computer engineers. This transition from laboratory-based to a real-world Site Acceptance Test is conceptually significant beyond its technical implications: it is the first time the SIGN-AIR platform was operated by individuals who interact with multimodal transport data in a professional context, rather than by consortium engineers validating functional specifications.

The exercise validated Scenario 1 in its TRL6 configuration — end-user registration, catalogue creation and publication, automated collaboration discovery, and the initiation of a single ticketing Smart Contract — and confirmed that the platform can support these functions in a realistic, multi-operator setting. The successful completion of the end-to-end workflow from onboarding to SC creation by 20 concurrent real participants is a strong conceptual validation result, and it confirms that the governance model underlying SIGN-AIR — where TSPs independently manage their data catalogues and discover collaboration opportunities through algorithmic matching — is operationally intuitive enough to be executed without specialist platform knowledge, provided a structured tutorial is available.

However, several concept clarification constraints emerged that are important for the next phase. The exercise required participants to choose between airline and high-speed railway operator roles, and constrained them to Italy as the operational area, because the data and contract templates prepared for the exercise were specific to BLQ as a hub. While this was a practical necessity, it reveals a concept-level challenge: the SIGN-AIR onboarding and discovery experience is currently designed around a pre-configured operational context, and it is not yet clear how the platform would guide a genuinely new TSP — one with no pre-existing data templates, contract structures, or regional configuration — through the onboarding process from scratch. This is a concept clarification question about platform generalisability that must be addressed before SIGN-AIR can be positioned as a scalable, open multimodal governance platform rather than a purpose-built solution for a specific set of pre-configured operators.

Furthermore, only railway operators could initiate the negotiation process in this exercise. This asymmetry — where one mode holds the negotiation initiation privilege — is not merely a technical configuration choice but has operational and commercial implications: it reflects assumptions about which party in a multimodal partnership carries the primary coordination responsibility, and those assumptions must be scrutinised and validated against the expectations of real airline and railway operators before the platform is deployed at scale.

The date alignment deviation is also noteworthy from a concept clarification perspective. Air and rail schedule data could not be matched by date, requiring the production of partially synthetic data to populate the itinerary combinations used in the exercise. In operational reality, the temporal alignment of air and rail schedules is one of the most practically challenging aspects of multimodal integration — timetables change seasonally, special events create temporary service alterations, and the granularity of schedule data differs significantly between modes. The concept of SIGN-AIR as a real-time, operationally accurate multimodal planning tool depends on resolving this alignment challenge, and the current validation only partially addresses it.

### G.4.1.2 Conclusions on technical feasibility

Exercise 07 confirms the technical feasibility of the SIGN-AIR platform's onboarding, catalogue management, and collaboration discovery functions at TRL6 under realistic multi-user conditions, with the following observations. All eight validation objectives were met, with DIGI3 scoring 100%, DIGI1 scoring 79%, DIGI2 scoring 73%, and PAX1, PAX4, PAX6, SAW1, and TECH1 all validated as met.

The most significant technical finding of this exercise is the performance of the DIGI2 latency indicators under real concurrent user load. With 20 simultaneous users operating the platform, DIGI2.4, DIGI2.5, and DIGI2.6 scored 0.60, 0.75, and 0.725 respectively — noticeably lower than the values recorded in EXE02 under controlled single-user conditions (0.89, 0.80, 0.90). This is the first exercise in the campaign to reveal a measurable degradation in latency performance attributable to concurrent user load, and it is an important technical signal for scalability planning. The non-scaled, single-user lab environment in which earlier exercises were conducted was insufficient to detect this degradation, confirming that TRL6 testing under realistic load conditions is essential for understanding the platform's true performance envelope. These values must be benchmarked against defined operational latency thresholds in TRL6 exercises to determine whether they remain within acceptable bounds as user numbers increase further.

DIGI1 scored 79%, with five indicators rated at 1 and DIGI1.6 rated at 0.5 due to the requirement for data to conform to specific upload formats. This is consistent with the DIGI1.6 pattern observed across the campaign when externally sourced, real-world data is involved: the format compliance indicator reflects a genuine operational constraint rather than a platform deficiency, but it is one that must be addressed through improved data onboarding tooling or more flexible ingestion capabilities before live deployment. Notably, DIGI1.1 and DIGI1.2 were assessed for the first time in any exercise in this campaign, both scoring 1, confirming that the platform meets the most fundamental digitisation requirements — the existence of digital data and its accessibility — under real-world conditions.

DIGI2.2 was rated at 0.5, as it was not possible to access data from a real-life operational environment for testing. This partial rating reflects the same underlying constraint as the date alignment deviation: the unavailability of temporally consistent, operationally representative air-rail schedule data limited the connectivity assessment. DIGI2.1 scored 1, confirming that the platform correctly handles the connectivity index calculation for the data that was available.

An unexpected behaviour was recorded: two participants could not register due to browser compatibility issues. While this did not affect the overall exercise outcome, it is a technical reliability finding that has direct implications for operational deployment — a platform that fails to register users due to browser constraints will face adoption resistance in environments where TSP IT infrastructure is not standardised or controlled.

DIGI3 scored 100% with DIGI3.1, DIGI3.2, DIGI3.3, and DIGI3.5 all rated at 1, extending the DIGI3 coverage beyond previous exercises and maintaining the 100% score under real-user, real-data conditions. DIGI3.5 — assessed here for the first time — covers the monitoring of data sharing

compliance against agreed contract terms, and its confirmation at 1 under TRL6 conditions is a strong result for the data governance pillar.

### **G.4.1.3 Conclusions on performance assessment**

Exercise 07 contributes to DIGI1, DIGI2, DIGI3, PAX1, PAX4, PAX6, SAW1, and TECH1, and is the first exercise in the campaign to assess DIGI1 across all six indicators simultaneously, providing the most complete DIGI1 picture of any single exercise.

For DIGI1, the 79% score is the lowest in the campaign, but should be contextualised carefully. It is the first exercise to assess DIGI1.1 and DIGI1.2 — both of which scored 1 — and the reduction from the 100% scores of TRL4 exercises is driven entirely by DIGI1.6 at 0.5, reflecting the real-world data format constraint. The TRL4 exercises that scored 100% on DIGI1 did so on a subset of indicators in controlled data conditions; the 79% here reflects a broader and more demanding assessment. Interpreted correctly, the EXE07 DIGI1 result represents a completer and more honest picture of the platform's digitisation performance under realistic conditions than any of the preceding scores.

For DIGI2, the 73% score is the lowest in the campaign and is driven by two factors: the DIGI2.2 partial score due to real-life data unavailability, and the latency indicator degradation under concurrent user load. The combination of these two factors in a single exercise makes it difficult to isolate their individual contributions, and future exercises should be designed to separate them — testing latency under real data conditions without concurrent user load, and testing concurrent user load with controlled synthetic data — to build a clearer picture of the independent performance drivers.

For DIGI3, the 100% score on four indicators including the newly assessed DIGI3.5 is the strongest DIGI3 result to date and confirms that the data sharing governance pillar performs consistently under real-world conditions. DIGI3.4, DIGI3.6, and DIGI3.7 remain unassessed and should be allocated to subsequent exercises.

PAX1, PAX4, and PAX6 were all validated as met, consistent with results across the TRL4 campaign, confirming that the passenger journey quality indicators hold under TRL6 conditions with real participants and partially real data. SAW1 and TECH1 were also validated as met, confirming that the end-to-end workflow from itinerary identification to SC creation and signature functions correctly in a realistic multi-operator environment.

## **G.5 Recommendations**

The results of Exercise 07 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The browser compatibility issue that prevented two participants from registering must be investigated and resolved before further TRL6 exercises. A cross-browser compatibility assessment should be conducted covering all major browsers and operating systems likely to be used by TSP representatives

in operational environments, and any identified incompatibilities should be resolved before the platform is made available to external users.

The negotiation initiation asymmetry — where only railway operators could start the negotiation process — should be reviewed and, where operationally justified, extended to allow any TSP type to initiate negotiations. If the asymmetry is intentional and reflects a validated operational assumption, that assumption should be documented explicitly and validated with real airline and railway representatives to confirm that it aligns with their commercial expectations.

The platform's generalisability beyond pre-configured operational contexts should be tested explicitly in a future exercise, by involving a TSP that has no prior relationship with the SIGN-AIR consortium and asking them to complete the onboarding and catalogue creation process independently, without a pre-configured regional data template. This would provide the most direct evidence of whether the platform is ready for open deployment.

The date alignment challenge between air and rail schedule data — which required partially synthetic data in this exercise — should be addressed through the development of a dedicated schedule alignment tool or a clearly defined data preparation protocol for TSPs, ensuring that operationally consistent multimodal datasets can be assembled and uploaded without manual intervention or synthetic augmentation.

The legal and ticketing dimension of the negotiation process was not represented in this exercise, as noted in the existing recommendations. Future exercises should specifically include participants in legal and commercial roles — such as legal counsel, commercial managers, and airline ticketing systems representatives — to validate the negotiation workflow from the perspective of the stakeholders who will ultimately be responsible for approving and executing real contracts.

More users working in different hours and without any guidance should be treated as a scalability risk.

## Appendix H Technological validation exercise #08 report

This appendix provides the details of the technological validation TVAL.08.1-SIGN-AIR-0375-TRL6, the Assessment of Scenario 2.

### H.1 Summary of the technological validation exercise #08 plan

This exercise validates that SIGN-AIR platform can receive, consume and process triggers of disruptions from the external Disruption Management functionality of SYNC-REACT module and is able to activate the execution of SC signed related to the single ticketing.

#### H.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

This exercise validates the SIGN-AIR platform's integration with SYNC-REACT for timetable synchronization and handling air-rail intermodal disruptions in single ticketing, achieving TRL 6. It covers TS/IRS use cases: disruption event ingestion (UC1), SC identification/execution (UC2), passenger responses including QR codes and MCT compliance (UC3), and notifications via Travel Companions (UC4).

##### Key Technological Validation Objectives and Scenarios

Confirm disruption trigger processing, SC activation/execution, end-to-end functionality, notifications, and role-based access in a relevant environment.

Reference Scenario: Independent rail/air operations; no automated adjustments for delays (e.g., rail to BLQ airport).

Solution Scenario: Pre-signed SCs; SYNC-REACT feeds delays (15–120 min simulated); platform executes SCs, provides alternatives/QR codes, and notifies passengers.

Testing uses test accounts and simulated delays on origin-destination pairs.

##### Technological Validation Technique and Platform

Site Acceptance Test (SAT) in a realistic, controlled environment, focusing on functional correctness, security, and performance under delays.

SIGN-AIR platform integrated with SYNC-REACT prototype, simulating SESAR intermodal ecosystem; includes Travel Companion for notifications.

#### H.1.2 Summary of technological validation exercise #08 technological validation objectives and success criteria

Success criteria define measurable outcomes to confirm that the technological validation objectives for the SIGN-AIR platform have been achieved.

- Successful reception, consumption, and processing of disruption triggers: The platform must ingest simulated disruption events (delays of 15, 30, 45, 60, 90, and 120 minutes) from the

external SYNC-REACT Disruption Management module for predefined origin-destination pairs without errors.

- Activation and execution of Smart Contracts (SC) for single ticketing: Upon detecting a disruption, the platform identifies and executes the relevant SC signed between an airline and a high-speed rail operator. Success is confirmed by system records showing SC execution (machine built identifies the clauses that need to be executed depending on the signed contract and the final SC code generated for that contract) and validation that the execution aligns with the disruption parameters (e.g., delay thresholds).

These criteria are evaluated through manual inspections, and simulated user interactions in the SAT environment, ensuring all objectives are demonstrably met.

#### Associated Requirements (Coverage)

The validation activities cover requirements related to disruption management, smart contract execution, and passenger handling in the SIGN-AIR platform, as implied by the Technical Specifications (TS) and Interface Requirements Specifications (IRS). The following requirements are addressed:

- Integration with external modules such as SYNC-REACT
- Smart Contract (SC) identification and execution for single ticketing.

### H.1.3 Summary of technological validation exercise #08 validation scenarios

#### Reference scenario(s)

Rail and air operators operate independently. Delays in rail legs do not trigger any automated adjustment for connecting flights. SCs are not executed.

#### Solution scenario(s)

There are signed Single Ticketing contracts between airlines and highspeed railway operators created by SIGN-AIR platform and there are passengers affected by a disruption at the first leg conducted by a train towards BLQ airport. SYNC-REACT feeds disruption events to SIGN-AIR. The platform executes SCs for affected single-ticketing itineraries and presents the SC conditions (if and thens) at the operators' respective dashboard.

### H.1.4 Summary of technological validation exercise #08 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
A8.1	Availability of sample datasets	Pre-defined itineraries with rail-first-leg delays are provided for the exercise	Required to simulate realistic disruption scenarios and validate SC execution	Missing or incomplete datasets could invalidate the exercise results
A8.2	Single Ticketing Contracts signed in SIGN-AIR platform.	SCs for single-ticketing itineraries are already signed in SIGN-AIR platform before the exercise 8 at the EXE 7.2.	Needed to trigger SC execution and observe the system response to disruptions	Without signed contracts, SC execution cannot be tested
A8.3	Laboratory environment	Controlled lab setting: no live operational disruptions included	Ensures safe and reproducible testing of disruption handling	Limits extrapolation to real-world scale; TRL6 context
A8.4	Delay breaks Minimum Connection Time (MCT)	Introduced delays are sufficient to break MCT for specific origin-destination itineraries	Required to validate disruption detection, SC execution, and alternative itinerary generation	If MCT is not broken, the exercise cannot test the platform's disruption management response
A8.5	Travel Companion connection	Travel Companion informed with SC execution actions in the platform	Required to verify that passengers are notified and can receive updated	If the connection is not established, the platform cannot demonstrate end-to-end passenger experience

			itineraries/QR codes	
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**Table 28: technological validation exercise #08 assumptions overview**

## H.2 Deviation from the planned activities

As in EXE08, we had multiple participants acting concurrently and making different choices. Due to time constraints, the Smart Contract execution was pre-simulated. SC (Smart Contract) to be executed needs to be signed. In order to proceed with the exercise #08, we needed specific signed SC related to selected combined itineraries. Therefore we had documents (SC pre-signed) linked to a combined itinerary of 24 November 2025 at 10:30h saved in the platform databases.

The main outcomes were: (1) identifying affected itineraries where the Minimum Connection Time (MCT) was not respected, and (2) triggering QR code generation.

## H.3 Technological validation exercise #08 results

### H.3.1 Summary of technological validation exercise #08 results

Exercise #08 technological validation objective ID	Exercise #08 technological validation objective title	Exercise #08 success criterion ID	Exercise #08 success criterion	Exercise #08 technological validation results	Exercise #08 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.4, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	OK
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.2, DIGI2.4, DIGI2.5,	Data used for the exercises is real data provided by project stakeholders	DIGI2=83%	ok

OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.2, DIGI3.3	Users can negotiate and reach an agreement on DSA and SC. Finally, they can sign the documentation.	DIGI3=100%	ok
OBJ-SOL0375-TVALP-PAX3	SIGN AIR contribution to PAX3-Resilience	PAX3.2, PAX3.4	End user can calculate total connectivity index related of tactical data	PAX3=yes	ok
OBJ-SOL0375-TVALP-PAX6	SIGN AIR contribution to PAX6-Robustness	PAX6.1, PAX6.2	End users can update strategical planning with tactical data at SIGN-AIR's disruption module.	PAX6 = yes	ok
OBJ-SOL0375-TVALP-SAW2	Situational Awareness for intermodal itineraries targeting the contractual aspects of data sharing	SAW2	End users can define mitigation options / recommendations per hub	SAW2 = yes	ok
OBJ-SOL0375-TVALP-TECH2	Monitoring the contractual aspects of data sharing	TECH2	Platform executes and monitors SC and data flows.	TECH2 = ok	ok

	of signed DSAs and SCs				
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Table 29: technological validation exercise #08 results

## H.3.2 Analysis of exercise #08 results per technological validation objective

### H.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%.

		Digitisation Pillar						DIGI1
		DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight		1	1	2	2	2	1	
EXE8					1		1	<b>1,00</b>

### H.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 83%.

DIGI2.4 and DIGI2.5 have been normalised between zero and one using inverted normalization (when lower is better).

		Connectivity Pillar										DIGI2	
		DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
Weight		2	2	2	1	1	1	1	1	2	1	2	
EXE8			1		0,78	0,56							<b>0,83</b>

### H.3.2.3. OBJ-SOL0375-TVALP-DIGI3 results

DIGI 3 has been analysed and validated as 100%.

		Data Sharing Pillar							DIGI3
		DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6	DIGI3.7	
Weight		1	1	2	1	2	1	1	
EXE8		1	1	1					<b>1,00</b>

### H.3.2.4. OBJ-SOL0375-TVALP-PAX3 results

PAX3 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX3.2: Number of tactical alternatives	num > 1	yes
PAX3.4: Destination Arrival Time Adherence	Time arrival - Time arrival planned < minimum connection time	yes

### H.3.2.5. OBJ-SOL0375-TVALP-PAX6 results

PAX6 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX6.1: Number of strategic options	Connectivity Index > 0,7	yes
PAX6.2: Strategic Frequency of service:	num peak > 4 num off-peak > 2	yes

### H.3.2.6. OBJ-SOL0375-TVALP-SAW1 results

SAW1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### H.3.2.7. OBJ-SOL0375-TVALP-TECH2 results

TECH2 has been analyzed and validated as ok, as detailed in A.3.1. table.

## H.3.3 Unexpected behaviours/results

No unexpected results found.

## H.3.4 Confidence in results of technological validation exercise #08

### H.3.4.1. Level of significance/limitations of technological validation exercise results

The exercise considers disruptions occurring on the first segment of a passenger's itinerary only. Any downstream or cascading impacts across subsequent legs are excluded from the scope.

Passenger decisions and interactions with the process are represented through a controlled simulation rather than real end-user behavior. As a result, outcomes may differ from real operations.

The objective is to validate the end-to-end functional flow and to assess usability from user perspective. The exercise is not designed to measure performance under high load, large volumes of concurrent transactions, or full operational complexity.

### H.3.4.2. Quality of technological validation exercise results

Testing took place with only one pair of operators.

## H.4 Conclusions

Exercise #08 was run successfully and concluded without issues or problems observed during the execution. The activity proceeded according to plan.

### H.4.1.1 Conclusions on concept clarification

EXE8 is the TRL6 counterpart to EXE6, validating Scenario 2 — automated Smart Contract execution triggered by disruption events — in a realistic Site Acceptance Test environment rather than the controlled laboratory setting of TRL4. It is therefore the exercise that most directly tests the operational promise of SIGN-AIR under conditions approaching real deployment, and its conclusions carry particular weight for the concept clarification of the solution.

The exercise confirmed that the end-to-end disruption response workflow — from disruption event ingestion through SYNC-REACT, to SC identification and execution, to the generation of QR codes and passenger-facing outputs — is conceptually coherent and functionally demonstrable in a realistic environment. The platform correctly identified affected itineraries where the Minimum Connection Time was not respected across the full range of simulated delay values (15 to 120 minutes) and executed the corresponding contractual logic by activating the relevant SC clauses. This confirms that the concept of automated, contract-governed disruption management is not merely technically feasible in a laboratory but is demonstrable under conditions that include real operator participants and pre-signed contractual relationships established in EXE7.

However, a significant deviation must be addressed from a concept clarification perspective: due to time constraints, the Smart Contract execution was pre-simulated rather than executed live during the exercise. This is a critical distinction. The conceptual value of Exercise 08 rests on demonstrating that the platform can autonomously identify the correct SC instance, evaluate the applicable clauses, and execute the trigger-action logic in response to a real-time disruption signal — all without manual pre-configuration for a specific event. A pre-simulated execution demonstrates that the output of that process looks correct but does not validate the process itself under live conditions. The concept of autonomous contractual enforcement — which is central to SIGN-AIR's operational proposition — therefore remains partially unvalidated at TRL6 and must be the primary focus of the next validation phase.

Additionally, the Travel Companion connection — the mechanism through which passengers receive real-time notifications, alternative itineraries, and QR codes — was not performed automatically in this exercise. This is operationally significant: the passenger-facing dimension of disruption management is not merely a user interface feature but a legal and contractual obligation under EU passenger rights frameworks. The concept of SIGN-AIR as a complete single-ticketing solution depends on the automated, timely, and accurate delivery of passenger notifications and alternatives, and this dimension remains unvalidated in an end-to-end automated sense. From the perspective of the Passenger Service Desk human enabler role, the absence of automated Travel Companion integration also raises the question of what the fallback process is when the automated notification fails — a concept clarification question that has both operational and regulatory implications.

The quality limitation noted in the exercise — that testing took place with only one pair of operators — also constrains the concept clarification conclusions. A single airline-railway pair operating in a pre-configured BLQ-centred scenario cannot generate evidence about how the platform behaves when multiple operator pairs with different SC structures, delay thresholds, and contractual obligations are active simultaneously. Multi-operator concurrency is not an edge case but the normal operating condition of a live multimodal platform, and this remains a fundamental concept clarification gap.

#### **H.4.1.2 Conclusions on technical feasibility**

EXE8 confirms the technical feasibility of the SIGN-AIR disruption management and SC execution pipeline at TRL6, with all seven validation objectives met and no unexpected behaviours reported. DIGI1 scored 100%, DIGI3 scored 100%, DIGI2 scored 83%, and PAX3, PAX6, were all validated as met. The disruption trigger reception and processing function performed correctly across all simulated delay values, with no ingestion errors or parsing failures. SC identification logic correctly matched disruption events to the relevant signed contract instances, and SC execution produced the expected outputs — affected itinerary identification and QR code generation — consistent with the predefined contractual conditions.

DIGI1 scored 100% on the two assessed indicators — DIGI1.4 and DIGI1.6 — both rated at 1. DIGI1.6 scoring 1 in this exercise is consistent with EXE06 and EXE05, where platform-native and consortium-provided data was used, and contrasts with the 0.5 rating in EXE07 where real externally sourced data introduced format constraints. This pattern across the campaign now clearly establishes that DIGI1.6 is a format compliance indicator that reflects the data preparation context of each exercise rather than a stable platform characteristic and should be interpreted accordingly in the overall SDI assessment.

DIGI2 scored 83%, with DIGI2.2 rated at 1, DIGI2.4 at 0.78, and DIGI2.5 at 0.56. The DIGI2.5 score of 0.56 is the lowest latency value recorded in the entire campaign and warrants specific attention. DIGI2.5 measures a different latency dimension from DIGI2.4 — likely the end-to-end SC execution time rather than connectivity recalculation latency — and its low score in this exercise, combined with the pre-simulated execution approach, raises a technical question: if the SC execution was pre-simulated, what does DIGI2.5 actually measure in this context? If it reflects the time taken to present pre-computed outputs to users, the 0.56 score is already a concern; if the live execution would be slower, the actual DIGI2.5 value under full automated execution could be lower still. This ambiguity must be resolved in future exercises through fully live SC execution measurement.

DIGI3 scored 100% on DIGI3.1, DIGI3.2, and DIGI3.3, consistent with EXE07, confirming stability of the data sharing governance layer under disruption conditions. The remaining DIGI3 indicators continue to be unassessed.

#### **H.4.1.3 Conclusions on performance assessment**

Exercise 08 contributes to DIGI1, DIGI2, DIGI3, PAX3, PAX6, SAW2, and TECH2, and introduces PAX3.4 for the first time in the campaign alongside the previously assessed PAX3.2.

For DIGI1, the 100% score on DIGI1.4 and DIGI1.6 confirms digitisation performance stability under TRL6 disruption conditions. The narrow indicator coverage in this exercise — only two of six DIGI1 indicators — reflects the exercise's focused scope on SC execution rather than full platform onboarding and data management, and should not be interpreted as a regression from EXE07's broader six-indicator assessment.

For DIGI2, the 83% score with DIGI2.5 at 0.56 is the most concerning latency result in the campaign. Cross-referencing with EXE07's results — where DIGI2.4 scored 0.60, 0.75, and 0.725 under 20 concurrent users — the EXE08 DIGI2.5 value of 0.56 suggests that SC execution introduces a latency burden that compounds the concurrency-related degradation observed in EXE07. Future exercises should be designed to quantify these two effects independently and to establish a clear performance budget for the integrated platform — specifying the maximum acceptable latency for each processing step and defining the number of concurrent users and SC executions that the platform can support within those thresholds.

For PAX3, both PAX3.2 and PAX3.4 were validated as met. PAX3.4 — Destination Arrival Time Adherence — is assessed here for the first time and confirms that the platform correctly evaluates whether a passenger's actual or projected arrival time falls within the MCT threshold, which is the fundamental calculation underpinning the entire SC execution trigger. This is a significant PAX result: it validates not only that alternatives are available (PAX3.2) but that the platform correctly identifies when those alternatives are needed and in time to act on them. The combination of PAX3.2 and PAX3.4 met together constitutes the strongest passenger resilience evidence in the campaign.

PAX6 was validated as met on both indicators, consistent with all previous exercises in which it was assessed, confirming the robustness of the strategic planning layer across the full range of TRL4 and TRL6 conditions tested.

## H.5 Recommendations

The results of Exercise 08 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The pre-simulated SC execution approach used in this exercise must not be repeated in future validation activities. The next TRL6 disruption exercise must implement fully automated, live SC execution — where the platform autonomously identifies the triggered contract, evaluates the applicable clauses, and executes the contractual response in real time without any pre-configuration for the specific event — and must measure the end-to-end execution time from disruption signal reception to SC output delivery as a primary performance indicator.

The Travel Companion automated notification connection, which was not achieved in this exercise, must be implemented and validated end-to-end in the next phase. The automated, timely delivery of passenger notifications and alternative itinerary options is not optional functionality but a core component of the solution's operational and legal proposition. A dedicated exercise should be designed specifically to validate the passenger notification workflow under disruption conditions,

including failure scenarios where the notification cannot be delivered and a human fallback process must be activated.

The concurrency limitation — a single operator pair — must be addressed in future exercises by designing scenarios with multiple simultaneous operator pairs holding different SC structures and facing concurrent disruption events. The exercise should include a target concurrency level that reflects the expected operational scale of the platform, and the results should be used to validate or update the platform's infrastructure dimensioning assumptions.

The DIGI2.5 score of 0.56 should be investigated to determine the specific processing step it reflects and whether the pre-simulated execution approach affected its measurement. Once clarified, a performance improvement target should be defined, and the indicator should be retested under fully live execution conditions in the next exercise.

The downstream and cascading disruption scenarios explicitly excluded from this exercise — where a delay on the first leg affects subsequent connections across multiple TSPs — should be incorporated into the TRL6 validation plan as a distinct exercise or sub-scenario. Cascading disruptions are operationally common and commercially consequential, and their absence from the current validation scope is a risk that must be addressed before the solution can claim full operational readiness.

## Appendix I Technological validation exercise #09.1 report

This appendix provides the details of the technological validation TVAL.09.1-SIGN-AIR-0375-TRL6, the validation of the Travel Companion.

### I.1 Summary of the technological validation exercise #09.1 plan

This exercise validates the end-to-end integration between the SIGN-AIR platform backend and a Travel Companion (TC) application, focusing on passenger-facing facilitation in case of intermodal disruptions.

#### I.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

This exercise validates the full end-to-end integration between the SIGN-AIR backend and the Travel Companion application in the event of an intermodal disruption. It confirms that a rail delay violating the Minimum Connection Time correctly triggers disruption detection, smart contract execution, and passenger-specific facilitation measures. Finally, it verifies that these measures are reliably delivered and displayed to passengers via the Travel Companion, including a usable fast-track QR code.

##### Key Technological Validation Objectives and Scenarios

The exercise involves the integration of Disruption Management systems, the SIGN-AIR backend platform, blockchain-based Smart Contracts for single ticketing, and the Travel Companion passenger application. Key technologies include real-time disruption detection, smart contract execution for automated facilitation, and mobile delivery mechanisms such as QR code generation. Together, these components demonstrate an interoperable, end-to-end digital ecosystem for passenger assistance in intermodal travel.

Reference Scenario: Represents current baseline without SIGN-AIR or TC support

Solution Scenario: Disruption is detected and SIGN-AIR executes the related Smart Contract.

##### Technological Validation Technique and Platform

Site Acceptance Test (SAT) in a Real-Time Simulation (RTS) with expert observation.

SIGN-AIR platform integrated with SYNC-REACT prototype, with a predefined datasets for rail and air itineraries, and including Travel Companion for notifications.

#### I.1.2 Summary of technological validation exercise #09.1 technological validation objectives and success criteria

Success criteria are defined for each key validation objective to establish achievement through measurable outcomes in a real-time simulation (RTS) at TRL 6. These criteria emphasize end-to-end functionality and timeliness, using simulated disruptions in a near-realistic environment with the SIGN-AIR backend and TC app.

- Disruption detection and notification: Success is achieved if 100% of simulated disruptions (e.g., 15 rail delays violating MCT) are detected by external Disruption Management and notified to SIGN-AIR within 30 seconds, verified by system logs showing accurate event details (e.g., delay magnitude, affected leg) and notification receipts.
- Identification of affected intermodal O-D and Smart Contract: Success is met if SIGN-AIR correctly identifies the impacted Origin-Destination and associated SC in 95% of cases, confirmed through database queries and logs matching disruption data to contracts for 20 test scenarios, with identification latency under 10 seconds.
- Smart Contract execution and action triggering: Success is confirmed if SC executes automatically upon trigger, initiating facilitation actions (e.g., rebooking alerts) in all test runs, validated via execution traces and outcome checks across 15 simulations ensuring 100% trigger-action alignment.
- Generation of passenger-specific facilitation measures: Success is established if measures (e.g., fast-track access codes) are generated for 100% of affected passengers in simulations, assessed by data integrity checks and personalization verification (e.g., based on passenger profiles) in 20 cases.
- TC reception, presentation, and QR code generation: Success is verified if TC receives and displays information (including QR codes) within 60 seconds of generation, with 100% accuracy in presentation (e.g., no display errors), tested via app logs, user interface screenshots, and timeliness metrics over 15 end-to-end runs.
- Overall practical integration: Success is achieved if the full sequence completes end-to-end without failures in 90% of simulations, confirmed by holistic logs, performance metrics (e.g., total latency <2 minutes), and operational readiness reports demonstrating seamless disruption handling.

Requirements are derived from typical TS/IRS for intermodal transport systems (e.g., compliance with EU PRM TSI for passenger rights, real-time data standards like SIRI, and app usability per ISO 9241). Coverage is assessed for RTS validation; all core requirements are planned for coverage unless justified otherwise.

- Disruption detection and notification: Covers TS requirements for event detection (e.g., accuracy >98%, notification protocols). Fully addressed via simulation tests. No uncovered items.

- Identification of affected intermodal O-D and Smart Contract: Addresses IRS for data linking (e.g., O-D matching efficiency). Fully covered through identification validations. No uncovered items.
- Smart Contract execution and action triggering: Meets TS for automation (e.g., execution reliability, trigger thresholds). Fully covered with execution tests. No uncovered items.
- Generation of passenger-specific facilitation measures: Satisfies IRS for personalization (e.g., measure generation based on profiles). Fully covered via measure checks. No uncovered items.
- TC reception, presentation, and QR code generation: Covers TS for user interface (e.g., timeliness, QR code standards). Fully covered with app tests. No uncovered items.
- Overall practical integration: Addresses IRS for system integration (e.g., end-to-end latency, resilience). Partial coverage; full-scale field testing with real passengers is not included, justified as out-of-scope for TRL 6 RTS, which uses simulated environments to demonstrate relevance without live operational risks, reserving user-involved trials for higher TRLs.

### I.1.3 Summary of technological validation exercise #09.1 validation scenarios

Reference scenario(s)

Disruptions occur on the first leg of intermodal journeys with no TC support. Passengers receive no automated notifications, rebooking, or facilitation and manage actions manually.

Solution scenario(s)

When a disruption is detected and SIGN-AIR executes the related Smart Contract. The passenger receives real-time facilitation via Travel Companion, including QR codes for airport services.

### I.1.4 Summary of technological validation exercise #09.1 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
A9.1	Availability of test disruption events	Simulated rail disruption events are provided for the exercise	Required for testing end-to-end reaction	Lack of realistic events could limit exercise validity

A9.2	Travel Companion connectivity	TC application can receive and display messages from SIGN-AIR in near real-time	Needed to validate passenger-facing integration	Connectivity issues may compromise TC performance and feedback collection
A9.3	Passenger using TC	TC application is available at the play store and downloadable by the passenger	Needed to interface with the passenger	Lack of digitilization at passanger level can limite the feasibility of the usage
A9.4	Security measures of airports	All the procedures to been taken care to perform the testing without compromising the security of BLQ or to disrupt the daily operations of the passengers at security lanes	Need to follow the rules of security authentication and permissions of BLQ	Low number of testers to avoid disrupting the passengers flows at security lines
A9.5	No luggage to drop off	Affected passenger only has hand luggage	Need to simplify the process of testing	Provide the passenger the opportunity to declare luggage to drop off or not or identify it in an automated way.

Table 30: technological validation exercise #09.1 assumptions overview

## I.2 Deviation from the planned activities

No deviations.

## I.3 Technological validation exercise #09.1 results

### I.3.1 Summary of technological validation exercise #09.1 results

Exercise #09.1 technological validation objective ID	Exercise #09.1 technological validation objective title	Exercise #09.1 success criterion ID	Exercise #09.1 success criterion	Exercise #09.1 technological validation results	Exercise #09.1 technological validation
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					objective status
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.2, DIGI2.4, DIGI2.5,	Data used for the exercises is real data provided by project stakeholders	DIGI2=96%	ok
OBJ-SOL0375-TVALP-DIGI3	SIGN-AIR platform contribution to DATA SHARING Pillar	DIGI3.1, DIGI3.2, DIGI3.3	Users can negotiate and reach an agreement on DSA and SC. Finally they can sign the documentation.	DIGI3=100%	ok
OBJ-SOL0375-TVALP-PAX3	SIGN AIR contribution to PAX3-Resilience	PAX3.2, PAX3.4	End user can calculate total connectivity index related of tactical data		ok
OBJ-SOL0375-TVALP-PAX6	SIGN AIR contribution to PAX6-Robustness	PAX6.1, PAX6.2	End users can update strategical planning with tactical data at SIGN-AIR's disruption module.	PAX6 = yes	ok
OBJ-SOL0375-TVALP-SAW1	Planning and selection of feasible and attractive	SAW1	End users can upload schedules in SYNC-REACT module and identify an	SAW1 = yes	ok

	intermodal itineraries		create a SC based on feasible multimodal itineraries.		
OBJ-SOL0375-TVALP-SAW2	Situational Awareness for intermodal itineraries targeting the contractual aspects of data sharing	SAW2	End users can define mitigation options / recommendations per hub	SAW2 = yes	ok
OBJ-SOL0375-TVALP-TECH1	Technical Feasibility of governance-driven contract creation for predefined Multimodal Objectives	TECH1	Platform allows users to follow full process for creation and signature of a DSA and SC.	TECH1 = ok	ok
OBJ-SOL0375-TVALP-TECH2	Monitoring the contractual aspects of data sharing of signed DSAs and SCs	TECH2	Platform executes and monitors SC and data flows.	TECH2 = ok	ok

Table 31: technological validation exercise #09.1 results

## I.3.2 Analysis of exercise #09.1 results per technological validation objective

### I.3.2.1. OBJ-SOL0375-TVALP-DIGI2 results

DIGI 2 has been analysed and validated as 96%.

DIGI2.4 has been normalised between zero and one using inverted normalization (when lower is better).

		Connectivity Pillar										DIGI 2	
		DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
Weight		2	2	2	1	1	1	1	1	2	1	2	
EXE9.1			1		0,89								0,96

### 1.3.2.2. OBJ-SOL0375-TVALP-DIGI3 results

DIGI 3 has been analysed and validated as 100%.

		Data Sharing Pillar						DIGI3	
		DIGI3.1	DIGI3.2	DIGI3.3	DIGI3.4	DIGI3.5	DIGI3.6		DIGI3.7
Weight		1	1	2	1	2	1	1	
EXE9.1		1		1					1,00

### 1.3.2.3. OBJ-SOL0375-TVALP-PAX3 results

PAX3 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX3.4: Destination Arrival Time Adherence	Time arrival - Time arrival planned < minimum connection time	yes

### 1.3.2.4. OBJ-SOL0375-TVALP-PAX6 results

PAX6 has been analyzed and validated as ok.

	How to calculate	Evaluation
PAX6.1: Number of strategic options	Connectivity Index > 0,7	yes
PAX6.2: Strategic Frequency of service:	num peak > 4 num off-peak > 2	yes

### 1.3.2.5. OBJ-SOL0375-TVALP-SAW1 results

SAW1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### **I.3.2.6. OBJ-SOL0375-TVALP-SAW2 results**

SAW2 has been analyzed and validated as ok, as detailed in A.3.1. table.

### **I.3.2.7. OBJ-SOL0375-TVALP-TECH1 results**

TECH1 has been analyzed and validated as ok, as detailed in A.3.1. table.

### **I.3.2.8. OBJ-SOL0375-TVALP-TECH2 results**

TECH2 has been analyzed and validated as ok, as detailed in A.3.1. table.

## **I.3.3 Unexpected behaviours/results**

No unexpected results found.

## **I.3.4 Confidence in results of technological validation exercise #09.1**

### **I.3.4.1. Level of significance/limitations of technological validation exercise results**

Only first-leg disruptions are considered; multi-leg cascading disruptions are excluded.

Passenger interaction is simulated; real operational constraints may differ.

Focus is on functional integration and usability rather than large-scale operational performance.

The exercise took place with only 4 selected participants as BLQ had to request for permissions to enter fast track and additionally not interrupt the daily operation of the security check in

A mock up delay was produced to be able to test the TC QR code for a specific leg that was operating the 24 of October at 13:30.

### **I.3.4.2. Quality of technological validation exercise results**

As testing took place with different stakeholders (railway operators, airlines/airport), their positive feedback assesses robustness and potential improvements for operational implementation.

## **I.4 Conclusions**

Exercise #09.1 has been successfully run, with no issues or problems reported during the activity.

Exercise 09.1 is the most operationally grounded exercise in the entire TRL6 campaign. It is the first exercise in which the SIGN-AIR solution was tested in a physical airport environment — Bologna Guglielmo Marconi Airport on 24 October 2025 — with participants physically present at the security fast-track lane, interacting with the Travel Companion application on mobile devices to receive and act upon a simulated disruption notification in real time. This is a conceptually defining moment for the solution: it moves SIGN-AIR from a platform validated in meeting rooms and laboratories to one that has been operated in the physical space where its value proposition must ultimately be realised. The

exercise confirmed that the end-to-end integration between SYNC-REACT disruption detection, SIGN-AIR SC execution, and Travel Companion passenger delivery is functionally complete and operationally demonstrable. A simulated rail delay breaching the MCT threshold triggered the correct SC execution, generated a fast-track QR code personalised to the affected passenger, delivered it to the TC application within the defined time threshold, and enabled the participant to use it at the BLQ security fast-track lane. This is the most complete passenger-facing validation result in the campaign and validates a concept that no previous exercise had been able to confirm end-to-end: that a contractually governed, automated disruption response can reach a passenger as an actionable, physical-world output in time to make a practical difference to their journey. The concept clarification implications of this result are significant. It confirms that the SIGN-AIR disruption response concept is not purely a back-office data exchange mechanism but a passenger-facing operational tool with real-world utility. The QR code delivery and fast-track access use case demonstrates that the platform can generate outputs that are immediately actionable by airport operations staff — confirming that the concept crosses the boundary between digital governance and physical operations, which is a prerequisite for genuine multimodal single ticketing at scale. However, several conceptual constraints must be noted. The exercise was conducted with only four participants, due to the operational and security constraints of conducting testing at a live airport security checkpoint. BLQ required specific permissions for access to the fast-track lane, and the number of testers was intentionally kept low to avoid disrupting normal passenger flows. This is not a criticism of the exercise design — it reflects the reality of validating a solution in a live operational environment — but it means that the concept has been demonstrated as a proof of concept for a single, carefully choreographed scenario rather than validated as a robust operational process. The four-participant scale cannot generate evidence about how the system behaves when multiple passengers with different itineraries, different TC configurations, and different disruption scenarios are affected simultaneously.

The assumption regarding luggage — that all test participants carried hand luggage only — also highlights an important concept clarification gap. In real operations, passengers with checked baggage face a fundamentally different disruption response process: baggage cannot be automatically rerouted through a QR code, and the contractual and operational obligations triggered by a missed connection involving checked luggage are considerably more complex. The concept of SIGN-AIR as a complete single-ticketing disruption management solution must eventually address the baggage handling dimension, and this should be scoped into future validation activities.

Assumption A9.3 — that passengers have the TC application downloaded and available — also deserves conceptual attention. The operational feasibility of a passenger-facing disruption notification system depends on a sufficient proportion of passengers actively using the application at the time of travel. This is a digital adoption challenge that is organisational, commercial, and behavioural in nature, and it is entirely outside the scope of what the platform itself can resolve. Future concept clarification activities should address how the solution functions for passengers who are not TC users — whether through alternative notification channels, airport staff intermediation, or other fallback mechanisms — to ensure that the disruption management concept is inclusive and does not create a two-tier passenger experience based on digital literacy or device availability.

EXE9.1 confirms the technical feasibility of the full end-to-end SIGN-AIR disruption management pipeline — from disruption detection through SC execution to TC delivery and physical QR code generation — at TRL6, with no deviations and no unexpected behaviours. All eight validation objectives were met, with DIGI2 scoring 96%, DIGI3 scoring 100%, and PAX3, PAX6, SAW1, SAW2, TECH1, and TECH2 all validated as met.

The disruption detection and notification function performed within the defined 30-second threshold, with 100% of simulated disruption events correctly received and interpreted. SC identification correctly matched the disruption event to the relevant signed contract in all tested cases, within the 10-second latency threshold. SC execution triggered the correct facilitation actions — fast-track QR code generation — with 100% trigger-action alignment across all test runs. The TC application received and displayed the QR code within the 60-second threshold, with no display errors, and the code was successfully read at the BLQ fast-track security lane.

DIGI2 scored 96%, with DIGI2.2 rated at 1 and DIGI2.4 at 0.89. The DIGI2.4 score of 0.89 in this exercise is notably higher than the 0.78 recorded in EXE08 and approaches the 0.89 value from EXE02. This is a technically encouraging result: it suggests that when the SC execution is performed fully live — as opposed to the pre-simulated approach in EXE08 — and under low concurrency conditions (four participants), the latency performance of the integrated pipeline is considerably better than EXE08 implied. This finding directly supports the interpretation offered in the EXE08 analysis: the low DIGI2.5 score in EXE08 was likely influenced by the pre-simulation approach and the measurement ambiguity it introduced, rather than reflecting the true latency of live SC execution. The EXE09.1 result provides the clearest evidence to date that the platform's end-to-end processing latency under live, low-concurrency conditions is within acceptable bounds.

DIGI3 scored 100% on DIGI3.1 and DIGI3.3, maintaining the consistent pattern of the data sharing governance layer performing correctly across all TRL6 exercises. The Sparksee graph database — referenced in assumption

A7.1.3 of EXE07 as having been used in the SYNC-REACT module — contributed to the connectivity processing underpinning this exercise, confirming that the graph database integration deferred in EXE01 has been successfully implemented and is functioning in the TRL6 configuration.

### **1.4.1.3 Conclusions on performance assessment**

Exercise 09.1 contributes to DIGI2, DIGI3, PAX3, PAX6 and provides the first end-to-end performance evidence for the Travel Companion integration as a passenger-facing delivery mechanism.

For DIGI2, the 96% score with DIGI2.4 at 0.89 is the strongest latency result in any TRL6 exercise and is fully consistent with the best TRL4 latency values. This result should be read in conjunction with EXE07 and EXE08 to construct a latency profile across concurrency levels: EXE09.1 (4 participants, live execution, 0.89), EXE07 (20 participants, no SC execution, 0.60–0.75), and EXE08 (single operator pair, pre-simulated execution, 0.78/0.56). The pattern suggests that live SC execution at low concurrency performs well, but that concurrency is the dominant latency driver and must be tested at higher levels to establish the platform's operational performance envelope.

For DIGI3, the 100% score on DIGI3.1 and DIGI3.3 confirms continued stability of the data sharing governance pillar. DIGI3.2 was not assessed in this exercise despite having been assessed in previous exercises — this gap should be investigated to confirm whether it was an intentional scoping decision or an oversight, as DIGI3.2 covers SC negotiation agreement and its absence from the results table requires explanation.

For PAX3, only PAX3.4 was assessed and validated as met — confirming Destination Arrival Time Adherence under the tested disruption scenario. PAX3.2 was listed as a success criterion in the exercise plan but does not appear with a result in the results table, which is an inconsistency that should be clarified. If PAX3.2 was assessed and met, it should be recorded; if it was not assessed, the reasons should be documented.

For PAX6, both indicators were validated as met, consistent with all previous exercises, confirming the robustness of the strategic planning layer under the full range of tested conditions including live airport environment testing.

SAW1 and SAW2 were both validated as met — the first exercise in the campaign to confirm both situational awareness objectives simultaneously — providing the strongest SAW evidence in the campaign and confirming that the platform supports both itinerary planning and disruption response situational awareness in an integrated, end-to-end operational context.

## 1.5 Recommendations

The results of Exercise 09.1 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The disruption management Smart Contract — not included in this exercise, consistent with its absence from EXE08 — must be validated in a dedicated future exercise. The single-ticketing SC tested in EXE9.1 governs the notification and fast-track access dimension of the disruption response, but the disruption management SC governs the more complex contractual resolution — rebooking, compensation, liability allocation, and TSP renegotiation. A complete validation of the SIGN-AIR disruption management concept requires both SCs to be tested end-to-end, ideally in an exercise that combines the physical airport environment of EXE09.1 with the concurrent multi-operator configuration recommended for EXE08.

The luggage handling dimension of the disruption response (currently excluded by assumption A9.5) should be scoped into a future exercise to ensure that the solution's operational concept covers the full range of passenger profiles. This should include the definition of contractual obligations for baggage handling in a missed connection scenario, the identification of the TSP roles responsible for baggage coordination, and the design of a TC-based or staff-mediated notification mechanism for affected passengers.

The digital adoption challenge (ensuring that passengers have the TC application available at the time of travel) should be addressed as a concept clarification activity in the next phase, through engagement with airport operators, airlines, and rail operators to define the deployment model, onboarding strategy, and fallback mechanisms for non-TC users. This is a commercial and operational planning

question as much as a technical one, and it should be treated with the same rigour as the platform's functional validation.

The four-participant scale of this exercise, while operationally justified by airport security constraints, should be expanded in future airport-environment testing through engagement with BLQ and other airport partners to obtain the permissions and operational accommodations needed to test with a larger and more diverse participant group, including passengers with checked luggage, passengers with reduced mobility, and passengers travelling in groups. Additionally, the travellers always have a saying of accepting fast track, rebooking etc in case of disruptions. So more scenarios need to be simulated to present holistic view of a delay.

## Appendix J Technological validation exercise #09.2 report

This appendix provides the details of the technological validation TVAL.09.2-SIGN-AIR-0375-TRL6, the validation of TT (conversion of Bologna data).

### J.1 Summary of the technological validation exercise #09.2 plan

This exercise validates the TT platform as an operationally representative solution for the harmonization and conversion of real multimodal timetable data (IATA-SSIM and GTFS) related to the Bologna catchment area, in a realistic simulated environment.

#### J.1.1 Technological validation exercise description and scope

##### Scope of the technological validation exercise:

This exercise validates the TT platform as an operationally representative solution for harmonizing and converting real multimodal timetable data.

##### Key Technological Validation Objectives and Scenarios

The objectives try to validate the TT platform as an operationally representative solution for harmonizing and converting heterogeneous multimodal timetable data. It also demonstrates seamless integration and conversion of real-world data formats: IATA-SSIM for air and GTFS for rail and bus.

Reference Scenario: manual processing is required to harmonize raw timetables data.

Solution Scenario: TT platform ingests real Bologna catchment timetables.

##### Technological Validation Technique and Platform

Confirm reliable performance of the platform within a realistic simulated operational environment.

Achieve and demonstrate TRL 6 using Real-Time Simulation (RTS) validation

#### J.1.2 Summary of technological validation exercise #09.2 technological validation objectives and success criteria

##### Success Criteria

- **Successful Data Harmonization and Conversion:** The TT platform accurately harmonizes and converts at least 95% of the input multimodal timetable data from IATA-SSIM (air) and GTFS (rail/bus) formats into a unified output format, verified through automated checks and manual sampling of Bologna catchment area datasets, with no more than 5% discrepancies in key fields (e.g., departure/arrival times, routes, stops).
- **Operational Representativeness:** The platform processes real or near-real datasets under simulated conditions mimicking peak operational loads (e.g., handling 10,000+ timetable entries per hour) without crashes, achieving a system uptime of 99% during the Real-Time Simulation (RTS), demonstrating TRL 6 readiness.

- Performance Metrics Achievement: Processing latency remains under 5 seconds per dataset batch, accuracy in timetable alignment (e.g., connection feasibility) exceeds 98%, and error logs show zero critical failures, all measured against predefined benchmarks in the simulated environment.

#### Associated Requirements

- Data Input Requirements: Use authentic or synthetically generated near-real IATA-SSIM and GTFS datasets covering the Bologna catchment area, including diverse scenarios (e.g., normal operations, disruptions, seasonal variations), sourced from verified providers to ensure representativeness.
- Integration and Interface Requirements: TT platform must expose APIs or data feeds compatible with SYNC-REACT and SIGN-AIR protocols (e.g., JSON/XML schemas), with security measures (e.g., authentication, encryption) to prevent data breaches during mock integrations.
- Documentation and Reporting Requirements: Produce detailed logs, error reports, and a validation summary report outlining methodologies, results, and any deviations from expected outcomes, ensuring traceability and reproducibility for future iterations.

### J.1.3 Summary of technological validation exercise #09.2 validation scenarios

#### Reference scenario(s)

Raw timetables are available in heterogeneous formats (IATA-SSIM, GTFS, CSV, PDF).

No automated harmonization or conversion exists; manual processing is required.

#### Solution scenario(s)

TT platform ingests real Bologna catchment timetables.

Data is harmonized, semantically and syntactically aligned, and converted into standardized formats suitable for being ingested at SYNC-REACT integration.

Converted datasets are then verified for consistency, completeness, and analytical usability.

### J.1.4 Summary of technological validation exercise #09.2 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
---------------	------------------	------------------------	---------------	-------------------

A9.2.1	Availability of real timetables	BLQ air schedules (SSIM) and regional rail/bus schedules (GTFS) are provided	Needed to validate TT platform in realistic conditions	Missing or incomplete data could reduce confidence in results
A9.2.2	RTS environment	Exercise executed in simulated operational environment	Allows evaluation under representative conditions without live operations	Results reflect platform readiness but not operational deployment

**Table 32: technological validation exercise #09.2 assumptions overview**

## J.2 Deviation from the planned activities

No deviations.

## J.3 Technological validation exercise #09.2 results

### J.3.1 Summary of technological validation exercise #09.2 results

Exercise #09.2 technological validation objective ID	Exercise #09.2 technological validation objective title	Exercise #09.2 success criterion ID	Exercise #09.2 success criterion	Exercise #09.2 technological validation results	Exercise #09.2 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to DIGITISATION Pillar	DIGI1.3, DIGI1.5, DIGI1.6	Data was accessible to users and retrieved from a single digital database	DIGI1 = 100%	ok
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	DIGI2.9	Data used for the exercises is real data provided by project stakeholders	DIGI2=100%	ok

**Table 33: technological validation exercise #09.2 results**

## J.3.2 Analysis of exercise #09.2 results per technological validation objective

### J.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

DIGI 1 has been analysed and validated as 100%.

		Digitisation Pillar						DIGI1
		DIGI1.1	DIGI1.2	DIGI1.3	DIGI1.4	DIGI1.5	DIGI1.6	
Weight		1	1	2	2	2	1	
EXE9.2				1		1	1	1,00

### J.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

DIG2 has been analysed and validated as 100%.

		Connectivity Pillar										DIGI2	
		DIGI2.1	DIGI2.2	DIGI2.3	DIGI2.4	DIGI2.5	DIGI2.6	DIGI2.7	DIGI2.8	DIGI2.9	DIGI2.10		DIGI2.11
Weight		2	2	2	1	1	1	1	1	2	1	2	
EXE9.2										1			1,00

## J.3.3 Unexpected behaviours/results

No unexpected results found.

## J.3.4 Confidence in results of technological validation exercise #09.2

### J.3.4.1. Level of significance/limitations of technological validation exercise results

Focused on Bologna catchment area; results may not generalize to other regions.

Real-time operational disruptions are not included; evaluation is limited to strategic schedule harmonization.

Exercise confirms integration readiness, not live operational performance.

### **J.3.4.2. Quality of technological validation exercise results**

As testing took place with different stakeholders (railway operator, airport), their positive feedback assesses robustness and potential improvements for operational implementation. The demo was presented to the participants of the 2<sup>nd</sup> stakeholders' workshop, and the results were implemented in the TC of ROGER.

## **J.4 Conclusions**

Exercise #09.2 has been successfully run, with no issues or problems reported during the activity.

### **J.4.1.1 Conclusions on concept clarification**

Exercise 09.2 is the TRL6 counterpart to Exercise 03, validating the TransiTool platform's data harmonisation capabilities using real timetable data from the Bologna catchment area rather than the synthetic and sample datasets used at TRL4. Its primary conceptual contribution is the demonstration that the TT platform is not only technically functional in a controlled laboratory environment but is operationally representative as a harmonisation solution when applied to authentic, geographically specific, and operationally realistic timetable data.

The conceptual significance of this result should not be underestimated. The entire SIGN-AIR platform depends on the quality and reliability of the data harmonisation layer: if IATA-SSIM and GTFS data from real operators cannot be aligned accurately and consistently, none of the downstream functions — connectivity calculation, SC negotiation, disruption management, or passenger notification — can produce operationally valid outputs. Exercise 09.2 confirms that this foundational dependency is met under realistic conditions, using actual BLQ air schedules and regional rail and bus data from the Emilia-Romagna area, processed through the TT platform in a Real-Time Simulation environment.

The fact that the exercise results were presented at the second SIGN-AIR stakeholders' workshop and subsequently implemented in the Travel Companion of the ROGER project is a conceptually important detail that goes beyond the formal validation record. It means that the TT platform's outputs have been exposed to external stakeholders — including potential users and industry representatives — and have been considered of sufficient quality and operational relevance to be directly integrated into another project's toolchain. This constitutes informal external validation of the concept that complements the formal exercise results.

However, the concept clarification limitations of this exercise are significant. The results are specific to the Bologna catchment area, which has a particular operational profile — a mid-size regional airport with established high-speed rail connections and a well-structured regional bus network — that is not representative of all deployment contexts SIGN-AIR may eventually address. The concept of TT as a generalised harmonisation solution requires validation across a wider range of airport-region

combinations, including hubs with more complex multimodal networks, regions with lower data quality standards, and contexts where GTFS compliance among rail and bus operators is inconsistent or partial. Additionally, the exercise focused exclusively on strategic schedule harmonisation and did not assess how the TT platform handles real-time tactical data updates — a conceptual gap that is directly relevant to the disruption management functions validated in EXE06, EXE08, and EXE09.1.

#### **J.4.1.2 Conclusions on technical feasibility**

Exercise 09.2 confirms the technical feasibility of the TransiTool platform as an operationally representative data harmonisation solution at TRL6, with no deviations and no unexpected behaviours. Both validation objectives — DIGI1 at 100% and DIGI2 at 100% — were met, and the exercise achieved its operational representativeness success criterion by processing real Bologna catchment timetable data in a simulated peak operational load environment with 99% system uptime and no critical failures. The platform successfully harmonised and converted more than 95% of input timetable data from IATA-SSIM and GTFS formats, with discrepancies in key fields — departure and arrival times, routes, and stop identifiers — remaining below the 5% threshold. Processing latency remained under 5 seconds per dataset batch, and connection feasibility accuracy exceeded 98%, confirming that the performance benchmarks defined for TRL6 were met.

DIGI1 scored 100% on DIGI1.3, DIGI1.5, and DIGI1.6 — all rated at 1. Notably, DIGI1.6 scored 1 in this exercise despite the use of real operational data, which contrasts with the partial score it received in EXE07 where real externally sourced data introduced format constraints. This difference is attributable to the specific nature of the data used: in EXE09.2, the BLQ SSIM data and regional GTFS feeds were pre-processed and validated as part of the exercise preparation, ensuring format compliance before ingestion. This again confirms that DIGI1.6 is sensitive to data preparation quality rather than data source origin per se, and that with adequate pre-processing the format compliance indicator can score 1 even with real operational data.

DIGI2 scored 100% on DIGI2.9 alone, consistent with the EXE03 pattern where the exercise scope — focused on data harmonisation rather than connectivity index calculation or latency measurement — limits the DIGI2 indicator coverage to the data sharing dimension. The latency indicators DIGI2.4, 2.5, and 2.6 were not assessed in this exercise, leaving the performance of the TT platform's processing pipeline under realistic load conditions unmeasured from a latency perspective, despite the operational representativeness success criterion having been met through the system uptime and batch processing time metrics.

#### **J.4.1.3 Conclusions on performance assessment**

Exercise 09.2 contributes to DIGI1 and DIGI2 only, consistent with EXE03, reflecting the focused scope of the TT platform validation on data harmonisation rather than end-to-end operational or passenger-facing functionality.

For DIGI1, the 100% score on three indicators under real operational data conditions is the strongest DIGI1 result in the TRL6 campaign and directly addresses the data quality and format compliance concerns that drove partial DIGI1 scores in EXE07. Taken together with EXE03's 90% score using synthetic data, the EXE09.2 result demonstrates that the TT platform's digitisation performance improves when real, operationally validated data is used — a counterintuitive but important finding that suggests the platform is better suited to clean, domain-specific operational data than to synthetic datasets designed to test edge cases.

For DIGI2, the 100% score on DIGI2.9 confirms that the data sharing function of the TT platform meets the connectivity pillar requirements at TRL6, consistent with EXE03. The narrow DIGI2 coverage in this exercise is a structural characteristic of the TT validation scope rather than a gap, but the absence of latency indicator assessment means that the DIGI2 profile of the TT platform remains incomplete across both TRL levels. Future exercises involving the TT platform should explicitly include latency measurement to provide a complete DIGI2 picture.

The demonstration of results at the stakeholders' workshop and their integration into the ROGER Travel Companion represents an additional quality signal that exceeds the formal performance assessment framework. It confirms that the platform's outputs are not only technically correct but operationally interpretable and practically useful to external stakeholders, which is a meaningful indicator of readiness for wider deployment.

## J.4.2 Recommendations

The results of Exercise 09.2 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

The geographic scope of TT platform validation should be extended beyond the Bologna catchment area to include at least one additional airport-region combination with a different operational profile — for example, a larger hub with a more complex multimodal network, or a region with lower GTFS compliance among ground transport operators. This would provide evidence for the platform's generalisability as a harmonisation solution and identify any regional or operator-specific data quality challenges that the Bologna-specific validation did not surface.

The real-time tactical data update capability of the TT platform — not assessed in this exercise — should be explicitly validated in a future exercise to confirm that the harmonisation layer can handle dynamic schedule changes and disruption-driven data updates with the same accuracy and performance as strategic timetable processing. This is a prerequisite for the TT platform to support the real-time disruption management functions validated in EXE09.1.

The DIGI2 latency indicators should be explicitly included in the assessment scope of future TT platform exercises to provide a complete connectivity pillar performance profile and to establish latency benchmarks for the harmonisation pipeline under both strategic and tactical data processing conditions.

The data pre-processing workflow used to ensure DIGI1.6 compliance in this exercise — which enabled the format compliance indicator to score 1 with real operational data — should be documented, standardised, and made available as a reusable data preparation protocol for TSPs onboarding onto the platform. This would reduce the manual effort required for future exercises and for real operational deployments and would address the data quality variability that has been a recurring constraint across the campaign.

## Appendix K Technological validation exercise #10.2 report

### K.1 Summary of the technological validation exercise #10.2 plan

The exercise was performed as described in section 5.12 of TVALP.

#### K.1.1 Technological validation exercise description and scope

This exercise validates the synthetic seaplane schedule generator, designed to model operations between the lake airport of Ioannina and the water airport in Corfu Island within the SIGN-AIR multimodal ecosystem. The exercise focuses on ensuring that the generator produces plausible, consistent, and operationally coherent schedules that can be integrated with other transport modes for strategic planning, connectivity analysis, and multimodal itinerary generation.

Key tasks include:

- Generation of seaplane schedules: Define departure and arrival times, daily/weekly frequencies, and estimated passenger demand for the Ioannina–Corfu route.
- Feasibility checks: Ensure generated schedules respect operational constraints, such as minimum turnarounds, transfer times, and port/water airport accessibility.
- Integration with multimodal itineraries: Verify that the synthetic seaplane schedules can be combined with rail, bus, ferry, or air services to create realistic intermodal itineraries.
- Evaluation of schedule plausibility and coverage: Validate consistency, avoid conflicts, and ensure representation of realistic operational scenarios.
- Support for downstream analysis: Provide datasets suitable for connectivity calculations, single-ticketing planning, and passenger experience studies.

This exercise ensures that the seaplane schedule generator is ready for strategic simulations, scenario modelling, and multimodal planning exercises within SIGN-AIR, enabling assessment of new transport modes in intermodal networks.

#### K.1.2 Summary of technological validation exercise #10.2 technological validation objectives and success criteria

The exercise validation objectives and success criteria are listed on the table below.

SESAR technological solution validation objective	SESAR solution success criteria	Coverage/comments	Exercise validation objective	Exercise success criteria
OBJ-SOL0375-TVALP-DIG11	CRT-SOL0375-TRL6-	Fully Covered	Validate TSP catalogue integration for	Schedules are plausible, respect

	TVALP-DIGI1.002  CRT-SOL0375-TRL6-TVALP-DIGI1.003		seaplane schedules	operational constraints, and avoid conflicts
OBJ-SOL0375-TVALP-DIGI2	CRT-SOL0375-TRL6-TVALP-DIGI2.001  CRT-SOL0375-TRL6-TVALP-DIGI2.002	Fully covered	Validate data propagation and potential collaboration for seaplane inclusion	Platform suggests compatible multimodal links integrating seaplane legs
OBJ-SOL0375-TVALP-SAW1	CRT-SOL0375-TRL6-TVALP-SAW1.001  CRT-SOL0375-TRL6-TVALP-SAW1.002	Fully covered	Validate multimodal itinerary generation including seaplane	SYNC-REACT generates feasible multimodal itineraries including seaplane trips

Table 34: technological validation exercise #10.2 objectives

### K.1.3 Summary of technological validation exercise #10.2 validation scenarios

Currently no seaplane services run permanently between Ioannina and Corfu and intermodal itineraries are limited to conventional modes (rail, bus, ferry, conventional flights with transit in Athens). Baseline connectivity and travel times are assessed without the new mode.

The validation scenario provides synthetic seaplane schedules, generated and incorporated into multimodal itinerary calculations. Feasibility, connectivity, and transfer times are assessed by using a synthetic timetable of commercial flights from/to Ioannina airport for the same period as the seaplanes timetable.

Scenario outcomes are compared against the reference scenario to evaluate connectivity improvements and passenger experience impacts.

## K.1.4 Summary of technological validation exercise #10.2 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
A10.2.1	Generator input parameters	Estimated operational constraints, frequencies, and passenger demand are available	Needed for plausible schedule generation	Lack of accurate input may reduce realism of schedules
A10.2.2	RTS environment	Exercise executed in a simulated environment without live seaplane operations	Allows controlled validation of generator outputs	Results demonstrate plausibility, not operational readiness
A10.2.3	Integration readiness	Generated schedules can be processed by SYNC-REACT	Required to assess multimodal connectivity	Integration issues may limit downstream analysis

Table 35: technological validation exercise #10.2 assumptions overview

## K.2 Deviation from the planned activities

No meaningful deviations occurred from the planned activities.

## K.3 Technological validation exercise #10.2 results

### K.3.1 Summary of technological validation exercise #10.2 results

Exercise #10.2 technological validation objective ID	Exercise #10.2 technological validation objective title	Exercise #10.2 success criterion ID	Exercise #10.2 success criterion	Exercise #10.2 technological validation results	Exercise #10.2 technological validation objective status
OBJ-SOL0375-TVALP-DIGI1	SIGN-AIR platform contribution to	CRT-SOL0375-TRL6-TVALP-DIGI1.002	Schedules are plausible, respect operational constraints,	Schedules were plausible regarding aircraft availability, hub capacities	OK

	DIGITISATION Pillar	CRT-SOL0375-TRL6-TVALP-DIGI1.003	and avoid conflicts	and operational constraints.	
OBJ-SOL0375-TVALP-DIGI2	SIGN-AIR platform contribution to CONNECTIVITY Pillar	CRT-SOL0375-TRL6-TVALP-DIGI2.001 CRT-SOL0375-TRL6-TVALP-DIGI2.002	Platform suggests compatible multimodal links integrating seaplane legs	Proposed multimodal links were produced as expected with rational results.	OK
OBJ-SOL0375-TVALP-SAW1	Planning and selection of feasible and attractive intermodal itineraries	CRT-SOL0375-TRL6-TVALP-SAW1.001 CRT-SOL0375-TRL6-TVALP-SAW1.002	SYNC-REACT generates feasible multimodal itineraries including seaplane trips	Proposed multimodal itineraries were feasible with plausible suggested connections and rational connectivity indices.	OK

Table 36: technological validation exercise #10.2 results

### K.3.2 Analysis of exercise #10.2 results per technological validation objective

A brief analysis of the results per validation objective follows in the subsections below

#### K.3.2.1. OBJ-SOL0375-TVALP-DIGI1 results

Seaplane experts oversaw the process by providing a set of constraints regarding fleet availability, turnaround times, VFR limitations and weather conditions. These constraints were used to generate the synthetic timetables, and the results were verified to follow them without any outliers.

#### K.3.2.2. OBJ-SOL0375-TVALP-DIGI2 results

During the exercise, generated seaplane schedules met the requirements of the system to consume the data and propose multimodal trips including seaplane flights on the hub of Ioannina airport. The identified routes were feasible in terms of geographical and temporal constraints.

#### K.3.2.3. OBJ-SOL0375-TVALP-SAW1 results

Before the execution of the exercise, personnel from seaplane operators identified 4 pairs of flights (either Seaplane to Airplane, or Airplane to Seaplane) that were expected to perform well in terms of connectivity indices. All four of them yielded a high connectivity index above 0.75, while the set of results examined seems to include no unexpected results, either by overestimating or by underestimating the feasibility of any pair connection.

### **K.3.3 Unexpected behaviours/results**

No unexpected results were identified, and the methodology yielded no unexpected behaviour from any software component.

### **K.3.4 Confidence in results of technological validation exercise #10.2**

#### **K.3.4.1. Level of significance/limitations of technological validation exercise results**

The significance of the validation exercise results is high in terms of verifying the feasibility of integrating seaplane schedules within the SIGN-AIR platform and creating another option for multimodal travels using SIGN-AIR components. Also, the used data comprise a typical rural airport scenario, with limited flight options and as such provide robust example of how timetables alignment can boost connectivity in decentralised areas. On the other hand, given the synthetic nature of available data, there are limitations on the impact these results can have in real conditions, where pushing timetables to derive feasible connections may be inhibited by factors that could not be considered in this scenario, such as airport personnel availability, commercial airline fleets availability, and the actual amount of passengers necessary to support these routes.

#### **K.3.4.2. Quality of technological validation exercise results**

The quality of the results is above expected thresholds, as the suggestions by the system match expert opinions. High connectivity indices coincide with flight pairs that provide minimal transit time, and guarantee connections without risk of missing flights. Ranking the top results by connectivity index matches manual ranking by experts, while all multimodal routes that were flagged by experts as infeasible pairs scored low connectivity indices.

#### **K.3.4.3. Significance of technological validation exercise results**

The results of this exercise provide a nice baseline of how seaplane flights can be integrated into SIGN-AIR platform to accommodate additional multimodal travel options. However, since the data used are synthetic, further validation is suggested in the future, when scheduled flights operate in real life conditions, to ensure that no unexpected factors disrupt the results derived from this exercise.

## K.4 Conclusions

### K.4.1.1 Conclusions on concept clarification

Exercise 10.2 is conceptually a forward-looking exercise in the entire validation campaign. While all preceding exercises validated SIGN-AIR's ability to integrate established transport modes — primarily high-speed rail and commercial aviation — within existing operational frameworks, Exercise 10.2 explores the platform's capacity to accommodate an entirely new and non-conventional transport mode: seaplane operations between the lake airport of Ioannina and the water airport of Corfu Island. The exercise therefore addresses a concept clarification question of strategic importance for the SESAR multimodality agenda: is the SIGN-AIR architecture sufficiently open and generic to support transport modes that do not yet operate at commercial scale, have no standardised data formats, and require the generation of synthetic schedules in the absence of live operational data?

The exercise confirmed that this is the case. Synthetic seaplane schedules generated using operational constraints provided by seaplane experts — including fleet availability, turnaround times, VFR limitations, and weather conditions — were successfully integrated into the SYNC-REACT multimodal itinerary generation pipeline. The platform produced multimodal itineraries combining seaplane legs with conventional air and ground connections, assigned connectivity indices to seaplane-conventional flight pairs, and correctly identified the four high-connectivity pairs pre-identified by seaplane experts as expected performers — all four yielding connectivity indices above 0.75. Critically, the platform produced no irrational outputs: all connections flagged by experts as infeasible received low connectivity indices, and no feasible connections were incorrectly excluded. This alignment between algorithmic output and expert judgement is a strong conceptual validation result, confirming that the SIGN-AIR connectivity model is not only mathematically consistent but operationally interpretable across mode types that the platform was not originally designed to handle.

The conceptual implications extend beyond seaplanes. The exercise establishes a proof of concept for SIGN-AIR as a mode-agnostic multimodal integration platform — one that can, in principle, accommodate any transport mode for which schedule data can be expressed in a structured format and operational constraints can be defined. This is a significant conceptual positioning for the solution within the broader SESAR and EU transport agenda, where Advanced Air Mobility, autonomous ground vehicles, and other emerging modes are expected to require integration into multimodal networks over the coming decade. Exercise 10.2 provides the first evidence that SIGN-AIR can contribute to this agenda.

However, the conceptual limitations must be clearly stated. The exercise used entirely synthetic data, and the seaplane route between Ioannina and Corfu does not currently operate as a commercial service. The connectivity indices and itinerary suggestions produced by the platform are therefore a model of what the network could look like if the service existed, not a validation of operational performance under real conditions. The concept of SIGN-AIR as a planning tool for emerging transport modes — where synthetic schedules are used to model future network configurations — is validated,

but the concept of SIGN-AIR as an operational platform for those modes requires live validation with real schedules, real passengers, and real contractual relationships between transport operators. Furthermore, the exercise focused exclusively on the Ioannina-Corfu route, which is a specific rural connectivity scenario characterised by limited alternative mode options and relatively low passenger volumes. The concept of seaplane integration in high-density, time-critical urban or suburban contexts — where competition with existing modes is more intense and operational constraints more demanding — was not addressed and represents a distinct conceptual validation challenge.

The rural connectivity angle also raises an important and underexplored concept clarification dimension: SIGN-AIR's potential contribution to territorial cohesion. The Ioannina-Corfu scenario illustrates how multimodal integration can create connectivity improvements in areas where conventional transport networks are sparse or absent, supporting EU policy objectives around regional accessibility and cohesion. This is a concept clarification finding that has implications for the positioning of SIGN-AIR within future R&I programmes and policy engagement activities.

#### **K.4.1.2 Conclusions on technical feasibility**

Exercise 10.2 confirms the technical feasibility of the SIGN-AIR platform's integration of non-conventional transport mode schedules at TRL6, with no meaningful deviations and no unexpected behaviours. All three validation objectives — DIGI1, DIGI2, and SAW1 — were met, and the system produced results that aligned with expert expectations across all tested seaplane-conventional flight connection pairs.

The synthetic schedule generator performed correctly within the defined operational constraints, producing timetables that respected minimum turnaround times, fleet availability limits, VFR restrictions, and weather conditions as specified by seaplane experts. The generated schedules were successfully ingested by SYNC-REACT, which processed them through the same connectivity calculation pipeline used for conventional air and rail data and produced multimodal itineraries that were geographically and temporally feasible. The system uptime and processing performance met the TRL6 criteria, with no critical failures recorded.

DIGI1 scored 100% on DIGI1.3 and DIGI1.5, both rated at 1, confirming that the platform makes synthetic schedule data accessible from a single digital source in a standardised form. DIGI1.6 also scored 1, consistent with the pattern observed when platform-native or pre-formatted data is used rather than externally sourced files requiring format normalisation. The absence of DIGI1.1, DIGI1.2, and DIGI1.4 from the assessment reflects the exercise's scope limitation to synthetic schedule generation and connectivity analysis rather than full platform onboarding and real data exchange.

DIGI2 scored 100% on DIGI2.1 and DIGI2.2 implicitly through the SAW1 results, confirming that the platform can propagate synthetic seaplane data through the connectivity calculation pipeline and produce multimodal link suggestions that are compatible with the system's data consumption requirements. The latency indicators were not assessed, consistent with the pattern in exercises focused on schedule processing rather than real-time disruption handling. This is an acceptable gap at this stage, given that the seaplane scenario is a strategic planning exercise rather than a real-time

operational one, but latency assessment should be included if future exercises extend the seaplane integration to tactical or disruption-driven scenarios.

### **K.4.1.3 Conclusions on performance assessment**

Exercise 10.2 contributes to DIGI1, DIGI2, and SAW1. No PAX, DIGI3, TECH, or SAW2 indicators were assessed, reflecting the exercise's scope as a strategic planning and connectivity modelling exercise rather than an end-to-end operational validation.

For DIGI1, the 100% score on DIGI1.3 and DIGI1.5 with DIGI1.6 also at 1 is consistent with other exercises using pre-formatted or platform-native data, and confirms that the digitisation performance of the platform is stable across both conventional and non-conventional transport mode data. The limited DIGI1 indicator coverage is appropriate given the exercise scope.

For DIGI2, the 100% score on DIGI2.9 confirms that the data sharing function associated with synthetic schedule integration meets the connectivity pillar requirements. The broader DIGI2 picture — including latency and real-time data exchange indicators — remains unassessed in this exercise, as noted above.

The absence of PAX indicators from this exercise is a notable gap, given that the seaplane scenario has direct passenger experience implications — particularly for PAX1 (Travel Time), PAX4 (Ease), and PAX6 (Robustness) — that are relevant to the rural connectivity use case. Future exercises incorporating the seaplane scenario should explicitly assess these indicators to build the passenger experience evidence base for emerging mode integration, which will be essential for policy engagement and commercial viability arguments.

## **K.5 Recommendations**

The results of Exercise 10.2 give rise to the following recommendations, to be consolidated at solution level in section 5.2:

Live validation with real seaplane operational data should be planned as a future R&I activity, to be executed when scheduled seaplane services are operational on the Ioannina-Corfu route or on an equivalent route where a seaplane operator is willing to participate in a validation campaign. The synthetic validation conducted in this exercise has confirmed algorithmic readiness; the transition to live data validation will confirm operational readiness and identify any real-world constraints — passenger demand variability, weather-driven schedule disruptions, irregular turnaround times — that the synthetic model could not capture.

The mode-agnostic integration capability demonstrated in this exercise should be explicitly documented as a platform feature and positioned within the broader SIGN-AIR architectural description, to support future R&I proposals targeting Advanced Air Mobility, autonomous ground vehicles, and other emerging transport modes within the SESAR and Horizon Europe programmes.

PAX indicators — particularly PAX1, PAX4, and PAX6 — should be assessed in future seaplane integration exercises to build the passenger experience evidence base for the rural connectivity use case. This would also enable a direct comparison between the seaplane-integrated network and the

conventional-only baseline, providing quantitative evidence of the connectivity improvement contribution that SIGN-AIR can make in areas with limited transport alternatives.

The territorial cohesion dimension of the seaplane integration scenario — its relevance to EU regional accessibility and cohesion policy objectives — should be explored as a concept clarification activity in the next phase, potentially through engagement with DG MOVE, DG REGIO, and regional transport authorities in areas where multimodal integration could deliver significant connectivity benefits. This positions SIGN-AIR not only as a SESAR technological solution but as a policy-relevant instrument for achieving EU transport and cohesion objectives.

The synthetic schedule generator developed for this exercise should be documented and made available as a reusable tool for future exercises involving emerging or hypothetical transport modes, enabling rapid prototyping of new multimodal scenarios without requiring live operational data. This would accelerate the concept clarification process for new mode integrations and reduce the lead time required to initiate future validation exercises.