Demand and supply scenarios and indicators

Deliverable ID:	D3.2
Dissemination Level:	PU
Project Acronym:	Modus
Grant:	891166
Call:	H2020-SESAR-2019-2 SESAR-ER4-10-2019
Topic:	ATM Role in Intermodal Transport
Consortium Coordinator:	BHL
Deliverable Lead:	BHL
Edition date:	02 November 2021
Edition:	00.01.10
Template Edition:	02.00.02

Authoring & Approval

Authors of the document

Name/Beneficiary	Position/Title	Date
Annika Paul/ BHL	Project coordinator	26/07/2021
Andrew Cook/ UoW	Project team	26/07/2021
Tanja Bolic/ UoW	Project team	26/07/2021
Gerald Gurtner/ UoW	Project team	26/07/2021
Ulrike Schmalz/ BHL	Project team	26/07/2021
Damir Valput/ INX	Project team	26/07/2021
Isabelle Laplace/ ENAC	Project team	26/07/2021
Pierre Arich/ ENAC	Project team	26/07/2021
Nadine Pilon/ ECTL	Project team	26/07/2021
Vanessa Perez/ UIC	Project team	26/07/2021
Cécile Gendrot/ UIC	Project team	26/07/2021
Fabrice Setta/ UIC	Project team	26/07/2021

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date
Ulrike Schmalz/ BHL	Project team	29/07/2021
Annika Paul/ BHL	Project coordinator	29/07/2021
Andrew Cook/ UoW	Project team	29/07/2021

Approved for submission to the SJU By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date
Annika Paul/ BHL	Project coordinator	30/07/2021

Rejected By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

Document History

Edition	Date	Status	Author	Justification
00.01.00	30/07/2021	Submitted	Modus consortium	Submitted for review by the SJU

00.01.10	02/11/2021	Submitted	Modus consortium	Updated version, addressing the comments and feedback by the SJU

Copyright Statement

Modus

MODELLING AND ASSESSING THE ROLE OF AIR TRANSPORT IN AN INTEGRATED, INTERMODAL TRANSPORT SYSTEM

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 891166 under European Union's Horizon 2020 research and innovation programme.

Abstract

The main objective of this Deliverable D3.2 is to present supply and demand scenarios (considered time horizon: 2040), seven passenger archetypes as well as connectivity, performance and intermodal indicators.

The Modus scenarios are derived from European high-level mobility objectives, existing scenario studies as well as the work conducted within the Modus project. Each scenario focuses on particular aspects which are envisaged for the future, and which have the potential to significantly change the transport system as we see it today. Four scenarios are developed and presented with the related characteristics: 1) Pre-pandemic recovery (baseline); 2) European short-haul shift; 3) Growth with strong technological support; and 4) Decentralised, remote and digital. Taking a traveller-centric perspective, this deliverable also presents seven future European traveller archetypes.

Further, the deliverable discusses connectivity, performance and intermodal indicators, offering reviews of the states of the art for each of these, and setting the Modus context. These indicator categories are not mutually exclusive, but the section divisions present a practical approach to focusing on these specific types of measurement. The differences between air and rail metrics, and the associated regulatory contexts, is also discussed.

Finally, the deliverable elaborates on the interactions of the results within the other work packages in the Modus project.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Acronym	Definition
4HD2D	4-hours door-to-door (ACARE mobility target)
ANS	Air navigation service
ANSP	Air navigation service provider
ATFM	Air traffic flow management
ATM	Air traffic management
CO_2eq	CO_2 equivalent
CSA	Coordination and Support Action
D2D	Door-to-door
DG	Directorate General
EC	European Commission
EFTA	European Free Trade Association
ER	Exploratory research
EU	European Union
FRACS	France Aviation Civile Services
GCD	Great Circle Distance
GDP	Gross Domestic Product
HSR	High-speed rail
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
KPA	Key performance area
KPI	Key performance indicator

MFA	Mobility focus areas
NUTS	Nomenclature of Units for Territorial Statistics
O-D	Origin-Destination
PRM	Persons with reduced mobility
RENFE	Red Nacional de los Ferrocarriles Españoles
SES	Single European Sky
WATS	World Air Transport Statistics

1 Introduction

1.1 Objectives of Modus

In the context of increasing environmental awareness, regulatory measures, capacity shortages across different modes, or the need for a more seamless and hassle-free passenger journey, the future evolution of European travellers' demand for mobility is still unknown, as well as its potential impacts on the European transport system. The optimisation and alignment of multimodal transport is therefore of utmost importance for the overall performance of the (future) European transport system, especially in regard to providing a seamless and hassle-free journey for passengers as well as mitigating (air) capacity constraints. In line with this, the high-level objective of Modus is to analyse how the performance of the overall European transport system can be optimised by considering the entire door-to-door journey holistically and considering air transport within an integrated, multimodal approach. This is pursued by:

- Identifying and assessing (future) drivers for passenger demand and supply of mobility, and how these affect passenger mode choice,
- Applying and further advancing existing models to determine the demand allocation across different transport modes, especially air and rail, and the effects on the overall capacity of these modes, and
- Developing and assessing performance and connectivity indicators which facilitate the identification of gaps and barriers in meeting high-level European (air) transport goals and solutions to gaps can be addressed.

Modus wants to explore how air transport management (ATM) and air transport can better contribute to improve passengers' multimodal journeys and how this translates into an enhanced performance of the overall transport system. A multimodal journey from door to door comprises different steps. The focus of Modus within this door-to-door travel chain is on multimodal transport that includes as a main segment either rail or air transport in Europe. Other transport modes such as public transport are considered as access and egress modes (feeder traffic) to either the airport or the rail station.

1.2 Objectives of this deliverable

Currently, the European transport sectors face a wide range of opportunities and challenges, including the decarbonisation debate, the potential of data usage within the digital transformation, addressing the long-term impacts of the Covid-19 pandemic, and moving towards a better and efficient integration of transport modes within Europe. In line with the overall objectives and scope of Modus, this deliverable looks at the overall performance of door-to-door transport with a specific focus on the relationship between air and rail transport. Specifically, the objectives of this deliverable are:

- The development of scenarios and passenger archetypes that depict various potential future development paths which the European transport system might be facing, such as new regulatory contexts meeting new environmental standards, or new transport operators' business models, covering a time horizon of 2040, which will be modelled to assess the respective landside and airside impacts in the subsequent Work Packages WP4 and WP5 of Modus.

- The derivation of performance and connectivity indicators, as well as passenger mobility metrics, with specific business and operational targets, constraints, and performance metrics that are common to all transport modes, thus addressing how capacity constraints at airports can be alleviated by fostering a better air-rail integration (WP4). These indicators are to be assessed throughout the project and by an Industry Board (WP4, WP5) to derive and assess recommendations and solutions on how the overall performance of the transport system can be increased.

The scenarios defined in this deliverable, based on the work conducted in Task 3.3, hence describe the evolution of multimodal supply and demand by 2040. These scenarios include the relevant factors identified in Deliverable 3.1 as well as the modal choice analysis, and highlight e.g. changes in the regulatory context, and/or significant changes in the business models of transport operators.

Further, seven traveller archetypes with distinct characteristics are developed and presented. The profiles show the diverse travel needs on the passenger side and help to take a user-centric perspective on the European transport systems. Distinguishing between different passenger archetypes is important since the door-to-door journey components, such as the access mode to the airport or railway station and hence the access times, may vary according to passenger requirements, preferences and behaviour along the journey. The respective travel characteristics identified in this deliverable will be integrated in the landside model of the Mercury model in WP4.

In addition to this, performance, connectivity and intermodal indicators are identified and prioritised to be evaluated and further developed within the next steps of Modus. The prioritised key performance areas (KPAs) are *Capacity*, *Predictability* as well as *Environment*, which reflect the Modus' overall objectives, and include a defined set of respective headline indicators.

1.3 Deliverable structure and content

This Deliverable D3.2 consists of the following sections:

- Introduction to the project, and context of this deliverable (Section 1)
- An overview of European mobility strategies and goals (Section 2.1)
- An outline of modal choice variables (Section 2.2)
- The development of four Modus scenarios (Section 2.3)
- The identification of traveller archetypes and respective travel behaviour (Section 3)
- The definition of multimodal performance and connectivity indicators (Section 4)
- Summary and next steps (Section 5)

2 Supply and demand scenarios

Within this section, as a starting point, relevant high-level agendas and strategies for the European transport system are outlined as well as existing scenarios that depict the evolution of mobility supply and demand (Section 2.1).

Section 2.2 on modal choice presents the data collection and processing work. In this section we will introduce the data corresponding to the rail and air modes as well as the socio-economic data that will allow us to contextualise our model but also to interact with it. All the data collected is at the origin of a unique dataset that we is used in the modelling work.

Based on high-level strategies and scenarios as well as the indicators applied in the modal choice model, four scenarios are established that describe distinct development paths and according parameters that depict the air transport and railway sectors (Section 2.3).

These scenarios will be modelled in subsequent work in work packages WP4 and WP5 in regard to their effects on e.g. overall passenger travel time or airport capacities.

2.1 Objectives and goals European transport system

Part of these strategic transport agendas and studies on the development of the European mobility sector have been compiled for the definition of Modus use cases in Deliverable D5.1. In addition to this, this section also outlines scenario studies which depict potential future development paths in particular regard to the rail and air transport sectors.

Table 1: European mobility strategies and scenarios

Author	Year	Title	Short description
European Commission, [1]	2020	Sustainable and Smart Mobility Strategy	This strategy lays the foundation for how the EU transport system can achieve its green and digital transformation and become more resilient to future crises. As outlined in the European Green Deal, the result will be a 90% cut in emissions by 2050, delivered by a smart, competitive, safe, accessible and affordable transport system.
NLR and SEO, [2]	2020	Destination 2050	Destination2050 outlines a possible route toward net zero European aviation by the combination of four key measurements.
European Commission [3]	2019	The European Green Deal	The European Green Deal provides an action plan to boost the efficient use of resources by moving to a clean, circular economy, to restore biodiversity and cut pollution. The plan outlines investments needed and financing tools available. It explains how to ensure a just and inclusive transition.

Author	Year	Title	Short description
European Commission, [4]	2017	Strategic Transport Research and Innovation Agenda (STRIA)	STRIA is the EU's Strategic Transport Research and Innovation Agenda. It sets out the areas where the EU needs to act in concertation with EU countries and stakeholders to radically change transport.
ACARE, [5]	2017	Strategic Research and Innovation Agenda	The Strategic Research and Innovation Agenda (SRIA) provides the strategic roadmap for aviation research, development and innovation developed by ACARE (Advisory Council for Aviation Research and Innovation in Europe) that accounts for both evolutionary and revolutionary technology.
ERRAC, [6]	2014	Strategic Rail Research and Innovation Agenda	This Strategic Rail Research and Innovation Agenda (SRRIA) is well placed to guide and inspire future research and innovation over the coming decades. Through this SRRIA, ERRAC reaffirms Europe's need to offer a well-balanced, business-led and strong programme of research and innovation for the railway system over the coming decades.
SESAR Joint Undertaking, [7]	2020	Strategic Research and Innovation Agenda – Digital European Sky	Complementing the European ATM Master Plan 2020 and the High-Level Partnership Proposal, this Strategic Research and Innovation Agenda (SRIA) details the research and innovation roadmaps to achieve the Digital European Sky, matching the ambitions of the "European Green Deal" and the "Europe fit for the digital age" initiative.
Shift2Rail, [8]	2019	Multi-Annual Action Plan	The S2R Master Plan provides a high-level view of what needs to be done; it explains why and by when. It sets the framework for the research and innovation (R&I) activities to be performed as part of and beyond the S2R Programme and the deployment activities to be carried out by all operational stakeholders, coordinated to achieve a Single European Rail Area.
European Commission, [9]	2011	Flightpath 2050	This document outlines the vision of the European Union for the aviation sector until 2050.
EUROCONTROL Aviation Sustainability Unit, [10]	2021	Think Paper #11 - Plane and train: Getting the balance right	The paper reviews the latest literature comparing air and rail sustainability, assesses whether shifting from air to rail across Europe is a realistic option, and identifies areas where air and rail could be complementary, rather than mutually exclusive.

Author	Year	Title	Short description
EEA, [11]	2020	Transport and environment report 2020 – Train or plane?	The report assesses the value of travel by train and plane. Rail travel is the best and most sensible mode of travel, apart from walking or cycling. Aviation's emission impacts are much higher on a passenger-kilometre basis. But flying is not necessarily the most harmful choice. Travel by a petrol or diesel-powered car, especially if traveling alone, can be more harmful.
European Commission, [12]	2020	TEN-T Review	The Trans-European Transport Network (TEN-T) policy supports and symbolises connectivity and accessibility for all regions of the Union. Through several revisions, the policy has coped with growing transport demand, geo-political developments (several EU enlargements) and evolving transport policy challenges (e.g. liberalisation, standardisation, technological innovation).
EREA, [13]	2021	EREA Vision Study - The Future of Aviation in 2050	This report describes four alternative scenarios for 2050 for the aviation sector, in the context of its integration into a multimodal system and the socio-economic context the aviation sector is placed in.
Leipold et al., [14]	2021	DEPA 2050	The DEPA 2050 report outlines different aircraft technology scenarios, and the emissions, climate or noise impact, the implications for the economy as well as mobility and vehicle productivity. The DEPA 2050 study was conceptualised and, to a large extent, already conducted before the full impact of the Covid-19 pandemic became apparent. Thus, the results of this study have to be regarded and interpreted in the light of a pre- Covid-19 environment.
EUROCONTROL, [15]	2018	European Aviation in 2040 – Challenges of Growth	Within this report, four distinct scenarios are depicted which outline potential traffic development paths for the aviation sector until 2040. It highlights the most likely scenario "Regulation and Growth", which considers moderate growth rates for the aviation sector. This study also focuses on a pre- Covid-19 environment.
CER, [16]	2020	Activity Report 2020	This report includes targets for rail modal shares in 2030 and 2050.
Roland Berger and UIC, [17]	2021	White Paper: The Post-Covid-19 "NEW Normal"	This report outlines several goals for the railway sector, assessing the impact of Covid-19 on

Author	Year	Title	Short description
			railway mobility and it formulates recommendations for stakeholders.

These high-level agendas as well as scenarios provide input for the scenarios defined in Section 2.3, in combination with the Modus objectives and the respective research focus, in the design and definition of Modus scenarios.

2.2 Modal choice data and indicators

This section presents and details the data collection task and all the necessary adjustments to merge data from different databases and obtain a single dataset. This dataset, unique by the quality and the diversity of its data, is the key to build and assess a relevant modal choice econometric model.

We therefore highlight in this section all the tasks, assumptions and choices made to build such an innovative dataset.

Geographic and temporal framing:

All of the collected data apply to the territory of the European Union (28 countries) as well as to the countries belonging to the European Free Trade Association (EFTA), excluding Liechtenstein. As a reminder, the countries belonging to this association and taken into account here are Iceland, Norway and Switzerland. They relate to the period 2015-2017 and to the year 2019, but only the year 2016 is fully available.

Overview of the databases acquired:

Our study requires numerous data of different kinds. We shall therefore devote this preamble to a brief reminder of our objectives, followed by a fairly succinct presentation of all the data we have collected. We will then come back to the detail of each database in order to present their interest, specificity and the reprocessing work carried out if necessary.

The objective of our modelling work is to estimate air/rail competition (via operators' market shares) on the European territory and on common origin-destination cities. Therefore, we need traffic data which we will find respectively in the OAG database for air transport and MERITS for rail transport. The data from these two databases are real traffic data for the countries concerned and for the periods defined later. In addition to the supply data, we need information on the demand for these modes of transport. In the case of air transport, we will find the demand in the FRACS database, which is an actual and real demand between airports pairs. Unfortunately, we do not have access to any passenger traffic data between stations for rail transport. We have therefore chosen to assess this rail demand by using the average number of passengers per train obtained from average yearly indicators per operator. We will come back in more detail to the calculation methods and the hypotheses made in Section 2.2.1.

2.2.1 Database and main variables

In order to structure the detailed presentation of the databases, we will categorise them by transport mode. In a first step, we will present the rail transport databases and then the air transport data. In each part, we will start by presenting the data that characterise transport supply, travel demand and then price index data. Following these two first parts, we will discuss the case of socio-economic data.

2.2.1.1 Rail databases collected

MERITS

MERITS is a database that we have acquired from our partner International Union of Railways (UIC). This database contains very rich information. As a reminder, MERITS, as used in the Modus project, contains traffic data for the years 2016, 2017 and 2019 as well as for the last two weeks of December 2015 for the 28 countries of the European Union and in addition for EFTA except for Liechtenstein. However only the 2016 year provides full data for all the trains that were operated during the period.

This dataset constitutes a very large and varied volume of information that has to be reworked to be compatible with air databases and useable for the econometric modelling. This heavy task is the first step to be able to exploit the information contained. We come back later to this issue of restructuring by specifying the modifications made and their purpose.

Since MERITS is a database referencing rail traffic, we naturally find all the information characterising a journey between an origin and a destination (noted O-D). MERITS provides information on the departure and terminus stations, as well as the corresponding departure and arrival dates and times. An O-D can also be made up of intermediate stops, i.e. stops between the departure station and the arrival station (terminus), for which we also get arrival and departure times. The common codification adopted for stations is the one used by UIC. It consists of seven digits. The first two digits code the network, i.e. the country to which the station belongs, and the last five digits code the station itself. The correspondence between the station code and the station name has been provided by UIC.

MERITS also provides information about the conditions of the journey such as the railway company which operates the journey and the rolling stock it uses (Thalys, night train ...). The information on the used rolling stock allows us to classify each link into three categories: high-speed, long distance (Intercity, interregional & night train) and short distance (regional train). In addition to these key variables, MERITS also provides details on the quality of the service, such as the presence of an on-board Wi-Fi or a bar car. To summarise, MERITS provides the elements characterising the rail supply (origin-destination, date, departure and arrival times, operator and equipment used).

Using these data for the modal choice econometric estimation requires to restructure and harmonise them with the other databases. The goal is to have a uniform structure between each database allowing us to merge them. In the case of MERITS, this required a considerable effort to ensure that we had all the characteristics of the journey on a single line for each train that ran. To do this, we copied the structure of the OAG database providing details on the supplied capacity per origin-destination and per airline operator and applied this structure to MERITS data (operator, train used, timetable, date, etc.). Still with a view to standardising our databases, we have modified the nomenclature of the days of the week by adopting a unique code. Each day of the week is coded from 1 to 7, Monday being coded as 1 and Sunday as 7. This coding of the days of the week makes it possible to read the information in a simple and understandable way. Moreover, as the days are important in our modelling work, this will allow a better understanding of the effects of seasonality.

Estimated rail demand and capacity

Unfortunately we did not have access to any database providing the passenger demand for rail transport. In addition to that, the train capacity was also missing in the MERITS database. As a result and given the importance of these variables for our modelling work, we have assessed them by mixing MERITS data with average yearly indicators of rail operators' traffic. These yearly indicators provided to UIC per operator and per category of train (short distance, long distance and high speed) are: the average number of passengers per kilometre, the average number of trains per kilometre and the average occupancy rate. On the basis of these three pieces of information, we were able to estimate an average number of passengers per operator and per category train. On the basis of the occupancy rate per operator and the average number of passengers per operator and train type, we got a capacity which corresponds to the quantity of transport offered by the operators. As some operators had not provided or had only partially provided their yearly indicators to UIC, we were forced to make assumptions.

The first one relates to the operators' rolling stock. When we were unable to know the rolling stock used by an operator when this information was not provided, we considered that the average number of passengers and the capacity of the trains were identical for this operator, whatever the type of train. Of course, we kept the general classification (high-speed train, long distance and short distance).

The second assumption made was to calculate an average occupancy rate for all operators combined per year and per train type and to apply it to operators who did not provide this information. This assumption helps overcoming the missing information and estimating the supplied capacity.

All these average indicators obtained per operator and train category, crossed with MERITS data then provided estimated rail capacity and demand[1].

Rail transport price index

Our data collection work was hampered by missing data on rail fares. Once again, we had to overcome this difficulty and manage to get around it, by collecting EUROSTAT data on the consumer price index for rail transport. The EUROSTAT price indices are provided by country on a monthly basis. Despite the fact that we do not have any price information at O-D level, getting monthly national data will help integrating seasonal effects in the modal choice model.

The EUROSTAT rail transport price index[2] is constructed on the basis of rail fares revealed on a number of lines and for all operators providing the links. The indices resulting from these data make it possible

[1] Based on the demand information available to the Modus consortium, it is not possible to take account of seasonal effects on demand. Nevertheless, the supply data available to the consortium is rather exhaustive. This will allow us to observe to a lesser extent the effect of seasonality through a significant variation in supply over a period.

[2] For the consistency of our study, prices will be expressed using the price index rail transport in €2016 for the modelling based on the year 2016 and €2019 for the year 2019. Given the difficulty in obtaining pricing data for

to illustrate the evolution of rail passenger transport prices over time. Our data is appended for the year 2015. This means that the year 2015 is used as a reference year, so the price indices collected make it possible to compare fare developments since 2015.

2.2.1.2 Air databases collected

OAG

The OAG database is the equivalent database to MERITS, but dedicated to air transport. The data used in the Modus project contains all daily air supplied capacity information for the years 2015, 2016, 2017 and 2019 for the EU countries and the EFTA countries initially specified. In addition to basic traffic variables such as departure and arrival airport (country, city and airport), departure and arrival time, flight duration from take-off to landing and the aircraft used to make the connection. The database has variables such as the total number of seats offered with a breakdown by class (economy seats, first seats and business seats).

FRACS

FRACS database is a very important and high value-added database providing the monthly air transport demand on the main European city-pairs. The database provides the total monthly air passenger traffic between two airport pair, without distinction between airlines.

To analyse the individual choice of transportation and to estimate the econometric model, monthly passenger traffic per airline and route is required. To retrieve this necessary information, we collect monthly airline route capacity from OAG database, and calculate a proxy of monthly passenger numbers per airline route by applying the average annual load factor per airline, collected in the WATS (World Air Transport Statistics) database.

This process calculates a proxy of the monthly number of passengers per airline route, as well as the total number of monthly passengers per route. We adjust these proxies using the FRACS data described above. We can then deduce the monthly market share of the airlines per route.

Air transport price index

Concerning the price aspect of air transport, we were confronted with the same difficulties as in the case of the rail sector. Therefore, we opted for the same strategy by collecting EUROSTAT yearly national air price indices.

The same structure and the same information is used, i.e. we have one index per month for each country. These indices are indexed on the year 2015, which therefore serves as a reference.

The method used to construct the price indices is similar to the one described for the rail transport price index.

---

the years 2016 and 2019, the price index is a scientific way of expressing pricing data collected in €2016 and €2019 in accordance with the reference years on which the modelling is based.

2.2.1.3 Socio-economic databases collected

Different socio-economic data have been collected from **EUROSTAT**

GDP, unemployment rate, population by age group and gender, population by level of education achieved by gender and age, household income, level of rail infrastructure and finally international passenger transport. All of these data were collected on an annual basis at a regional level, except for railway infrastructure only available at a national scale.

NUTS coding

Merging all the data presented in Section 2.2.1 requires finding a common way to characterise each O-D whatever the considered transport mode. The NUTS level revealed being the most adapted one. NUTS (Nomenclature of Territorial Units for Statistics) is a system for dividing up the territory of the EU. We therefore used NUTS 2, which divides up the territory with a demographic threshold of between 800,000 and 3,000,000 individuals. We therefore attached all the airports and railway stations to the NUTS 2 in which they were found. Subsequently, we refined this work further to a finer level, which is NUTS 3. NUTS 3 divides the territory using a demographic threshold of between 150,000 and 800,000 individuals.

We have therefore chosen to use NUTS 3 as the common coding for all our databases for various reasons. As we are working on origin-destination, it was important to adopt a geographical codification. Subsequently, NUTS 3 overcomes a major difficulty, that of the possibility of finding several stations or airports in the same city or that of having a station and/or airport outside a major city (London Stansted airport which is an airport serving London, but not in the city). The NUTS 3 code therefore allows for a more flexible review of city boundaries. As a result, origins-destinations will be between two NUTS 3, which correspond to geographical areas. These geographical areas will allow us to study the competition of air and rail modes between two NUTS 3.

2.2.2 Synthesis

The building of a single dataset merging all the data from different databases is a big task requiring a lot of effort to not only when gathering the data but also when adapting them to ensure their mutual coherency. Such preparation of the data is a crucial step for the next stage which is the econometric modelling stage. The more consistent and richer will be this unique dataset, the more relevant will be the econometric assessments. Modus will be one of the first project having such a unique and promising dataset.

The variables applied in the modal choice analysis are outlined in Table 2, each of these will be assumed to exhibit a distinct development across the scenarios developed in the following section.

Table 2: Modal choice variables

Type of data	Variables	Source
Rail	Rail transport frequency	MERITS
	Day of operation in a week	MERITS
	Share of train leaving or arriving on a time slot	MERITS

Type of data	Variables	Source
	Quality of service (free Wi-Fi, dining…)	MERITS
	Station of departure or arrival	MERITS
	Travel time	MERITS
	Type of train used	MERITS
	Price index	Eurostat
	Supplied capacity	Estimated rail demand and capacity
	Average number of travellers	Estimated rail demand and capacity
Air	Air transport frequency	OAG
	Travel time	OAG
	Day of operation in a week	OAG
	Share of aircraft leaving or arriving on a time slot	OAG
	Airport of departure or arrival	OAG
	Type of aircraft used	OAG
	Air supplied capacity per class	OAG
	Number of traveller per city-pairs	FRACS & WATS
	Price index	Eurostat
Socio-economic	NUTS 2 population	Eurostat
	NUTS 2 unemployment rate of departing and arriving airports/stations	Eurostat
	NUTS 2 GDP of departing and arriving airports/stations	Eurostat
	NUTS 2 average households' income	Eurostat
	NUTS 2 Level of education	Eurostat
	Level of railway infrastructure[3]	Eurostat

[3] This variable makes it possible to contextualise the provision of rail infrastructure for each country. The trend (creation, suppression or stabilisation) of the length of the network and its level of electrification can also be observed. For the moment, the significance of this variable is still being investigated, therefore it is not yet included in the further analysis in Section 2.3.

2.3 Scenario development

2.3.1 Overview of scenarios

The Modus scenarios are derived from high-level mobility objectives, existing scenario studies as well as the work conducted within the Modus project. Each scenario focuses on particular aspects which are envisaged for the future, and which have the potential to significantly change the transport system as we see it today.

The strategic research agendas and European mobility goals outlined in Section 2.1 were considered in an internal process and exchange within the Modus consortium to identify different development paths of the future European mobility system. All scenarios are checked for consistency and have been reviewed several times by the consortium, which contains both railway and aviation experts keeping the multi-modal view.

Considering the European mobility goals, Modus objectives, and existing transport scenarios the following developments play an essential role and are considered for the scenario development. Based on these goals, four scenarios are established which represent a strong focus on one or more of these aspects, as represented in Table 3, and further detailed below.

Table 3: Mobility goals and scenario development

Relevant mobility goals and developments (Section 2.1)	Aspects	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Connectivity [1] [4] [6] [16] [17]	Reduction of travel time Connection of remote regions		x		x
Environmental impact [1] [6] [16] [17] [2] [3] [8] [9] [11]	Reduced reliance on fossil fuel Reduction of CO_2 emissions Internalisation external costs		x		
Integration of additional demand [1] [6] [17] [8] [9] [5] [7] [13] [15]	Meeting increasing transport demand by adjusting and extending capacities More efficient resource allocation within transport network	Baseline		x	
Technological innovation and (widespread) implementation [1] [17] [2] [8] [9] [7] [5] [13] [14]	Develop more fuel-efficient, hydrogen-powered and (hybrid-)electric aircraft and bring these into operation through continued fleet renewal Ensure that low and zero emission technology options are deployed, including through retrofitting and appropriate renewal schemes in all transport modes			x	x

For each scenario, a nominal (sunshine item in Figure 1) as well as a disruptive version (volcano item) will be considered. The nominal scenarios (sunshine item) depicts the scenarios as they are described in Table 8. For each scenario, a disruptive version (volcano item) is considered, in which a disruptive event is introduced in order to assess the effect across the different scenarios. A disruption will be applied commonly and comprehensively across all scenarios to measure the resilience of future scenarios; disruptions are not applied to individual parameters, this not within the scope of the work The main objective is to provide further insights into the impact on air and rail capacity provision across the different scenarios. The time horizon considered is 2040, and the development of the different parameters (Table 8) is considered within this timeframe.

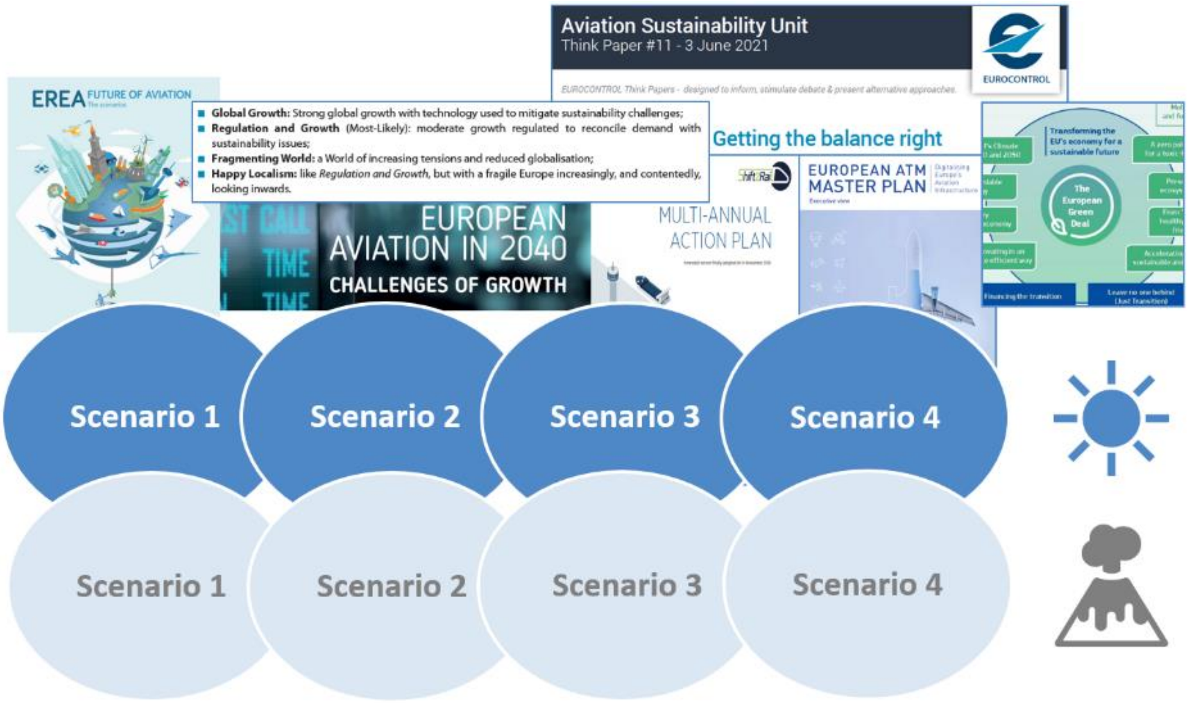
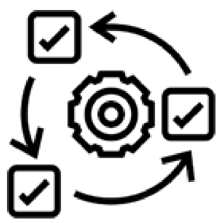


Figure 1: Modus scenarios

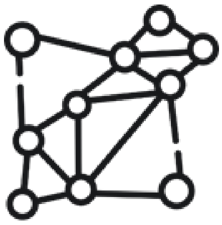
The following overview of the four Modus scenarios briefly emphasises the main and distinct features of each scenario. The parameters describing each scenario in more detail are provided further below in Table 8.

Table 4: Pre-pandemic recovery



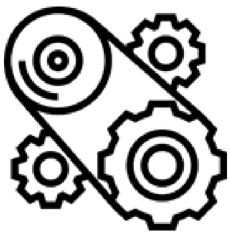
Scenario 1 – 'Pre-pandemic recovery' (baseline scenario)
The European transport market recovers to pre-crisis levels; air transport and railway network structure remain similar to todays. The implementation of innovative technologies as well as market-based measures facilitate the reduction of emissions in the transport sector. This scenario serves as the baseline for the comparison with different future development paths.
References: [15] [18] [19]

Table 5: European short-haul shift



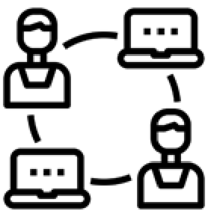
Scenario 2 – 'European short-haul shift'
A high share of short-haul air traffic is replaced by a cooperation between rail and air, which leads to a reduction in overall air traffic on short-haul routes in Europe. In this scenario, a high quality transport network with high-speed rail services on short-haul distances is established, and with clean aviation services improving the coverage of long-haul routes. Scenario assumptions include that by 2030 the high-speed rail traffic will double (this mainly concerns major links inter and extra EU), and that scheduled collective travel of under 500 kilometres should be carbon neutral within the EU. The relevance of rail increases significantly in the segment between 200 to 1500 kilometres. Furthermore, there is an increased level of cooperation between air and rail to provide both door-to-door solutions as well as efficient connectivity of European regions.
References: [1] [11] [20] [16] [17] [21] [4] [6] [2] [3] [8] [9]

Table 6: Growth with strong technological support



Scenario 3 – 'Growth with strong technological support'
This scenario exhibits high growth rates of the transport sector until 2040, which significantly exceeds that in the baseline scenario. As a reference for an upper limit for intra-European annual air traffic growth, the Boeing market forecast for the time horizon 2020-2039 is considered. This scenario emphasises the uptake of technological innovations to both reduce emissions and alleviate capacity shortages, especially the widespread implementation of respective innovative technologies in the air transport sector exceeds those levels envisaged by Destination2050, Flightpath2050, EU Smart and Sustainable Mobility Strategy, for example.
References: [22] [1] [2] [9] [6] [17] [8] [5] [7] [13] [15] [13] [14]

Table 7: Decentralised, remote and digital mobility



Scenario 4 – 'Decentralised, remote and digital mobility'
The trend in urbanisation, as forecast by the UN World Urbanization Prospects, is not proceeding as anticipated in Europe, but the population becomes more dispersed across rural and remote regions. These regions are becoming much more attractive due to increased options for remote working and virtual meetings. In line with the EU Smart and Sustainable Mobility Strategy, remote and rural regions will be better connected to the European transport network. This also incorporates a significant uptake of small and regional airports as well as additional railway stations into the current network, moving towards a more decentralised (air) transport network structure. This is also accompanied by the widespread implementation of technological innovations for regional aircraft.
References: [1] [23] [4] [6] [16] [17] [2] [8] [9] [7] [5] [13] [14]

2.3.2 Parameter description

As a reference for the parameter development outlined below is the pre- Covid-19 situation in Europe the baseline scenario *Pre-pandemic recovery*.

Table 8: Modus scenario parameters

Scenario parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Socio-economic[4]				
NUTS2 population*	Aging and increasing | UN medium fertility variant [15]			
NUTS2 GDP of departing and arriving airports/stations*	Current status	Moderate increase in GDP and average household income ++	Strong increase in GDP and average household income +++	Moderate increase in GDP and average household income ++
NUTS2 average households' income*				
Environmental / political				
Environmental regulations, incentives, restrictions	Low increase The focus is placed on a mix of **market-based measures** as well as incentives to foster and implement **innovative technologies** and fuels reducing transport emissions ++	Strong increase Regulations, incentives and restrictions strongly increase to induce **shift from air to rail** on short-haul market segments +++	Strong increase A high focus is placed on incentives to foster and implement **innovative technologies** and fuels reducing transport emissions significantly +++	Moderate increase The focus is placed on a mix of **market-based measures** as well as incentives to foster and implement **innovative technologies** and fuels reducing transport emissions ++
Transport supply				
Rail transport frequency*	Low increase +	Strong increase +++	Strong increase +++	Moderate increase ++

[4] 2 The modal choice model variables 'NUTS2 unemployment rate of departing and arriving airports/stations' and 'NUTS 2 level of education' are currently not included in the scenario framework since economic developments across scenarios are reflected by the variables 'household income' and 'GDP'; 'unemployment rate' as well as 'education' are connected to those two variables and hence, indirectly considered here as well. Further refinement of these variables will be applied in the modelling exercises in Modus.

Scenario parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Air transport frequency*	Low increase +	Decrease in offered frequencies -	Strong increase +++	Moderate increase ++
Rail supplied capacity (maximum number of carried passengers)*	Low increase +	Strong increase +++	Strong increase +++	Moderate increase ++
Air supplied capacity (maximum number of carried passengers)*	Low increase +	Decrease in the number of passengers -	Strong increase +++	Moderate increase ++
Supplied capacity per class (air): First class seats, business class seats, economy class seats*	Current status	Mainly economy class seats on offer	All seat class capacities are increasing	As the segment with the highest growth rates, regional flights mainly comprise economy class seats
Type of train used*	More HSR trains are employed, focus on specific high-demand routes +	The use of HSR services and trains increases significantly +++	The use of HSR services and trains increases significantly +++	More HSR trains are employed ++
Travel time (air or rail segment)*	Current status	Reduced travel times rail due to improved railway network and increased frequencies / capacities	Current status Strong increase in transport demand	Reduced travel time in the air transport sector to well established rural and remote connections
Share of train leaving (or arriving) on time*	Current status	Strong increase +++	Moderate increase ++	Moderate increase ++
Share of aircraft leaving (or arriving) on time*	Current status	Moderate decrease --	Decrease Due to high air traffic growth, more delays are incurred and cascading throughout the system -	Moderate increase ++

Scenario parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Quality of on-board service*	Current status	Strong increase +++	Moderate increase ++	Moderate increase ++
Monthly price index for rail transport*	Current status	Weak increase +	Moderate increase ++	Moderate increase ++
Monthly price index for air transport*	Current status	Strong increase +++	Moderate increase ++	Moderate increase ++
Level of air-rail integration and cooperation	Low degree Cooperation of air and rail providers on specific routes/ connections	High degree Strong focus on air-rail feeder connections to large hub airports	Medium/low degree Including single ticketing (cooperation not needed with strong growth on both modes)	High degree Focus on air-rail feeder connections to regional airports
Technological				
Implementation degree of new aviation technologies	Current status	Moderate degree ++	High degree Focus on the uptake and facilitation of implementation of new and innovative technologies +++	Moderate degree Especially regional air traffic exhibits a high degree of implementation of emission reduction technologies ++
Implementation degree of new rail technologies	Current status	High degree Focus on technological uptake in the rail sector +++	Moderate degree ++	Moderate degree Focus on regional railway ++
Mobility network				
Air traffic demand (passengers per city pairs)	Current status	Decrease in growth -	Strong growth +++	Moderate growth ++
Rail traffic demand (average number of passengers)	Current status	Strong growth +++	Strong growth +++	Moderate growth ++

Scenario parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Assumed air space improvement	Current status	Weak improvement +	Strong improvement Especially to incorporate the high level of air traffic growth +++	Moderate improvement ++
Assumed rail network improvement	Low level of improvement in railway station accessibility from urban and rural areas +	High level of improvement in railway station accessibility from urban and rural areas +++	Moderate level of improvement in railway station accessibility from urban and rural areas ++	High level of improvement +++
City archetypes (change from current status quo)[5]	Continuation of *status quo* structure (recovered to pre-pandemic)	Stronger focus on existing hubs and large airports (long-haul traffic focus) Feeder rail connections to airports are increasing, strong cooperation between air and railway sectors Inter-city and HSR connectivity on corresponding short-haul segments significantly improved by more connected rail network and higher frequencies	Uniform growth across air and rail networks, with little or no differentiation between route or node types	Decentralised air transport network Integration of existing and new small and regional airports to increase overall connectivity of urban and remote regions Lower importance of hub airports, increasing importance of and traffic growth at small to regional airports

[5] City archetypes are defined and described within Modus Deliverable D4.1. Here, airport and railway station archetypes have been developed, the combination of these yields city archetypes. For further analysis in Modus in WP4, in line with the various scenarios under which the model is run, different levels of 'promotion' will be applied to the city archetypes, to reflect improved connectivity in the future. This means that in a particular scenario a certain share of city archetypes of a specific category is promoted to a higher category which exhibits better connectivity. This will be further quantified in Deliverable D4.2.

Scenario parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of airports	Current status	Current status	Uniform increase	Moderate increase Focus on increase in small and regional airports
Number of HSR lines	Small increase +	Strong increase +++	Strong increase +++	Moderate increase ++
Airport catchment area effects	Small increase in airport catchment areas; small amount of large and hub airports are equipped with improved HSR connections. +	Increase in airport catchment areas due to a very well connected railway network, including the provision of improved airport access. ++	Both air and railway networks are improved and more efficiently connected, leading to increased airport catchment areas. ++	Airport catchment areas, especially those of small and regional airports increase due to better accessibility from rural and remote regions ++

* These variables are included in the modal choice model as outlined in Section 2.2.

3 Passenger archetypes

Next to cargo, travellers are users and main stakeholder of the European transport system, both for rail and air. Taking a traveller-centric perspective helps to improve this system, its system components (infrastructure, networks) as well as mobility offers. Creating archetypes, referring to exemplary traveller profiles or user segments, can support to take a passenger-centric view and understanding their diverse travel needs and options for personalisation. It also supports the Modus modelling exercise. Determinants of demand, high-level travel profiles, and individual characteristics of users as well as psychological and sociological drivers on users' mode choices are already explored and presented in the literature review in Deliverable D3.1 [24].

For the purpose of the Modus-project, future traveller archetypes from the CAMERA project are adapted [25]. Within this EU-funded endeavour, two types of future passenger profiles were developed based on a meta-analysis of previous studies on future passengers: first, for shorter, day-to-day mobility, the future urban passengers. Second, for travelling longer distances, the so-called future, long-distance travellers. The latter includes an air travel segment and might hence be a suitable starting point for the Modus project. In total, seven future, long-distance traveller archetypes were developed. Please note that these profiles may not cover all possible passenger types and scenarios.

We followed several steps for adapting the profiles for the purpose of the Modus project and for connecting the profile with the model frameworks. First, depending on the given income level, we allocated each profile with a price elasticities characteristic: a profile can either be a premium traveller with a low price elasticity, an economy traveller with a high price elasticity - or in some cases both. Within the booking process, the archetypes are either booking flexible ticket classes (high-yield traveller) or more budget, inflexible travel classes (inflexible in terms of connections, re-booking etc.). Through these classifications, we are able to connect the Modus future archetypes with the Mercury model provided by the University of Westminster and Innaxis. Each profile has further distinct characteristics. We align these with the demand drivers already explored in Deliverable 3.1. In case of missing information, the consortium derived possible characteristics from the overall profile description. An overview of all seven future archetypes including individual and socio-economic characteristics is depicted in Table 9.

Each passenger archetypes exhibits distinct characteristics which can be translated into according parameters for the different components in the landside model This approach is described in more detail in Modus Deliverable D4.1, and implemented in the further course of Work Package WP4.

Table 9: Overview of future traveller archetypes (adapted from [25])

Characteristics	Business flyer	Digital Gen Z Flyer	Environment-minded Flyer	Premium Flyer	Cultural Jetsetter	Holidayer	Golden Senior Flyer
Icon							
Main motive of travel	Business	Mainly private	Private & business	Mainly private	Mainly private	Mainly private	Private
Frequency of travel	frequently / very frequently	occasionally	occasionally	occasionally to frequently	occasionally to frequently	occasionally	frequently

Characteristics	Business flyer	Digital Gen Z Flyer	Environment-minded Flyer	Premium Flyer	Cultural Jetsetter	Holidayer	Golden Senior Flyer
Travel party size	1 to 2	1 to 2	1 to 2	up to 5 persons (family size)	1 to 2	single and up to 5 persons (family size)	1 to 2 (could also travel as part of organised travel group)
Burden (travelling with dependent people)	no	no	no	travelling with kids	no	travelling with kids	travelling with impaired companion
Booking/ Information gathering	online, travel agency (high-yield traveller)	online (high-yield traveller)	online (inflexible booking options)	in-person, travel agency (high-yield traveller)	online (inflexible booking options)	online (inflexible booking options)	in-person, travel agency (high-yield traveller)
Individual characteristics of users (criteria that define an individual)							
Predominant age group	18 - 65	15 - 70	15+	18+	15 - 65	30+ (with children under 15)	60+
Occupation	Business or job-nomad (project work)	Student, business, knowledge worker	student, business	business	Student, business, knowledge worker	from low profile job to business	mostly retired
Category of salary / income	medium / high	high	medium	high	low / medium / high (more medium / high)	low / medium	medium
Price elasticity	low (premium)	low (premium)	medium (premium /economy)	low (premium)	medium / high (premium)	medium / low (economy)	medium (premium / economy)
Household size	not relevant	1+	1+	from solo-traveller up to 5 persons (family size)	1+	from solo-traveller up to 5 persons (family size)	1 to 2
Psychological and sociological representations (travel needs that help to understand how profiles archetypes transport)							
Expected level of comfort	high	high	low	medium to high (premium)	medium	medium / high	medium
Degree of personalisation	high	high	high	high	low to medium	low	high
Technological affinity	high	high	low / medium	medium	high	medium	medium
Value of time	high	high	medium	medium	high	Low / medium	low
Further characteristics / requirements and values							
	workings during travel	high digitalisation; environmental conscious	environmental conscious and act accordingly	high space requirements	travel as experience; environmental conscious	high space requirements	might need assistance

4 Connectivity, performance and intermodal indicators

4.1 Overview of state of the art; indicator design

4.1.1 Overview and context

Table 10: Eleven Key Performance Areas introduced and developed by ICAO

KPA	Name	Meaning
1	Access and equity	"all airspace users have right of access to the ATM resources needed to meet their specific operational requirements [...] shared use of airspace by different users"
2	Capacity	"meet airspace user demands at **peak times** and locations while minimizing restrictions on traffic flow [...] **resilient** to service disruption"
3	Cost effectiveness	"cost of service [...] should always be considered when evaluating any proposal to improve ATM"
4	Efficiency	"airspace users want to depart and arrive at the times they select and fly the trajectory they determine to be optimum"
5	Environment	"contribute to the protection of the environment by considering noise, gaseous emissions and other environmental issues"
6	Flexibility	"ability of all airspace users to modify flight trajectories dynamically and adjust dep. & arr. times"
7	Global interoperability	"uniform principles [...] non-discriminatory global and regional traffic flows"
8	Participation	"ATM community [...] continuous involvement in the planning, implementation and operation"
9	Predictability	"ATM service providers to provide consistent & dependable levels of performance"
10	Safety	"highest priority [...] uniform safety standards [...] applied systematically"
11	Security	"protection against [...] intentional acts (e.g. terrorism) or unintentional acts (e.g. human error, natural disaster) "

The International Civil Aviation Organisation (ICAO) first defined [26] and later elaborated the context of [27] eleven KPAs for the improvement of the air traffic management system. These are shown in Table 10, with extracts from the ICAO definitions. While ICAO's ATM-system objectives differ from the broader mobility, connectivity and intermodal metric context of Modus, the nomenclature used by ICAO has already proven to be a good basis for wider mobility assessment. ICAO subdivides the KPAs into Focus Areas, and in Section 4.2.2.3 we outline how they were subdivided into Mobility Focus Areas in the DATASET2050 (2017) project [28]. Many of these KPAs will be captured through the indicators used in Modus, although it is pointed out at this stage that safety and security (both requiring specialist modelling) are out of scope. It is worth noting that capacity is importantly defined as meeting demand at peak times (since meeting demand in quiet periods is not the challenge) and in a manner that is resilient to disruption (as we will discuss later in this report). Key issues, to which careful attention must be paid in Modus and, indeed, similar modelling and simulation projects are to:

- avoid a proliferation of KPIs in the reporting; this is often a challenge with complex (ER) projects with multiple scenarios - it rapidly becomes difficult to 'see the wood for the trees' in massive output tables;
- identify headline KPIs and reserve other metrics for subsequent analysis as we drill down into the data for interpretive insights;
- adopt some degree of complementarity with other ER work (notably the TRANSIT project);
- avoid inadvertently 'trivial' relationships with model assumptions (e.g. Scenario X assumes a capacity doubling (model input), which is then inappropriately discussed as a change in a KPI (model output); such comparisons are useful for calibration and validation, however).

Exploring these issues further, in Sections 4.2.1 to 4.2.3 we respectively discuss connectivity, performance and intermodal indicators, offering reviews of the states of the art for each of these, and setting the Modus context. It should be noted that these indicator categories are not mutually exclusive, but the section divisions present a practical approach to focusing on these specific types of measurement. We also discuss differences between air and rail metrics, and the associated regulatory contexts.

4.1.2 Indicator design

When designing indicators, they should be:

- **intelligible** - preferably to the point of being simple;
- **pertinent** - to accurately reflect the aspect of performance being measured;
- **stable** - we can’t refine them from one period to another without losing comparability;
- **sensitive** - a property which can be managed through the functional specification (e.g. for objective data) or the scale used (e.g. a Likert scale for subjective data in market research).

Some challenges associated with this include:

1. indicators are often limited by data availability (applies to objective and subjective data types);
2. it may be difficult to respond to new data or methods, and maintain stability;
3. if they are (too) simple, they may not afford the best understanding of system dynamics;
4. appropriate discriminatory power is required (e.g. for pax cf. flights; types of pax; hubs cf. network-level of measurement);

5. avoiding proliferation (as flagged above: adding new indicators only where the added-value is clear).

Trade-offs exist between these desirable properties and it not possible to optimise on all of them simultaneously. Regarding the challenge of discriminatory power, (4), we have developed for Modus a 'telescoping' log transformation function, as shown in Equation 1.

$$\Delta_i' = m\ln(\Delta_i + \tau) + k$$

Equation 1: Telescoping log transformation function

It is termed 'telescoping' in that it converts low values of the input variable (Δ_i) into higher, more user-friendly output values ($\Delta_{i'}$), disproportionately earlier on in the series of possible input values, as shown in Table 11. Thus, typically very small changes at the network level that might be observed as the result of a scenario change (e.g. 0.05 minutes of delay, averaged over the whole network), to much more user-friendly outputs (e.g., here, 1.6), rendering tables of such values much easier to inspect visually. This telescoping ('compression') effect is also illustrated in Figure 2.

Table 11: Telescoping transformation - numerical examples

Δ_i	$\Delta_{i'}$
0.005	1.0
0.05	1.6
0.1	2.2
0.2	3.3
0.3	4.4
0.4	5.3
0.5	6.2
0.6	7.1
0.7	7.9
0.8	8.6
0.9	9.3
1	10.0

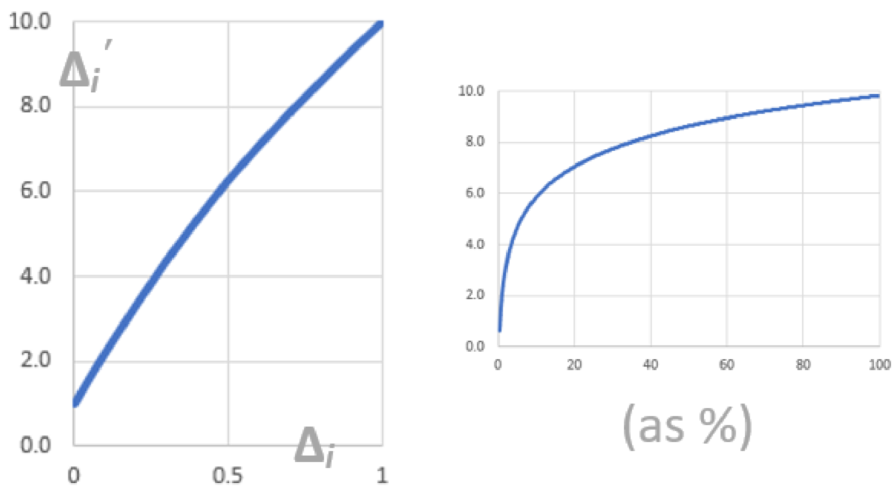


Figure 2: Telescoping transformation - compression illustration

According to the parameters chosen (gradient *m*; offsets τ and *k*), the output scale can be arbitrarily selected (here: 1-10), and adjusted to reflect an intuitive / target-related mid-point (e.g. a 32% reduction in delay, as we shall see in the SESAR example of Table 15, may be mapped to a mid-point of 5.0).

4.2 Review of state of the art

4.2.1 Connectivity indicators

4.2.1.1 Overview: What is connectivity

The mission of transport is to move people and goods, enabling business, tourism, education, and visiting friends & relations; and transport contributes economic and social benefits. Transport connectivity measures the extent and quality of the destinations that citizens can reach using means of transport. Transport connectivity can be defined by the number of means to connect from A to B for any citizen in Europe. Different types of connectivity for airports have been defined in DATASET2050 (2017) [28], as per Table 12.

Table 12: Type of connectivity [28]

Type of connectivity	Definition
Direct	These are the direct air services available from the airport – measured not just in terms of destinations, but also in terms of frequency (so for example, an airport with 5 daily flights to another airport, will register a higher score than one with only 4)
Indirect	This measures the number of places people can fly to, through connecting flights at hub airports from a particular airport. For example, if there is a flight to Amsterdam-Schiphol, Istanbul or Dubai – the large number of available onward connections from these airports expands the range of destinations available from the airport of origin. Indirect connections are weighted according to their quality, based on connecting time and detour involved

Type of connectivity	Definition
	with the indirect routing. For example, a flight from Manchester to Johannesburg via Paris-Charles de Gaulle will register a higher score than an alternative routing via Doha.
Airport	As the name suggests, this is the most comprehensive metric for airport connectivity – taking into account both direct and indirect connectivity from the airport in question. Airport connectivity is defined as the sum of direct and indirect connectivity – thus measuring the overall level to which an airport is connected to the rest of the World, either by direct flights or indirect connections via other airports.
Hub	This is the key metric for any hub airport big (such as London Heathrow) or smaller (such as Keflavik). Essentially, it measures the number of connecting flights that can be facilitated by the hub airport in question – taking into account a minimum and maxi-mum connecting times, and weighting the quality of the connections by the detour involved and connecting times.

For citizens living in an area where there is an airport, the Airport Connectivity indicates their 'reach', as a function of the travel and dwell (wait) times that need to be also considered from the passenger point of view.

4.2.1.2 European Air Connectivity Indicators (EUROCONTROL/ STATFOR)

EUROCONTROL/STATFOR has developed some EU air transport Connectivity Indicators in coordination with the EC DG Move. They were first presented at the informal Transport Council in Tallinn in 2017, where Ministers asked for extension to include intermodal connectivity. Since then they are constantly improved and discussed at the EU Observatory on Airport Capacity [29]. The EU air transport Connectivity Indicators focus on the travel options available door-to-door to European citizens. They measure how much citizens across Europe are connected to the rest of Europe, in particular to economic regions where jobs and facilities can be reached, in a reasonable time and comfort: for example, where can one go from Tallinn for a 10:00 meeting in Europe? How many alternative choices exist? etc. There are four Air Connectivity indicators currently defined:

- Travel Time D2D
- Reachable population
- Flight choice (how many flights a day to the destination?)
- Number of Carriers

The Air Connectivity Indicators can be calculated and visualised on a map at different granularity levels (or NUTS: Nomenclature of Territorial Units for Statistics standard, adopted in 2003, developed and regulated by the European Union): 1-Country, 2-Region, 3-Area (with a City-with-Airport).

Travel time D2D

The European air connectivity indicators consider door-to-door journeys with at least one flight and up to 5 hours on the ground, including dwelling time, access/egress at airports (with a maximum of 90 minutes drive from/to the airport): total D2D = gate-to-gate + (up to) 5 hours on ground transport.

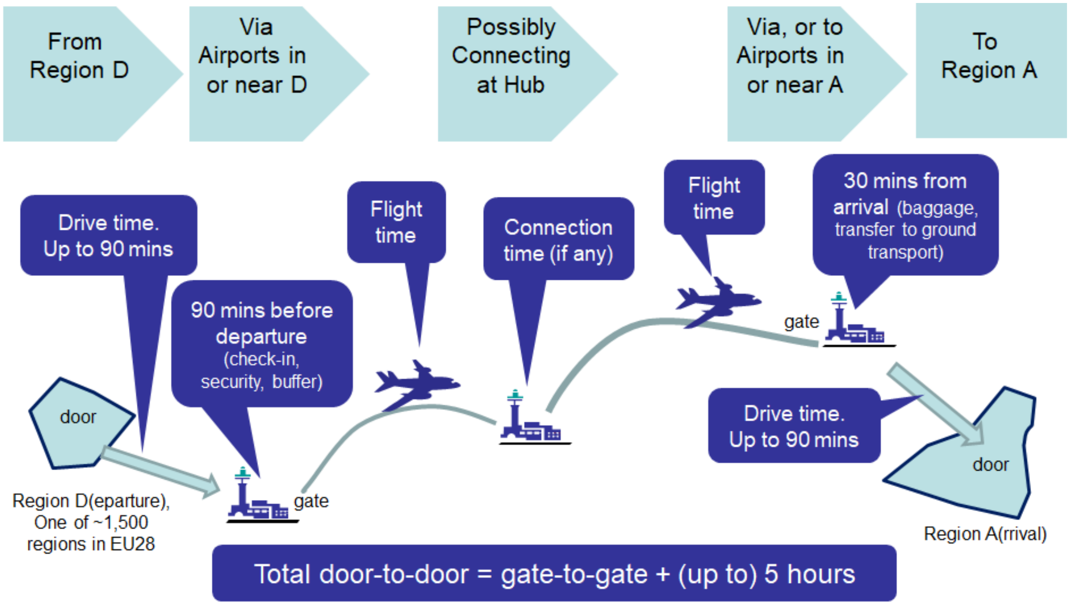


Figure 3: Travel time: the stages of a trip [30]

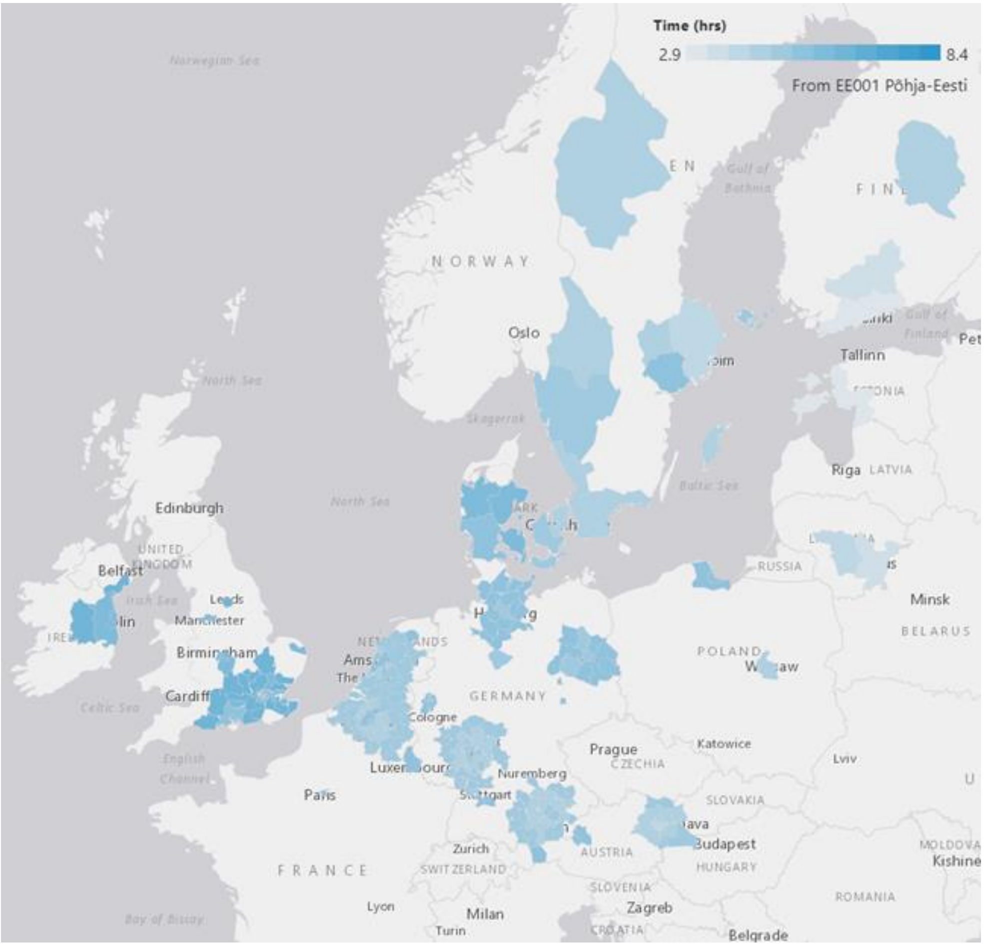


Figure 4: The EU air transport Connectivity Indicators dashboard [29]

This figure illustrates the connectivity for citizens living in the Tallinn area to reach a meeting starting at 10:00 somewhere else in Europe. The blue colour indicates the travel time, grading from 2.9 hours (light blue) to 8.4 hours (dark blue). This includes direct and connecting flights, and drive time to and from the airport (within 90 minutes, which cover 75% to 85% of passengers).

Reachable population

This indicator shows how many people can be reached from/ to an airport by direct or connecting flights, as in the example below:

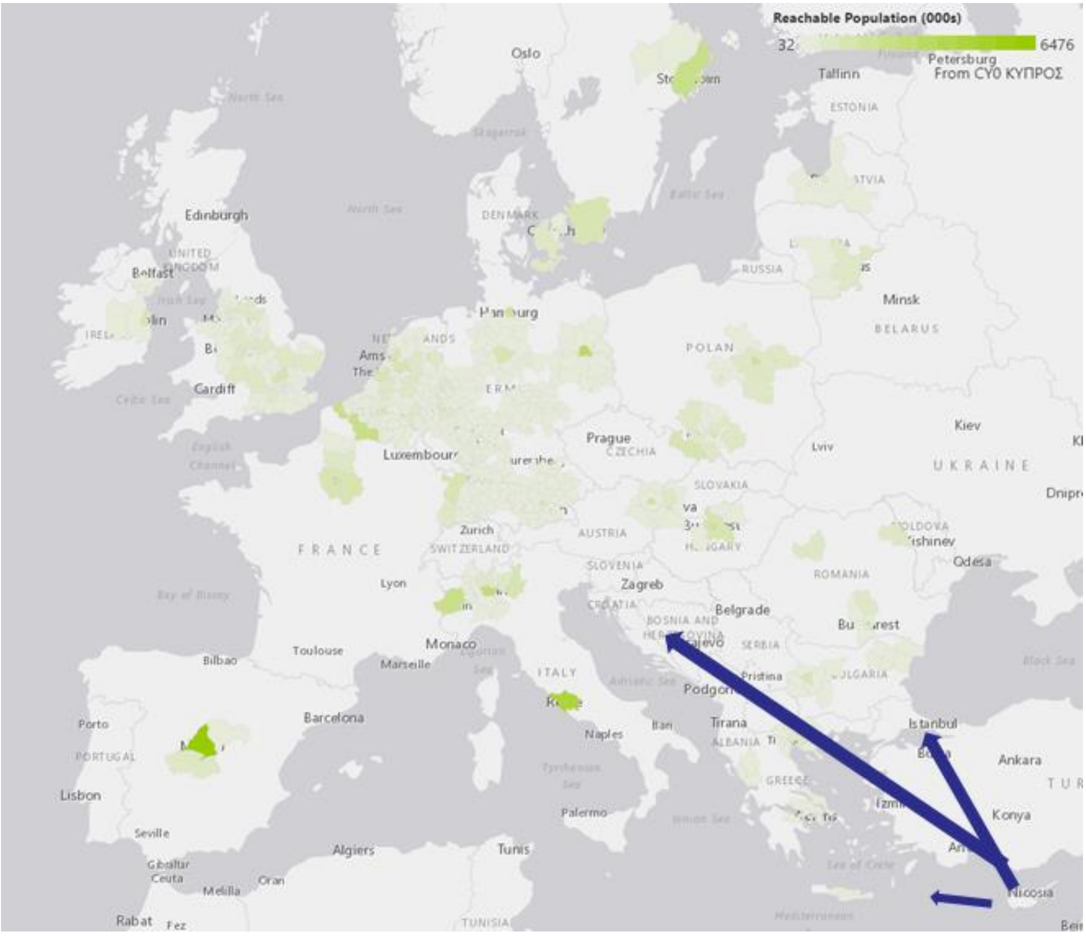


Figure 5: Reachable population from Cyprus by direct flights [29]

The green scale indicates the volume of population reached, i.e. the number of people in each (NUTS3) region in Europe that can reach Cyprus by a direct flight.

As the NUTS3 regions are typically small – 40 kilometres across, half a million people, it is assumed that if you can reach the centre of the region, its entire population is reachable. This indicator can also provide the population indicator in terms of the percentage of people who can be reached in a whole country.

Flight choice

This indicator illustrates how many flights there are a day/ a week to the destination, as shown in the next figure:

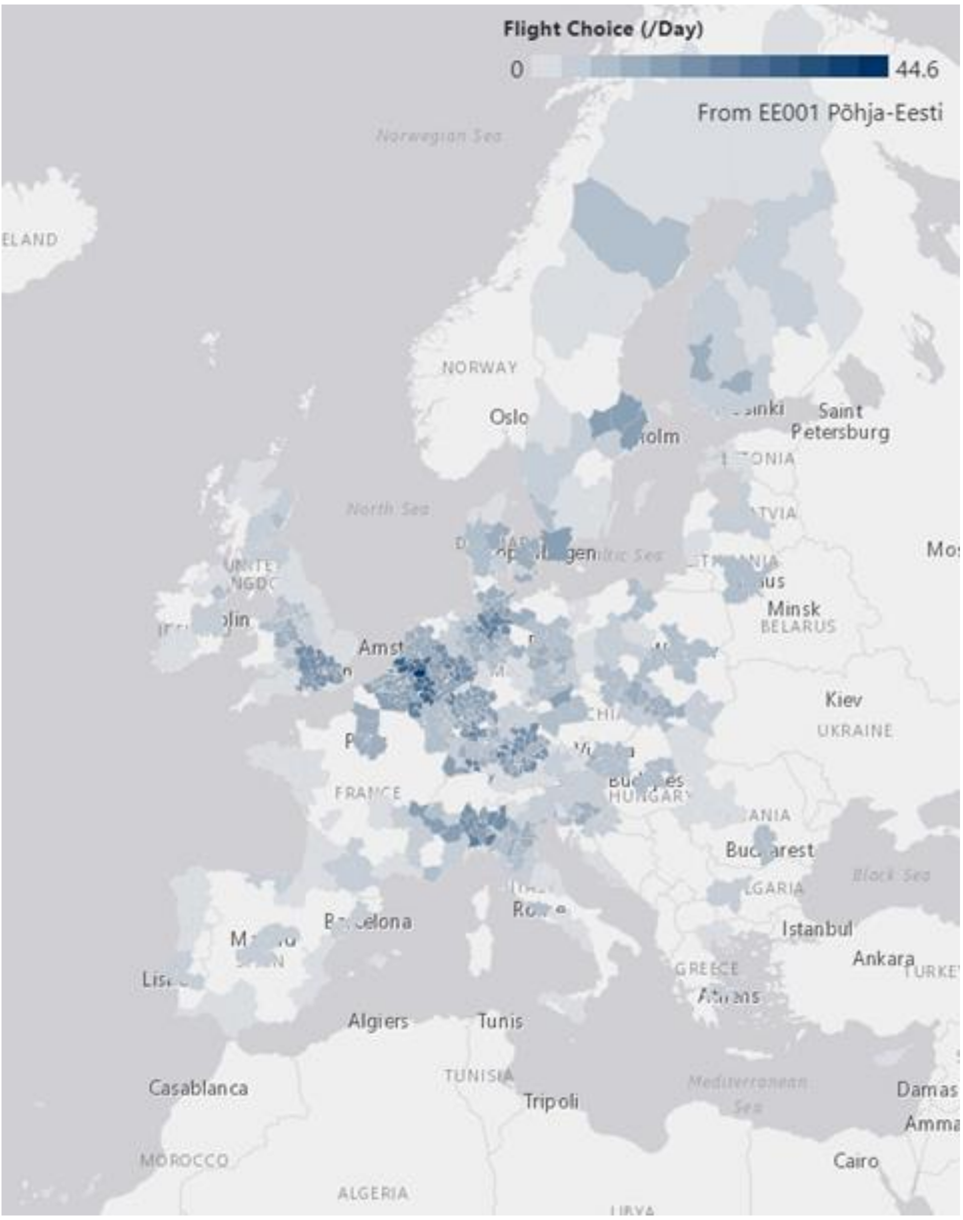


Figure 6: Flight choices from Tallinn [29]

The blue scale at the top indicate how many flights can be chosen per day, in this case between 1 per week and 45 per day, including with connecting flights via multiple airports (Brussels, Schiphol, Düsseldorf, Köln) (this is where high values can be found). Note: an aggregated flight choice indicator can be calculated as a weighted sum (Sum because the flights are distinct: no double-counting), weighted by origin and destination population as a fraction of the whole population:

$$f_{D,A,Q} = \sum_{i \in D, j \in A, q \in Q} \frac{p_i}{p_D} \frac{p_j}{p_A} f_{i,j,q}$$

Equation 2: Flight choice indicator

Where

- *i* is a NUTS3/4 departure region, j a NUTS3/4 arrival region
- *Q* is a selection of qualities *q*, each *q* a unique combination of (type, low-cost, time of day, number of changes, carrier, drive threshold)
- *D, A* are aggregate departure and arrival regions, respectively
- *f_(i,j,q)* is the number of flights from *i* to *j* with qualities *q*
- *p_i* is the population of *i, p_D* is the population of *D*, etc.

Number of carriers

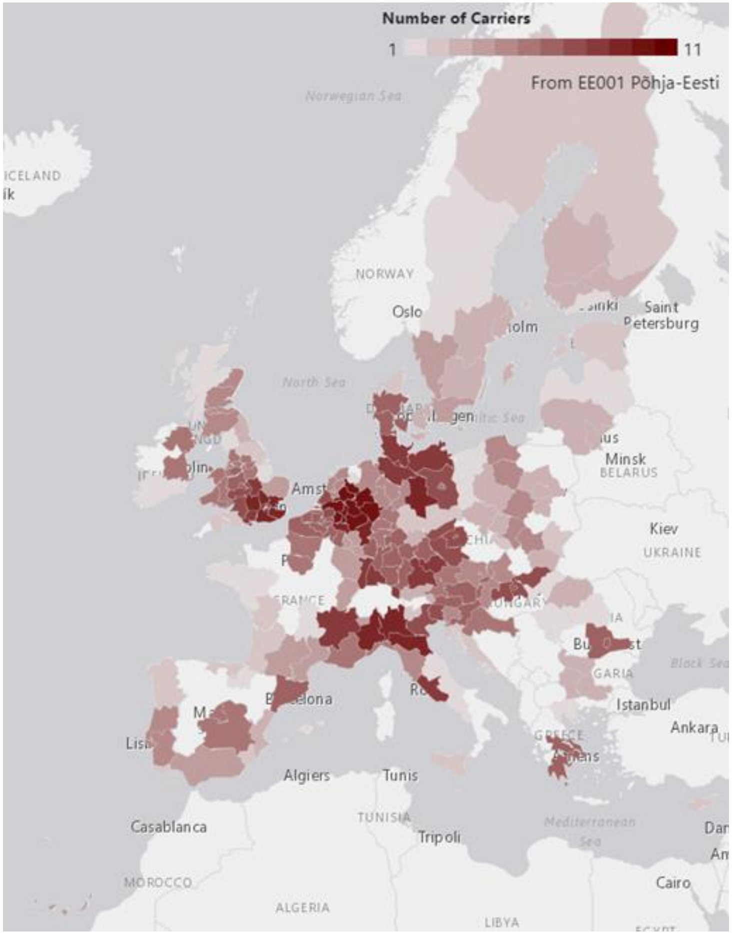


Figure 7: Number of carriers from Tallinn [29]

This indicator illustrates how many carriers serve each destination region. It shows which destinations are reliant on one or two carriers from any starting airport. The brown colour scale is a count of how many air carriers serve the route, regardless of how often they fly.

4.2.1.3 Summary Connectivity Indicators

The connectivity indicators described in this section are a means to measure how well a region within Europe is connected in terms of time it takes to get to other regions as well as the number of options offered to e.g. densely-populated European regions.

Table 13: Overview Connectivity Indicators

Indicator	Units
Travel time D2D	Travel time from door to door (minutes)
Reachable population	Volume of population reached in destination region (percentage)
Flight choice	Number of flights per day to destination region
Number of carriers	Number of carriers serving each destination region

4.2.2 Performance indicators

In this section we review the state of the art across a number of research domains and previous/ongoing research projects. These indicators measure the achievement towards particular mobility or system goals such as travel time savings or reduction of delay. We will return to review the overall priorities for Modus in Section 4.3.

4.2.2.1 Air transport and air traffic management

Air transport

Within the air transport context, there are essentially two major (sets of) thresholds for measuring performance. The first is the informal, historical rule of taking **15 minutes** to measure a flight as being on time. This arises from MCTs (Minimum Connecting Times) for transfer passengers, which were designed to be the time for a passenger with full mobility to walk between the worst-case pair of gates involved (including any transit link) *plus* 15 minutes' contingency. Thus, in theory, if a flight is 'on time', i.e. within 15 minutes of schedule on arrival, then the passenger should make their connection. At FRA, for example, the MCT is generally 45 minutes for LH group flights (there are exceptions, e.g. for TLV with extra security checks). This suggests it should be possible to get between the gates within 30 minutes even if having to wait for a transit or at the far end of the piers - and if arrival was up to 15 minutes late the passenger would still make their connection. If a flight is more than 15 minutes late, then booked connections will start to be broken, which is typically the critical point from an operational perspective.

The regulatory context is here determined by Regulation (EC) No 261/2004 (henceforth: "Regulation 261") [31], which establishes the rules for compensation and assistance to airline passengers in the event of denied boarding, cancellation or delay. Note that these rights are conferred on the passenger regardless of the cause, except for compensation, which is only due to the passenger in the case of airline-attributable delay. This thus excludes compensation payments being required under conditions declared to be 'extraordinary circumstances', which includes certain types of weather, for example. Figure 8 shows the main Regulation 261 entitlements by delay duration and length of haul (short haul <1500km; medium haul 1500-3500km; long haul >3500km). Note that the lowest trigger point is **2 hours**. Hotel accommodation rights are conferred in case where a stay of one or more nights becomes necessary or where a stay additional to that intended by the passenger becomes necessary. As we shall see later in this section, these costs and delays are already captured by Mercury.

Haul	≥ 2 hours	≥ 3 hours	≥ 4 hours	≥ 5 hours	
Short haul	[care]	[care] €250	[care] €250	[reimbursement] [care] €250	(accommodation)
Medium haul		[care] €400	[care] €400	[reimbursement] [care] €400	(accommodation)
Long haul		€300	[care] €600	[reimbursement] [care] €600	(accommodation)

[care] Care (e.g. reasonable meals and refreshments), refers to departure delay

[reimbursement] Reimbursement of ticket

Compensation, refers to arrival delay

Figure 8: Delay duration and Regulation 261 entitlements (own depiction)

Single European Sky Performance Scheme

The Single European Sky was launched by the European Commission in 2004, to:

- reform the architecture of European ATM;
- address issues at a European, rather than local, level;
- provide a legislative approach to meet future capacity and safety needs.

The key objectives were to:

- restructure European airspace as a function of air traffic flows;
- create additional capacity;
- increase the overall efficiency of the ATM system.

High-level, ambitious goals ("political targets"), also known as the SES '2005 vision', were set out as:

- **x3** increase in capacity (reducing delays);
- **x10** improvement in safety;
- **10%** reduction of flights' impact on environment;

- **≥ 50%** reduction in costs of ATM services to airspace users.

The literature on this is highly disparate with no readily digestible set of robust references, but the resource https://ec.europa.eu/transport/modes/air/ses_en [32] is a very good starting point, with https://webgate.ec.europa.eu/eusinglesky/content/welcome_en [33] providing up-to-date materials and new consultation details. A key legislative / regulatory element (in addition to the SES 'Charging Scheme') is the SES Performance Scheme, which is split into 'reference periods' (see Table 14). This allows each period to adapt to and build on the previous one. Having relatively shorter blocks avoids setting distant targets (e.g. for 2035) that may need to change as a function of the traffic. National performance plans submitted by the Member States refer to each reference period. Unlike the SESAR 'performance ambitions' (see below), the SES Performance Scheme KPIs are **legally binding** on the States. They face (small) penalties if they are not met.

Note that cost efficiency is progressively improving. In 2018, EU-wide actual unit costs were below the 'determined' unit costs (targets). We measure capacity through average en-route ATFM, although it is not really the best measure of capacity (cf. the 'pertinence' quality, flagged in Section 4.1.1). Since actual delay performance was not generally very good, the target for 2020 was relaxed pre-Covid-19. However, the SES PS risk-sharing mechanisms could not effectively deal with the collapse of air travel during Covid-19, and the cessation of the assumed underlying flow of revenue into the system (ultimately from passengers). Since it is difficult for ANSPs to scale operations to actual demand (their greatest costs are staff costs), in November 2020, the Commission and States adopted an exceptional measures Regulation, whereby airlines will have to cover the revenue gap of 2020-21, delayed to 2023 and spread over 7-5 years. RP3 is currently out to consultation. Member States should revise their PPs and submit them by October 2021.

The PRB has recommended that safety targets should remain the same, whilst environmental targets should be more ambitious during reduced traffic. ANSPs need flexibility in terms of capacity to restructure their business: revised capacity targets reflect lower traffic for 2021 and, with gradually increasing traffic, the system-wide cost optimum of 0.5 minutes delay/flight applies for 2023 and 2024. The targets will allow ANSPs to implement technological changes, responding to changes in demand. The PRB newly proposed (and current) targets (en-route ATFM minutes/flight) are: 2020, 0.9 (0.9); 2021, 0.35 (0.9); 2022, 0.5 (0.7); 2023-4, 0.5 (0.5). Regarding cost efficiency, ANSPs reported 2020 costs only 1% less than 2019 actual costs. However, only a limited number of ANSPs reported needing additional finance from third parties (e.g. the States, or banks) for 2020 and 2021: most were able to finance all or part of the revenue gap by their own means. The PRB proposes targets also requiring cost containment measures for ANSPs, such that airlines do not have to cover the whole shortfall.

Table 14: Single European Sky Performance Scheme targets by reference period

RP	Effective	**EU-wide binding KPIs** (NB. Other PIs and monitoring are in place)			
		Safety	**Environment**	**Capacity**	**Cost efficiency**
1	**2012-2014** (en-route focus)	N/A	↑ Average horizontal en-route flight efficiency re. last-filed flight plan ("KEP") …	**Minutes of en-route ATFM delay: 0.5 min/flight**	**Average determined unit cost for e/r ANS** ↓ 3.2% p/a ("original" target; 2009-2014)
2	**2015-2019** (extended to gate-to-gate; safety added)	↑ Effectiveness of safety management (EoSM) & applying severity classification scheme, 2017 onwards	… & actual trajectory ("KEA")	(& *national* KPIs for airport ATFM arrival delay)	**Average determined unit cost for e/r ANS** (& national KPIs for ANS terminal cost efficiency)
3	**2020-2024** (pre-Covid-19 plans shown; not designed for traffic collapse; new PPs by OCT21; reach ATFM targets sooner)	Continued application of EoSM "levels"; a "counterbalance" w.r.t. capacity and cost efficiency	… KEA falling to 2.40%, for 2022-24 (KEP now downgraded to indicator, from KPI, so no targets. It was a KPI only in 2019.)	**Relaxed to 0.9 min/flight in 2020, falling to 0.5 by 2023**	New method with better baseline ↓ 1.9% 2.7% p/a

SESAR

SESAR sets out a number of 'performance ambitions', which relate to the various ICAO KPAs introduced in Section 4.1.1 and the SES high-level goals, referred to above. These are presented and discussed in the ATM Master Plan [34] – see Table 15. They are used to assess the performance of SESAR Solutions, in terms of the contributions they make to the 'performance ambitions'. The target year is 2035. The baseline is 2012, from an earlier edition of the Master Plan. The 'performance ambitions' are not binding (cf. the targets of the SES Performance Scheme). They may be adapted, e.g. if traffic levels change significantly from forecast levels, noting that the look-ahead time (2035) is a lot further than the SES PS. Contributions from beyond SESAR are included and exogenous effects (e.g. increasing aircraft sizes and average flight times) are also taken into account. A prominent performance ambition example is the reduction in delay, with a target improvement of 1-3 minutes per departure. The upper end of the band equates to a 32% reduction in delay, which we discussed in terms of scale transformations in Section 4.1.2.

On the left are shown the SES high-level goals that we met earlier, so that the reader can compare the goals and ambitions across the rows, where applicable. An example is the 50% reduction in the unit costs (e.g. en-route charges) paid by the airlines. Their baseline year is 2005. The Master Plan talks of SESAR contributing to 'eliminating environmental inefficiencies'. The upper bound of the reduction (10%) corresponds to the SES target on the left. The safety Ambition has been increased relative to the previous MP, now expressed as zero accidents with direct ATM contribution. The Master Plan (ibid.) explains that: "Repeated contact and coordination with the Performance Review Body resulted in coordination of efforts between the technology and performance pillars of the SES to ensure the readability of the SESAR Performance Ambitions by the SES performance scheme. Efforts were also made to make more visible and explicit the link between the Master Plan's priorities and key objectives and the EU's aviation strategy."

Table 15: SESAR performance ambitions [34]

FIGURE 10. **PERFORMANCE AMBITIONS FOR 2035 FOR CONTROLLED AIRSPACE**

Key performance area	SES high-level goals 2005	Key performance indicator	Performance ambition vs. baseline			
			Baseline value (2012)	Ambition value (2035)	Absolute improvement	Relative improvement
Capacity	Enable 3-fold increase in ATM capacity	**Departure delay**[4], min/dep	9.5 min	6.5-8.5 min	1-3 min	10-30%
		IFR movements at most congested airports[5], million	4 million	4.2-4.4 million	0.2-0.4 million	5-10%
		Network throughput IFR flights[5], million	9.7 million	~15.7 million	~6.0 million	~60%
		Network throughput IFR flight hours[5], million	15.2 million	~26.7 million	~11.5 million	~75%
Cost efficiency	Reduced ATM services unit costs by 50% or more	**Gate-to-gate direct ANS cost per flight**[1] · EUR(2012)	EUR 960	EUR 580-670	EUR 290-380	30-40%
Operational efficiency		**Gate-to-gate fuel burn per flight**[2], kg/flight	5280 kg	4780-5030 kg	250-500 kg	5-10%
		Additional gate-to-gate flight time per flight, min/flight	8.2 min	3.7-4.1 min	4.1-4.5 min	50-55%
		Within the: Gate-to-gate flight time per flight[3], min/flight	(111 min)	(116 min)		
Environment	Enable 10% reduction in the effects flights have on the environment	**Gate-to-gate CO_2 emissions**, tonnes/flight	16.6 tonnes	15-15.8 tonnes	0.8-1.6 tonnes	5-10%
Safety	Improve safety by factor 10	**Accidents with direct ATM contribution**[6], #/year Includes in-flight accidents as well as accidents during surface movement (during taxi and on the runway)	0.7 (long-term average)	no ATM related accidents	0.7	100%
Security		**ATM related security incidents resulting in traffic disruptions**	unknown	no significant disruption due to cyber-security vulnerabilities	unknown	-

1 Unit rate savings will be larger because the average number of Service Units per flight continues to increase.
2 "Additional" means the average flight time extension caused by ATM inefficiencies.
3 Average flight time increases because the number of long-distance flights is forecast to grow faster than the number of short-distance flights.
4 All primary and secondary (reactionary) delay, including ATM and non-ATM causes.
5 Includes all non-segregated unmanned traffic flying IFR, but not the drone traffic flying in airspace below 500 feet or the new entrants flying above FL 600
6 In accordance with the PRR definition: where at least one ATM event or item was judged to be DIRECTLY in the causal chain of events leading to the accident. Without that ATM event, it is considered that the accident would not have happened.

Whilst the focus of Modus is on the passenger service delivery impacts of the simulations modelled, rather than the more ATM-specific metrics of the Single European Sky Performance Scheme and SESAR, as we shall see later, most of these are already captured in the Mercury model (safety, security and ANSP cost efficiency being the notable exceptions).

4.2.2.2 Rail

The regulatory context is here determined by Regulation (EC) No 1371/2007 (henceforth: "Regulation 1371") [35], which, inter alia, establishes the obligations of railway undertakings to passengers in cases of delay, missed connection or cancellation of a service. The minimum compensations for delays are 25% of the ticket price for a delay of **60 to 119 minutes**, 50% of the ticket price for a delay of 120 minutes or more, and, where the transport contract is for a return journey, "compensation for delay on either the outward or the return leg shall be calculated in relation to half of the price paid for the ticket". Notwithstanding these minimum European rights, they may additionally vary from state to state, and from operator to operator. **30 minutes** is the typical lower threshold. In particular, private operators might offer significantly better compensation than is typically found in the corresponding state, partly as a marketing tool for a premium service. One example is the HSR service operated in Spain (for RENFE 'AVE' services: 15 minutes delay: 50% refund, for more than 30 minutes, 100% refund). Table 16 shows typical compensations offered for delays in the UK.

Table 16: Typical compensations offered for delays in the UK

Delay	Compensation offered
30-59 minutes	50% of the cost of single ticket or 50% of the cost of either portion of return ticket
60 minutes or more	100% of the cost of single ticket or 100% of the cost of either portion of return ticket
Two hours or more for return tickets	If either or both the outward or return legs of the journey are delayed by more than two hours and a return ticket is held, entitled to receive up to 100% of the cost of the return ticket

Performance indicators are applied to monitor the current state of the system as well as the progress towards particular goals, as they are in other transport sectors. With no equivalent of the Network Manager (EUROCONTROL), nor of the SES PS, the only binding targets in the rail context relate to safety and technical interoperability requirements (which are out of scope for Modus in any case). The Shift2Rail Joint Undertaking outlines, however, three main quantitative targets and respective key performance indicators: (1) the reduction of life cycle costs by 50%, (2) **the improvement of reliability and punctuality by 50%**, and (3) doubling of the capacity [36]. More specific, life cycle cost is the "cost for the railway undertaking over the lifespan of the systems", including investment cost, operative cost, labour or energy cost and, the dismantling cost; capacity denotes the maximum possible capacity, "which is the maximum number of transportable passengers in one peak hour for the passenger transport scenarios and the maximum of tonne-kilometres in 24 hours for freight"; and reliability and punctuality is "measured as a 50% decrease of late arrivals mainly caused by unreliability of technologies" [36].

In line with these targets, several key performance indicators are employed to measure the progress compared to the benchmark, the state-of-the art of the system in the year 2014. The progress is monitored across different System Platform Demonstrators (SPDs), including the market segments high-speed rail, regional rail, urban (metro) and freight rail. In line with the objectives in Modus, the following KPIs are of relevance:

- % reduction in the costs of developing, maintaining, operating and renewing infrastructure and rolling stock and increase energy efficiency compared to "State-of-the-art"
- % increase the capacity of railway segments to meet increased demand for passenger and freight railway services compared to "State-of-the-art" 2014
- % decrease in unreliability and late arrivals compared to "State-of-the-art" 2014

In addition to these indicators, the 2018 PRIME Benchmarking report [20] and the Railways Statistics Synopsis (2021) [37] detail several indicators which characterise the railway system, its network utilisation, the environmental impact, and indicators relating to rail punctuality and reliability. Similar indicators are reported in the International Railway Statistics [38] overview:

- National modal share of rail in passenger transport (% of passenger-km), including cars, buses/coaches, aviation and railways
- *Total track-kilometres*
- *Total main track-kilometres*

- *Degree of network utilisation of passenger trains (daily passenger train-km per main track-km)*
- Degree of electrification (% of main track-km)
- Share of electricity-powered trains (% of train-km)
- Share of diesel-powered trains (% of train-km)
- Passenger trains' punctuality (% of trains); delay of less than or equal to 5:29 minutes / Punctuality of passenger trains (local trains, long-distance trains)
- *Freight trains' punctuality*
- Delay minutes caused by the infrastructure manager (minutes per train-km)
- *Asset failures in relation to network size (number per thousand main track-km)*
- *Average delay in minutes per asset failure (minutes per failure)*
- *Train movements on the network of the infrastructure manager*
- *Number of stations and stops for passenger traffic*
- Punctuality on the network of the infrastructure manager
- *Passenger transport: split by type of service (short-distance trains, long-distance trains, high-speed trains)*
- Energy Consumption by Rail Tractive Stock

As in other transport sectors, a specific focus is placed on assessing and measuring the environmental impact of the rail sector and its progress towards European emissions reduction goals. The Environment Strategy Reporting System [39] outlines several indicators which are employed to measure the progress towards specific energy consumption goals in the railway sector:

- Specific energy consumption from passenger trains
- Total CO_2eq emissions
- Specific CO_2eq emissions from passenger trains
- Total energy consumption
- Specific passenger energy consumption (kWh/pkm)

Indicators / variables shown above in italics are not of primary interest for Modus. Others are likely to be used in WP4 as model inputs, or correspond to KPIs / output metrics (as discussed further below). User preferences also play an important role when it comes to measuring the performance of the rail sector. The Ride2Rail project [40] outlines categories which are important for users when making their travel choice. Results from a user survey show that quick, reliable and cheap transport is of highest importance, followed by comfortable, door-to-door, environmentally friendly, and short (minimising the travel distance) travel offers. In addition to this, users want to be able to engage in different tasks while travelling (multitasking).

4.2.2.3 Mobility assessment – CAMERA and DATASET2050

In the H2020 Coordination and Support Action DATASET2050, the ICAO key performance areas already outlined in Section 4.1.1 were further subdivided into Mobility Focus Areas (MFAs), see Table 17. This is in line with the ICAO approach towards further detailing its KPAs into focus areas. Within DATASET2050 [28] the MFAs were derived from air transport goals, to distinguish them from other potential focus areas such as ATM, safety etc. These MFAs have been inspired by the expected future transport properties (affordable, quick, seamless etc.) given in the "Meeting societal & market needs" section of Flightpath 2050 [9]. Some of the MFAs have also been derived/inspired/complemented by the European Commission Aviation Strategy [41], which describes several research areas in the context of tackling challenges to growth in air transport. Within DATASET2050, the main focus was on monitoring the progress of the transport industry towards the mobility/connectivity goal of having 90% of travellers that involve an air segment taking 4 hours or less from door to door (4HD2D).

Within the scope of the H2020 Coordination and Support Action (CSA) CAMERA a performance framework has been developed [25]. In this framework, the mobility performance can be measured according to several key performance areas such as efficiency, capacity, or access and equity, which are again detailed by multiple key performance indicators. The application of these within the scope of CAMERA allows an assessment of the contribution of the current research landscape towards European mobility goals.

Mobility Focus Areas and respective KPIs from DATASET2050 and CAMERA are outlined in the table below. In line with the specific objectives of the Modus project, certain indicators from the DATASET2050 project and the CAMERA performance framework may be relevant for application within the modelling of Modus WP4. The KPIs shown are later consolidated in Table 20 and Section 4.2.3, wherein we propose the consolidated intermodal metrics for Modus. Those shown in italics (below, "DATASET2050 and CAMERA KPIs" column) are not planned for use in Modus.

Table 17: Mobility Focus Areas

KPAs	MFAs	DATASET2050 and CAMERA KPIs
Access and equity	Affordability Equity Reach	• 4-hour reach: The distance that can be attained, within Europe, from 90% of European doors of origin in exactly 4 hours • Journeys within 4 hours door-to-door • The distance that can be attained, within Europe, from 90% of European doors of origin in exactly 4 hours
Cost effectiveness	Beneficiary Cost Value for money	*Not in scope for Modus*
Efficiency	Duration Speed (Comfort)*	• Best possible journey time/actual time of travel
Flexibility	Diversity of destinations	• Distance diversity of destinations • Cultural diversity of destinations (Number of NUTS1 regions reachable number of countries reachable, for a given origin)^

KPAs	MFAs	DATASET2050 and CAMERA KPIs
	(Multimodality)**	• Frequencies: number of possible itineraries for the same OD per unit of time
	Resilience	• Average time necessary for a replacement service to be available to replace a cancelled one^^
Interoperability	Seamlessness	• Journey transition time (Total time spent in transitions during a journey) • Number of phases required to complete a journey • Average of (Time spent during transitions / total travel time for the journey) • Average of time spent per transition
Predictability	Variability	• Variability of delay at arrival: standard deviation of delays at destination. • Variability on intra-European flights • *Variability on airport public transport*
	Punctuality	• Percentage of passengers arriving more than 15 minutes late at destination / Likelihood of arriving more than 15 minutes late at destination • Punctuality of intra-European flights (Percentage of scheduled flights that arrive within 10 minutes of their scheduled arrival time (irrespective of their departure time) • *Punctuality of airport public transport (Percentage of scheduled public transport journeys that arrive at the airport within 5 minutes of their scheduled arrival time)*
	Reliability	• Reliability of intra-European flights (Percentage of scheduled flights that are cancelled or delayed by more than two hours) • *Reliability of airport public transport (Percentage of scheduled public transport journeys that are cancelled or delayed by more than 30 minutes)* • Likelihood of missing a flight (Probability that delays in the door-to-kerb and kerb-to-gate segments of the journey will result in the passenger's not being able to board their plane) • Average minimum buffer time required at the door of origin to ensure a 95% chance of arriving at destination within 15 minutes of the planned arrival time
Safety	Safety	*Not in scope for Modus*
Security	Security	*Not in scope for Modus*
Sustainability	Environmental aspects; Social aspects	• Energy efficiency of transport: average energy needed per passenger per km. • CO_2 efficiency of transport: equivalent CO_2 emissions (in terms of radiative forcing) per passenger per km. • Sum of CO_2 produced per passenger-km for each mode of travel used times kilometres spent in that mode
Capacity	Capacity	• Total number of journeys per year (regardless of travel time) • *Percentage of door-to-door journeys using a public service air carrier in one leg of the journey, made within 4 hours/ over 4 hours but within 6 hours*

* "Comfort" was included as an MFA here. Whilst this is as a largely subjective measure, importantly contributing to market share drivers, it is only truly captured through surveys.

** Multimodality was included under flexibility in this context, whereas in Modus it embraces all KPAs, as we focus on in Section 4.2.3.

^ Taken forward as an equity KPI Table 20.

^^ See Table 20 and Section 4.2.3 for discussions on resilience and measures thereof.

4.2.2.4 Performance scenario modelling – Vista

Various performance metrics are commonly used in ATM, and can be grouped by different stakeholders, as proposed in various research projects (e.g. Vista, Domino). The purpose of these metrics is to assess the performance of the ATM system, its impact on stakeholders and their trade-offs. As can be seen, the metrics presented here are rather similar to the SESAR ones, presented above. The Mercury model collects sets of performance indicators across different stakeholders, as a default setting. Table 18 lists the indicators computed with Mercury simulator and their short description. Those shown in italics are unlikely to be used in Modus, as they are very ATM-specific.

Table 18: Mercury performance indicators

Stakeholder	Air transport and ATM metrics
Air Navigation Service provider (ANSP)	• *route charges (en-route portion only): the amount of route charging revenue an ANSP collects*
Airport	• *departure queue delay: cumulative delay for departing flights* • *arrival queue delay: cumulative delay for arriving flights* • number of operations: ○ departures: number of departing flights ○ arrivals: number of arriving flights
Airspace users	• flight departure delay: difference between scheduled and actual departure time • flight arrival delay: difference between scheduled and actual arrival time • fuel: amount of fuel consumed • delay per flight segment: delay accrued on the flight segment • reactionary delay: caused by the late arrival of aircraft from a previous journey - occurs when the arrival delay cannot be recovered in the turnaround process • ATFM delay: delay imposed on flights by the ATFM regulations • gate-to-gate time: the time from departure to arrival gate, comprises flight time and taxi times • cost of delay: ○ non-passenger related - e.g. increased crew, maintenance costs ○ passenger related (hard and soft) - the hard costs are due to Regulation 261*, and soft costs indicate possible loss of market share due to delays • cost ○ route charges - route charges the flight pays for ANS ○ fuel cost - flight fuel costs
Passengers	• departure delay - same as above, but takes into account the entire itinerary • arrival delay - same as above, but takes into account the entire itinerary • missed connections - count of missed flights • connecting time - the time between two connecting flights • gate-to-gate time - same as above, but takes into account the entire itinerary • door-to-door time

Stakeholder	Air transport and ATM metrics
Environment	• fuel kg • CO_2 tonnes

Note that similar metrics (e.g. delay) are measured across several stakeholders as their experience of the same phenomena could be rather different. For example, one minute of flight arrival delay corresponds to 1.3 minutes of passenger delay, due to missed connections [42]. Another point of note is that the indicators should not stop at demonstrating the average value, but should include the indicator distributions (as we discuss in Section 4.2.3).

Importantly, it is to be noted that these indicators currently correspond to the air transport and ATM contexts, although they include airport access and egress times in the actual model. In the development of the Mercury model for Modus, these indicators (including some estimates of the corresponding delay compensation costs), need to be extended to the rail context. These developments will be presented in Deliverable 4.2 (Mobility models description).

* These typically drive the overall cost of delay to the airspace user. The Mercury model has highly detailed cost functions, e.g. based on those outlined in Figure 8, and have been extensively updated in 2021 relative to a pre-Covid (2019) baseline

4.2.2.5 Centrality metrics – Domino

The ATM performance metrics described above address the impact on various stakeholders, but do not address the complexity of the network or provide information on how the different elements are related in the system. To address this aspect, network metrics can provide more specific understanding of the system-wide implications. Two types of network metrics have been explored in Domino project [43]: centrality metrics and causality metrics.

Centrality measures the importance of a node in a network. Different centrality metrics exist, but they are all based on some concept of connectivity of a node in terms of links, paths or walks joining it to the other nodes of the network. High centrality of a node (i.e. airport) indicates higher potential to travel the network passing through that node. The centrality can be measured for the scheduled and actually flown environment. In the case of such comparison, an example of the loss of centrality of a node (e.g. an airport) from the scheduled to actual network, indicates a diminished potential of travelling through the network passing through that node. Meaning that the performance of the network is diminished. Figure 9 illustrates three centrality indicators: betweenness centrality, Katz centrality and PageRank. Betweenness is based on the shortest paths (and distances) between the nodes. The Katz centrality and PageRank are based on walks (of any length) arriving to (or departing) the node. To be able to use centrality metrics in the ATM network that is dynamic by nature, the temporal and multiplex structure of such network must be considered (i.e. whether the passengers can use the links, based on the flight schedules). The Domino project proposed a set of centrality metrics that take these matters into account.

This kind of metric can readily be extended to the intermodal context. First, the land transportation side can be included in the network, defining new nodes (e.g. stations) and new links (e.g. trains). The multiplex nature of the network can be used to differentiate paths going through air or through land. Schedules, or frequencies when schedules are not available, can be used to weight the temporal paths on the network and compute centrality indicators that give an accurate picture of the connectivity of a node. This will be developed further in WP4, and reported initially in D4.2.

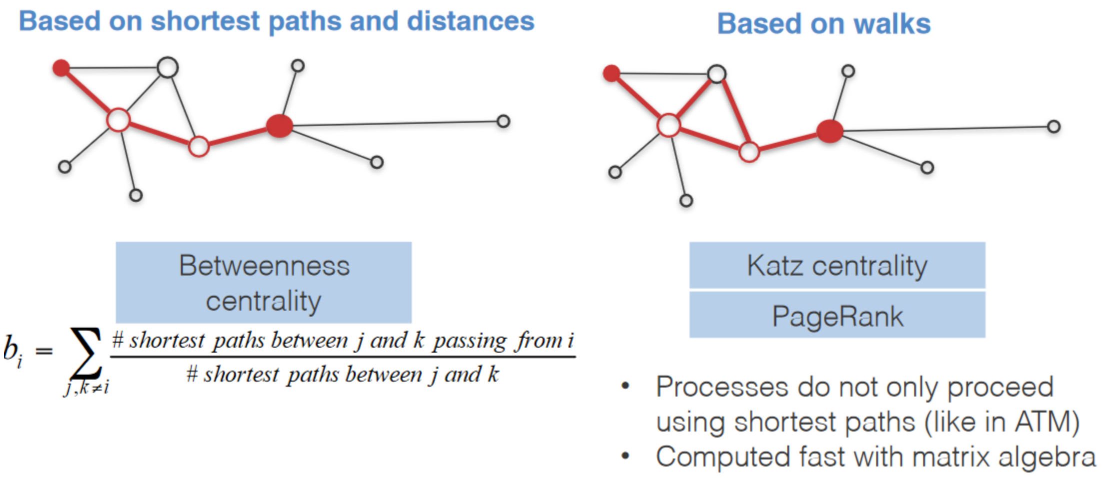


Figure 9: Measuring centrality

Another network metric type is causality. Causality describes connections between two processes. For example, it connects process one, the cause, with another process or state, in other words the effect, where the cause is partially responsible for the effect, and the effect is partially dependent on the cause. In the ATM network, the cause and effect could be the state of delay of two different airports, where the state of delay quantifies the amount of delays at that particular airport. "A causality relationship between these two processes could arise, for instance, when a flight departing with a delay from the first airport arrives at destination with a primary delay which induce delays in other flights because of rotational effects. Thus, the state of delay at the destination airport partially depends on that of the origin airport. This represents a process of delay propagation between two airports mediated by a one-leg effect, i.e., one flight connecting the two airports. However, a causality relationship might be mediated by more than one leg." [44]. Figure 10 illustrates such causality.

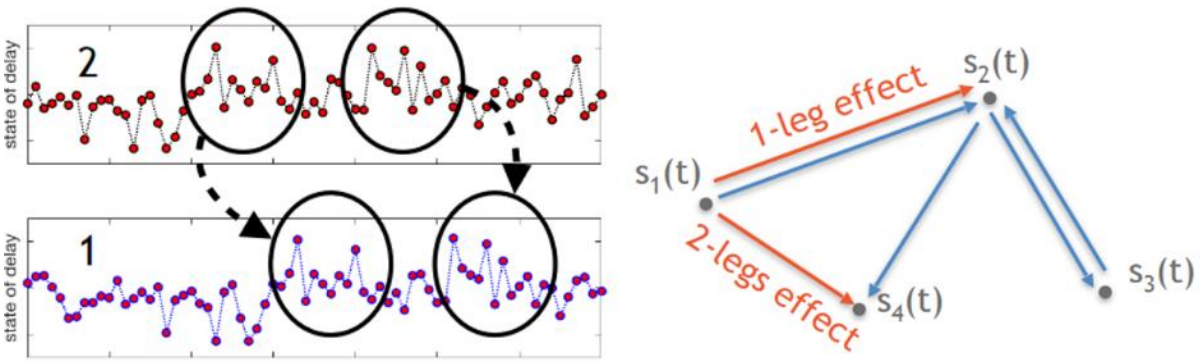


Figure 10: Measuring causality

Causality can also be extended to the intermodal context. The state of a node (or a link) on the landside can have an effect on the airside, and this can be captured by the causality metrics. For instance, a station (node on the landside) could have an effect on an airport (node on the airside) in terms of delays. Different metrics can also be used in different nodes, for instance delays at a station may cause missed flights at an airport. This will also be developed further in WP4, and reported initially in D4.2.

Indeed, both centrality and causality metrics will thus play an important part in understanding the relationships between the nominal and disrupted scenarios, e.g. the performance of one node (a HSR station) in recovering from disruption at another (an airport).

4.2.2.6 Summary Performance Indicators

The indicators in this section, referring to the performance of the transport system, measure the achievement towards particular mobility or system goals such as travel time savings or reduction of delay. For air transport and air traffic management, many high-level goals are defined by the SES and translated into key performance areas and indicators in the SESAR Performance Scheme, including the KPAs capacity, cost efficiency, operational efficiency, environment, safety, and security, plus KPAs based on the ICAO definitions, and within each of these areas related key performance indicators.

A similar approach is applied in the rail sector with key performance areas including network utilisation, environmental impact, punctuality and reliability, and related KPIs. In addition to this, this section analyses performance indicators from different EU projects: specific mobility indicators (CAMERA and DATASET2050 projects), performance scenario modelling indicators (Vista) as well as centrality indicators (Domino).

For Modus, only a subset of key performance areas is relevant, considering the overall objectives of focusing on passenger-centred mobility and assessing the performance of the transport system, with a focus on rail and air. Table 19 outlines representative indicators for each of these KPAs, indicating the type of performance which is being measured. The indicators for further analysis in WP4 will also be carefully selected to represent and be applicable to both air and rail transport.

Table 19: Overview Performance Indicators

KPA	Indicator	Units
Access and equity	4 hour door to door reach	The distance (km) that can be attained within 4 hours from door to door, or the number of destinations which can be reached
Efficiency	Journey duration	Number of connections and dwell times (mins) during stops
	Optimal journey time deviation	Actual time of travel/ best possible journey time/ (percentage)
Flexibility	Diversity of destinations	Number and type of destinations which can be reached from an origin (connectivity)
	Resilience	Average time necessary for a replacement service to be available to replace a cancelled one (mins)
Interoperability	Seamlessness	Journey transition time (between modes and stops) (mins) Number of legs/ modes required to complete a journey
Predictability	Punctuality	Share of passengers arriving late (within pre-defined time slot) (percentage)

KPA	Indicator	Units
Sustainability / Environment	Energy consumption	Energy (kilowatts) needed per passenger km
	CO_2-emissions	CO_2 emissions (kg) per passenger km
Capacity	Delay	Difference between scheduled and actual time (mins)
	Modal share	Share of transport modes in all passenger journey/ on a specific journey (percentage)
Network	Centrality	Betweenness centrality (dimensionless)

4.2.3 Intermodal indicators

4.2.3.1 Indicators focusing on the intermodal context

We saw in the two previous sections how certain indicator types may play a role in understanding and assessing intermodal performance. In this section we discuss some more specific considerations for intermodal indicators, especially those that pertain specifically to the intermodal context rather than that of either rail or air alone, and thus is taken to include metrics such as airport dwell times, since we consider the overall D2D context. Also importantly contributing to this state of the art, TRANSIT is a SESAR ER4 project focusing on the development of a methodological framework and a set of software tools that support the design, implementation and evaluation of new intermodal concepts and solutions based on better integration of the European air transport system with ground transport modes. For this purpose, a set of multimodal performance indicators has been developed, which are also valuable in regard to the Modus objectives [45]. Table 20 shows various metrics proposed by TRANSIT (paraphrased and/or otherwise edited), their alignment with the MFAs of Table 17 and the application of corresponding metrics in Modus. The TRANSIT KPIs are all potentially measurable in Mercury, giving an excellent basis for various KPI definitions and cross-project coordination, and are being actively considered for inclusion in the model being developed in WP4 (to be reported further in Deliverable 4.2 (Mobility models description)), although it is important to be mindful of the caveat stressed in Section 4.1.2 of avoiding a proliferation of indicator-scenario reporting. We return to this in Section 4.3. Many of these indicators will be used in discriminant analyses, e.g. examining reach by number of connections, and could of course be applied singularly to a given mode (air or rail) for comparative purposes. An exception is the indicators shown in italics, which will not be measured in Modus (since they are variously out of scope or not capturable in the scenario simulations).

Table 20: Consolidated intermodal metrics

KPAs	Mobility Focus Area (MFA)	KPIs TRANSIT	KPIs Modus
Access and equity	Reach	• % of trips that can be completed within 4-hours in Europe.	Other temporal *and spatial* (distance-based) contours can be calculated (not just 4 hours). Modus can achieve this at NUTS3 resolution. Equity may be further assessed in terms of geographical equity, e.g. whether peripheral states in Europe (e.g. Finland)

KPAs	Mobility Focus Area (MFA)	KPIs TRANSIT	KPIs Modus
			achieve 4HD2D targets, as well as central states (e.g. Switzerland), and for regional / more rural areas cf. large cities. This is particularly linked with Scenario 4. This could also include the economic/cultural diversity of destinations (by NUTS regions) reachable in given temporal constraints and across the scenarios. Access and equity should in principle address PRM (persons with reduced mobility) certifications, although this is out of scope for Modus.
Efficiency	Duration; Speed	• Fastest average travel time (Time to complete the trip with the fastest option, taking into account the different alternatives, passenger legs and needs (luggage, no luggage, etc.)). • Total Travel Time (Time to complete the whole D2D trip.) • Ratio In-vehicle Time / Total Travel Time (Ratio between the sum of in-vehicle times and the total travel time.) • Ratio Waiting Time / Total Travel Time (Ratio between the sum of waiting times and the total travel time.) • Ratio Transfer Time / Total Travel Time (Ratio between the sum of transfer times and the total travel time.) • Ratio Access time / Total Travel Time (Ratio between the [main mode] access and egress and the total travel time.) • Pax time efficiency - best possible journey time/actual time travel (Ratio between the best possible journey time and the average travel time by users.) • *Ratio TTprivate / TTtp (Ratio between the time to*	In this context, Modus plans to also include explicit metrics on: • the number of connections; • 'unnecessary' time spent waiting for a connection (i.e. time in addition to moving from one mode to another: the schedule offset); • airport dwell times (an important inefficiency in the 4HD2D target).

KPAs	Mobility Focus Area (MFA)	KPIs TRANSIT	KPIs Modus
		complete the trip by (private) car and public transport)	
Flexibility	Diversity of destinations	• Number of options to make a trip (Number of available options to make a trip.)	The number of options to make a trip should be constrained by a limitation on the (GCD) route extension, e.g. reflecting passenger unwillingness to travel a much greater distance for mode A cf. mode B (even if cheaper). This could be set at a 50% penalty on the GCD, for example. Flexibility should also include the ability to change plans, e.g. to change the time of the main mode within mode (e.g. catch a later flight), or across modes (e.g. change from a flight to a train). These will of course vary as a function of the fare paid (i.e. most expensive tickets are more flexible), and the conditions: nominal, or disrupted (the latter being driven by the regulatory context, e.g. rebooking/rerouting under Reg. 261). This is further subject to the available capacity. Having finalised the detailed rules under the corresponding scenarios for flexibility, a corresponding metric will be developed for this capture in Modus, most likely reflecting % transfers to alternative modes during disruption. Information sharing and ticket numbers (e.g. under integrated ticketing) will be implicit assumptions in the model, and thus not captured through metrics.
	Resilience	• *The time interval between the beginning of the system disturbance and the first response activity.* • *Time required to restore normal operation (The time interval between the beginning of the event and the system recovery, i.e., the moment when the system recovers nominal capacity.)*	Instead of deploying 'first response activity' and 'normal operation' definitions, Modus will use other metrics under nominal and disrupted scenarios (see Section 2.3) to measure the system resilience, notably the ratio of '% of cancelled trips' (see under 'predictability' below). See also the dedicated Section 4.2.3.3, below.
Interoperability	Seamlessness	• Number of legs required to complete a journey. • Number of modes used to complete a journey.	Legs and main modes can be captured in metrics.

KPAs	Mobility Focus Area (MFA)	KPIs TRANSIT	KPIs Modus
		• *Number of tickets used to complete a journey.*	As flagged above (under 'Flexibility'), ticketing cannot be realistically captured.
Predictability	Variability; Punctuality; Reliability	• Travel time variability (Measures the overall travel time variance, analysing the dispersion of the travel time.) • lambda skew (Measures the travel time skewness comparing the travel time difference between percentile 90% (T90) and 50% (T50) to the difference between percentile 50% (T50) and 10% (T10). lambda skew = (T90-T50)/(T50-T10)) • Temporal Variability Index (TVI) (Measures the travel time variability between the highest demand hour and the lowest demand hour.) • On-time performance (OTP) (Measures the ratio between the on-time trips and all the trips. Whether a trip is on-time or not depends on an acceptable delay which is a share of the activity utility.) • % of cancelled trips (Measures the % of trips that can't be completed given a service cancellation.) • *Potential Wait Time (Time difference between waiting time percentile 95% (W95) and the average waiting time* • *Buffer Time Measures the difference of the travel time percentile 95% (T95) and the average travel time*	These are all capturable through the distributions modelled in Mercury (the simulations use distributions as inputs, and produce them as outputs). Regarding '% of cancelled trips' this would be extended to include unsuccessful trips (e.g. the trip may be started, but curtailed/abandoned due to disruption). Regarding the last two items, further consultation with the TRANSIT team would be required regarding certain aspects of these definitions. For reliability, metrics such as: • likelihood of missing a flight (probability that delays in the door-to-kerb and kerb-to-gate segments of the journey will result in the passenger's not being able to board their plane); • average minimum buffer time required at the door of origin to ensure a 95% chance of arriving at destination within 15 minutes of the planned arrival time; from DATASET2050 may also be considered.
Sustainability	Environmental impact	• CO_2 per passenger-km • CO_2 per passenger. • CO_2 per km.	Modus can compute these at the NUTS3 (distance) and passenger levels.

KPAs	Mobility Focus Area (MFA)	KPIs TRANSIT	KPIs Modus
Capacity	Capacity	• Maximum number of passengers for an OD considering all the alternatives • Maximum number of passengers on an alternative.	Capacities are model inputs in Modus and will be used in derived metrics, such as load factors. Other model inputs will be reflected in indicators and used in calibration and validation (see also Section 4.3)

4.2.3.2 Intermodal trade-offs

In the addition to the individual metrics described above, several changes (*Δ*) in rail (*R*) performance cf. air (*A*) will be assessed as intermodal ratios, to produce trade-off metrics of the form shown in Equation 3.

$$\text{Trade-off} = \frac{\Delta'_R w_R}{\Delta'_A w_A}$$

Equation 3: General trade-off formulation

The weights (*w*) by mode (e.g. primarily by passenger numbers carried (demand) and capacities offered (supply) will be applied. Using the telescoping functionality of Equation 1, this is anticipated to be a highly powerful and user-friendly manner to reduce several data dimensions across the scenarios and present them as convenient oversight metrics for assessing the impacts of these scenarios.

4.2.3.3 Assessing the cost of resilience

Returning to the scenarios introduced in Section 2.3, and the illustration of Figure 1, we may figuratively extend this illustration through Figure 11, to show how the cost of resilience (R_C) may be represented as the relationship between performance in the nominal and disrupted scenarios. Cook et al. (2016) [46] presents a methodology for measuring the cost of resilience, having summarised the three main types of such resilience (Table 21).

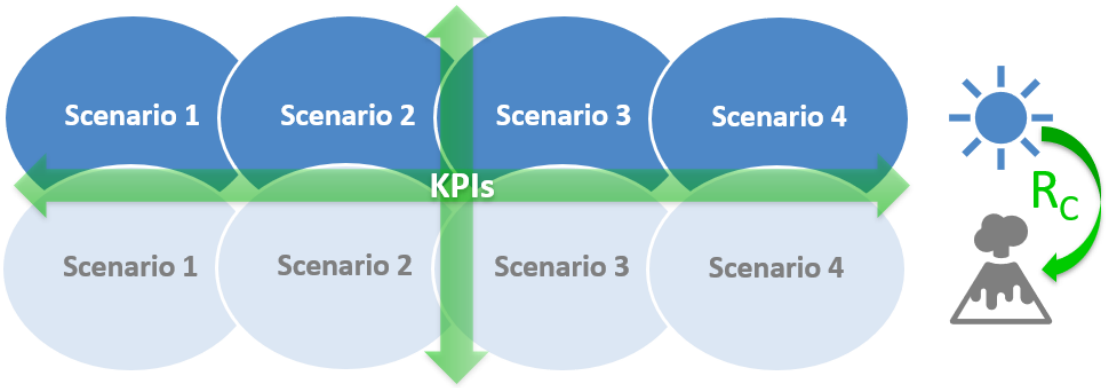


Figure 11: Modus scenarios and measuring resilience (own depiction)

Table 21: Three capacities of resilience [46]

Capacity	Key feature	Key association(s)	ATM focus
Absorptive	network can withstand disruption	robustness; little or no change may be apparent	strategic
Adaptive	flows through the network can be reaccommodated	change is apparent; often incorporates learning	strategic and/or tactical
Restorative	recovery enabled within time and cost constraints	may focus on dynamics/ targets; amenable to analytical treatment	tactical

Equation 4 is a measure of restorative resilience. (If time allows, Modus may propose appropriate future work for investigating both absorptive and adaptive resilience costs, and other strategic CBA metrics such as through the inclusion of life cycle costs). Formulating a novel method for quantifying the cost of (restorative) resilience, Equation 4 may be used in Modus to assess this in a multimodal context, if sufficiently robust investment running costs may be estimated (for various 'mechanisms' that may be modelled for delay recovery or disruption management - such as the fuel burn for re-routing an aircraft, or the re-booking cost of transferring passengers from rail to HSR). This will be determined downstream in Modus, i.e. in Deliverable 4.2 (Mobility models description). The disruptions costs themselves are already mostly known, and were shown in Table 18.

$$R_C \leq 1$$

$$R_C = \frac{\sum_u^d C_u(t) \; - \; \sum_u^d \sum_u^m C_u(t) \; - \; C_m(t)}{\sum_u^d C_u(t)}$$

- cost of disruption with mechanism
- investment running cost
- disruption cost
- flights; passengers; mode

Equation 4: Quantifying the cost of resilience

Essentially, R_C measures the effect of an investment mechanism w.r.t. the cost of disruption without the investment mechanism. $R_C = 1$ corresponds to a complete recovery of the cost; RC = 0 corresponds to no cost recovery (a completely failed mechanism or decision). It is noteworthy in the paper (*ibid.*) that even effective mechanisms may produce small values (e.g. $R_C = 0.06$ for a locally effective passenger-wait mechanism) at the network level, which has driven the development of the telescoping function (Equation 1) in Modus. Furthermore, detection of more localised effects (temporally and spatially), will be explored in Modus through the use cases and a node-centric approach, where applicable (see also Section 4.2.2.5 on the centrality metrics, for example).

4.2.3.4 Summary Intermodal Indicators

With Modus' specific focus on multimodal transport and specifically on the interaction between air and rail, a focus has been placed on the identification of specific intermodal indicators. The KPIs from the SESAR ER4 project TRANSIT are all potentially measurable in Mercury, giving an excellent basis for various KPI definitions and cross-project coordination, and are being actively considered for inclusion in the model being developed in WP4.

Furthermore, as explained in detail above, the trade-offs between various indicators will be considered in the analysis. The indicators in Table 22 provide a high-level overview of representative intermodal indicators, similarities and overlap with indicators identified in the previous sections exists. These may be filtered and variously analysed and compared as a function of the number and type of modes, and as functions of each other.

Table 22: Overview Intermodal Indicators

KPA	Indicator	Units
Access and equity	Reach	The distance (km) that can be attained within 4 hours from door to door, or the number of destinations which can be reached
Efficiency	Journey duration	Number of connections and dwell times (mins) during stops
	Optimal journey time deviation	Actual time of travel/ best possible journey time/ (percentage)
Flexibility	Diversity of destinations	Number and type of destinations which can be reached from an origin (connectivity)
	Resilience	Average time necessary for a replacement service to be available to replace a cancelled one (mins)
Interoperability	Seamlessness	Journey transition time (between modes and stops) (mins) Number of legs/ modes required to complete a journey
Predictability	Variability	Share of passengers arriving late (within pre-defined time slot) (percentage)
Sustainability / Environment	Environmental impact	CO_2 emissions (kg) per passenger km
Capacity	Passengers	(Maximum) number of passengers on a route/ OD pair

Section 4.2 reviewed and analysed connectivity, performance and intermodal indicators, with a particular focus on indicators relevant for investigating the Modus objectives. The following section elaborates the priorities for Modus.

4.3 Indicator priorities for Modus – recap

In Section 4.1.1 we flagged several key issues, to which careful attention must be paid in Modus:

1. avoiding a proliferation of KPIs in the reporting;

2. identifying headline KPIs and reserving other metrics for subsequent analysis (as we drill down into the data for interpretive insights);

3. adopting some degree of complementarity with other ER work (notably the TRANSIT project);

4. avoiding inadvertently 'trivial' relationships with model assumptions, such comparisons being useful for calibration and validation.

KPA	Air	Rail	Intermodal	
			Cooperative	Trade-off
Capacity	μ Arrival delay (airport) [per pax]	μ Arrival delay (station) [per pax]	D2D	
Predictability	1/σ [or tail] Arrival delay (airport) [per pax]	1/σ [or tail] Arrival delay (station) [per pax]	D2D	
Environment	Σ CO_2 [network]	Σ CO_2 [network]	D2D	

Figure 12: Overview of headline indicators (own depiction)

Figure 12 exemplifies the type of indicator prioritisation that will take place in Modus and be further refined during the course of the project. These examples may be adapted in light of the final results, in that we will select a limited number of leading indicators that capture the main performance features under the scenarios, across the modes. The essence is once again to avoid unnecessary proliferation and presenting the reader with endless tabulations of indicators in highly voluminous reporting, and rather highlighting the key results captured and reported in the most efficient manner. This does not preclude the appropriate use or prioritisation of other indicators, which remain accessible in the model.

Across Section 4 we have presented a wealth of indicators, many of which are already incorporated into the Mercury model, which will underpin the scenario simulations analysis in Modus. We have noted that many of these indicators (in Mercury) currently correspond to the air transport and ATM contexts (although they also include airport access and egress times), such that in the development of the Mercury model these indicators (including some estimates of the corresponding delay compensation costs), need to be extended to the rail context.

A number of indicators in Section 4.2.3, where we focused on the intermodal context, can be seen as 'cooperative' in nature, i.e. measuring specific outcomes (e.g. D2D reach) that will be improved through air-rail cooperation, and be driven through assumptions in the scenarios (e.g. particularly in Scenario 2). In contrast, we may often wish to measure trade-off ratios using a standard 'plug and play' approach for other specific air and rail metrics, as achieved through the common functionality of Equation 2. Other headline choices may well be added, but those used systematically to report on the scenario outcomes should be added with some caution. (Prime candidates are for flexibility and equity ('reach')). Assuming we use one KPI for each cell in the figure, and ultimately extend this to add one each for flexibility and equity, this already produces 20 metrics per scenario, i.e. **160 to report across all scenarios and their disrupted analogues!** This underlines the importance of observing (1) above, and using the wealth of indicators presented with great prudence in reporting and supporting (2). Many of the non-headline indicators will of course be used in discriminant analyses, e.g. examining 'reach' by number of connections, and may be applied singularly to a given mode (air or rail) for comparative purposes. Detection of more localised effects (temporally and spatially), will be explored in Modus through the use cases and a node-centric approach, where applicable.

This count of 160 is indeed even before any measures of centrality or causality are introduced into the picture, and we should reserve space for these in terms of their value in understanding the relationships between the nominal and disrupted scenarios in the intermodal context, e.g. the performance of one node (a HSR station) in recovering from disruption at another (an airport).

We will clearly expect to see certain patterns of relationships and dependencies between these headline indicators, such as delay typically decreasing as predictability increases and net environmental impact deteriorates, although there will doubtless be greater subtleties in the high-level trade-offs than this. To the best extent possible, it is desirable to monetise indicators to facilitate comparisons (e.g. how much is a 32% improvement of delay worth in terms of increased CO_2 output?).

Regarding (3), we have already explained in Section 4.2.3 that we have the capability to produce significant complementarity with the TRANSIT metrics, whereas future coordination efforts might do well to focus on the selected indicator priorities, rather than the depth in the detail of the additional indicators that can be mined (2). For reporting on (4), most of the calibration and validation in WP4 should be reported in deliverable annexes to avoid cluttering the output. Raw capacity values have been cited as an example.

Finally, regarding the indicator reporting, we also note that statistical significance testing will be applied to all appropriate comparisons (this may often be a bootstrapping approach) and non-significant values will typically be removed or lightened in font to render tables etc. much easier to inspect visually in the analytical outputs.

5 Summary and next steps

5.1 Synthesis

The main objectives of this Deliverable D3.2 have been to present supply and demand scenarios (considered time horizon: 2040), seven passenger archetypes as well as connectivity, performance and intermodal indicators.

The Modus scenarios are derived from European high-level mobility objectives, existing scenario studies as well as the work conducted within the Modus project. Each scenario focuses on particular aspects which are envisaged for the future, and which have the potential to significantly change the transport system as we see it today. Four scenarios are developed and presented with the related characteristics: (1) Pre-pandemic recovery (baseline), (2) European short-haul shift, (3) Growth with strong technological support, and (4) 'Decentralised, remote and digital'.

Taking a traveller-centric perspective, this deliverable also presents seven future European traveller archetypes: (1) Business Flyer, (2) Digital Gen Z Flyer, (3) Environment-minded Flyer, (4) Premium Flyer, (5) Cultural Jetsetter, (6) Holidayer, and the (7) Golden Senior Flyer. Each archetype exhibits distinct characteristics which can be translated into according parameters for the different components in the landside model. This approach is described in more detail in the Modus Deliverable D4.1 and implemented in the further course of WP4.

Further, the deliverable discusses connectivity, performance and intermodal indicators, offering reviews of the states of the art for each of these, and setting the Modus context. These indicator categories are not mutually exclusive, but the section divisions present a practical approach to focusing on these specific types of measurement. The differences between air and rail metrics, and the associated regulatory contexts, are also discussed, resulting in the prioritisation of the key performance areas *Capacity*, *Predictability* and *Environment*, and respective headline indicators which are being further identified and evaluated throughout the next steps of the Modus project (see below).

5.2 Interaction with other Modus WPs

The results of this deliverable are applied within further work packages and contribute to investigate and address the overall objectives of the Modus project, as detailed in Table 23.

Table 23: Interaction with other Modus work packages

Deliverable D3.2	D4.1 'Interface to modal choice model: methodology'	D4.2 'Mobility models description'	D5.2 'Report on overall final project results'
Modus scenarios (Section 2.3)	-	The Mercury and R-NEST models will be run on these scenarios (and on the input data prepared in WP2) in Task 4.4, which will be reported in D4.2.	The raw output from the simulations in WP4 will be statistically analysed to produce quantitative results for the different scenarios modelled.

Deliverable D3.2	D4.1 'Interface to modal choice model: methodology'	D4.2 'Mobility models description'	D5.2 'Report on overall final project results'
Modal choice variables (Section 2.2)	The interaction of the modal choice model, the respective variables, with the models developed in WP4 (Mercury and R-NEST) is described, alignment of required inputs and outputs is provided.	The results of the modal choice are applied to further develop the extensive R-NEST ATM modelling capabilities with a multimodal perspective (airport-to-airport connectivity combining air and rail) (Task 4.3). The high-level flows of the econometric modal choice model are converted into future supply and demand scenarios that can be translated into individual passenger itineraries which will then be fed into passenger mobility model Mercury (Task 4.2), which required this kind of input to be able to run the simulations, and used as an additional input for R-NEST.	-
Passenger archetypes (Section 3)	The theoretical transfer and importance of passenger travel characteristics for the Mercury landside model is described.	The Mercury model will integrate relevant travel characteristics of different passenger archetypes, covering all journeys for which air transport has any contribution in the door-to-door segment.	-
Performance and connectivity indicators (Section 4)	-	Consideration and integration of performance and connectivity indicators in the Mercury and R-NEST models. Indicators (notably including some estimates of the corresponding delay compensation costs) need to be extended to the rail context. The investigated and described KPIs are all potentially measurable in Mercury, giving an excellent basis for various KPI	The raw output from the simulations carried out in WP4 will be quantitatively analysed in this task, considering the new performance and connectivity indicators described in D3.2. A qualitative assessment (Task 5.3) will investigate how well the indicators can be met across the use cases, and which operational and/or technological approaches may provide

Deliverable D3.2	D4.1 'Interface to modal choice model: methodology'	D4.2 'Mobility models description'	D5.2 'Report on overall final project results'
		definitions and cross-project coordination, and are being actively considered for inclusion in the model being developed in WP4, being mindful of the caveat stressed in Section 4.1.2 of avoiding a proliferation of indicator-scenario reporting.	feasible solutions to the bottlenecks identified in the current and future transport system.

6 References

[1] European Commission, "Sustainable and Smart Mobility Strategy: Putting European transport on track for the future," https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789.

[2] NLR, and SEO, "Destination 2050," 2021, https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf, [retrieved 11 March 2021].

[3] European Commission, *The European Green Deal*, 2019.

[4] European Commission, "Strategic Transport Research and Innovation Agenda (STRIA): STRIA priority areas, roadmaps and related links.," https://ec.europa.eu/info/research-and-innovation/research-area/transport/stria_en.

[5] ACARE, "Strategic Research and Innovation Agenda - 2017 update," Advisory Council for Aviation Research and Innovation in Europe, 2017, https://www.acare4europe.org/sites/acare4europe.org/files/document/ACARE-Strategic-Research-Innovation-Volume-1.pdf.

[6] ERRAC, "Strategic Rail Research and Innovation Agenda: A step change in rail research and innovation," https://errac.org/publications/strategic-rail-research-and-innovation-agenda/.

[7] SESAR Joint Undertaking, "Strategic Research and Innovation Agenda: Digital European Sky," https://www.sesarju.eu/sites/default/files/documents/reports/SRIA%20Final.pdf.

[8] Shift2Rail, "Multi-Annual Action Plan," https://shift2rail.org/publications/multi-annual-action-plan/.

[9] European Commission, *Flightpath 2050. Europe's Vision for Aviation*, Publ. Off. of the Europ. Union, Luxembourg, 2011.

[10] EUROCONTROL Aviation Sustainability Unit, "Plane and train: Getting the balance right," https://www.eurocontrol.int/sites/default/files/2021-06/eurocontrol-think-paper-11-plane-train.pdf.

[11] European Environment Agency, "Transport and environment report 2020: Train or plane?," https://www.eea.europa.eu/publications/transport-and-environment-report-2020.

[12] European Commission, "TEN-T Review," 2020, https://ec.europa.eu/transport/themes/infrastructure/ten-t/review_en.

[13] EREA, "EREA Vision Study - The Future of Aviation in 2050," 2021, https://erea.org/erea-vision-studies/.

[14] Leipold, A., Aptsiauri, G., Ayazkhani, A., Bauder, U., Becker, R.-G., Berghof, R., Claßen, A., Dadashi, A., Dahlmann, K., Dzikus, N., Flüthmann, N., Grewe, V., Göhlich, L., Grimme, W., Günther, Yves, Jaksche, R., Jung, M., Knabe, F., Kutne, P., Le Clercq, P., Pabst, H., Poggel, S., Staggat, M., Wicke, K., Wolters, F., Zanger, J., and Zill, T., "DEPA 2050 Development Pathways

for Aviation up to 2050: Final Report," 2021, https://www.dlr.de/fw/desktopdefault.aspx/tabid-2937/4472_read-72217.

[15] Eurocontrol, "European Aviation in 2040: Challenges of Growth," 2018.

[16] CER, "Activity Report 2020," https://www.cer.be/sites/default/files/publication/CER_Activity-Report-2020_0.pdf.

[17] Roland Berger, and UIC, "White Paper: The Post-Covid-19 "NEW Normal"," 2021.

[18] IATA, "Outlook for the global airline industry," https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---april-2021---report/.

[19] Eurocontrol, *New EUROCONTROL Four-Year Forecast finds airtraffic not expected to reach 2019 levels until 2024 at earliest*, 21.05.2021.

[20] Platform of Rail Infrastructure Managers in Europe (PRIME), "2018 PRIME Benchmarking report: KPI & Benchmarking Subgroup PRIME," https://webgate.ec.europa.eu/multisite/primeinfrastructure/content/prime-members-present-third-benchmarking-report_en.

[21] Ruijters, H., "EUROCONTROL Stakeholder Forum strategic webinar on intermodal transport & regional connectivity: SSMS and TEN-T policy," 12 Jul. 2021.

[22] Boeing, "Commercial Market Outlook 2020-2039," https://www.boeing.com/commercial/market/commercial-market-outlook/.

[23] Schmalz, U., Paul, A., and Gissibl, V., "An explorative study of corporate travellers' perception at a German airport," *Journal of Air Transport Management*; Vol. 92, No. 8, 2021, p. 102040. doi: 10.1016/j.jairtraman.2021.102040.

[24] Modus project, "Modal choice analysis and expert assessment," https://modus-project.eu/2021/06/25/modus-d3-1-modal-choice-analysis-and-expert-assessment-report-already-available-for-download/.

[25] Paul, A., Kluge, U., Cook, A., Tanner, G., Gurtner, G., Delgado, L., Cristobal, S., Valput, D., López-Catalá, P., Gomez, I., Hullah, P., and Biscotto, M., "D2.1 - Establishment of Performance Framework (CAMERA project, H2020 GA No. 769606)," [retrieved 9 May 2021].

[26] International Civil Aviation Organisation, "Global Air Traffic Management Operational Concept, first edition, Doc 9854.," 2005.

[27] International Civil Aviation Organisation, "Manual on Global Performance of the Air Navigation System, first edition, Doc 9883," 2009.

[28] DATASET2050 project, "Mobility Assessment: Deliverable D5.1," 2017.

[29] Eurocontrol, "European Aviation Connectivty Dashboard," https://ext-test.eurocontrol.int/connectivity_web/from.

[30] Eurocontrol, "EUROCONTROL/STATFOR slides on EU Air transport Connectivity Indicators 2020 07 (update)," 2020.

[31] European Commission, *Regulation (EC) No 261/2004 of the European Parliament and of the Council of 11 February 2004 establishing common rules on compensation and assistance to passengers in the event of denied boarding and of cancellation or long delay of flights, and repealing Regulation (EEC) No 295/91. 261/2004*, 17.02.2004.

[32] European Commission, "Single European Sky," https://ec.europa.eu/transport/modes/air/ses_en.

[33] European Commission, "Performance review body of the Single European Sky," https://webgate.ec.europa.eu/eusinglesky/node_en.

[34] SESAR JU, "European ATM Master Plan: Edition 2020," 2019, https://www.atmmasterplan.eu/ .

[35] European Commission, *Regulation (EC) No 1371/2007 of the European Parliament and of the Council of 23 October 2007 on rail passengers' rights and obligations*, 2007.

[36] Shift2Rail, "Consolidated Annual Activity Report 2019," June 2020, https://shift2rail.org/wp-content/uploads/2020/06/GB-Decision-05-2020_AAR-2019_Annex_AAR-2019.pdf.

[37] UIC, "Railways Statistics Synopsis: 2021 Edition," https://uic.org/support-activities/statistics.

[38] UIC, "International Railway Statistics," 2016.

[39] UIC, "Environment Strategy Reporting System: The 2020 Report," 2020.

[40] Ride2Rail, "Final Conceptualization of Choice Criteria and Incentives: Deliverable D2.4," 2019.

[41] European Commission, "Aviation Strategy," https://ec.europa.eu/transport/modes/air/news/2015-12-07-commission-presents-aviation-strategy-europe_en.

[42] Vista project, "D5.2 Final assessment report," https://vista-eu.com/.

[43] Domino project, "WP5 Metrics and system analysis," https://domino-eu.com/the-project/.

[44] Domino project, "D5.1 Metrics and analysis approach," https://domino-eu.com/the-project/.

[45] TRANSIT project, "Multimodal Performance Framework: Deliverable D3.1," 2021, https://www.transit-h2020.eu/resources.

[46] Cook, A., Delgado, L., Tanner, G., and Cristóbal, S., "Measuring the cost of resilience," *Journal of Air Transport Management*; Vol. 56, No. 4047, 2016, pp. 38–47. doi: 10.1016/j.jairtraman.2016.02.007.