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SIMBAD

COMBINING SIMULATION MODELS AND BIG DATA ANALYTICS FOR ATM PERFORMANCE ANALYSIS

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Abstract

This deliverable provides the specification of the case studies that will enable to achieve SIMBAD objectives: on one hand, the use of data-driven methods for the estimation of hidden variables and trajectory models within WP3; on the other hand, the multiscale traffic pattern classifier of WP4 and; finally, the application of active learning metamodeling to air traffic simulations in WP5. Besides, these case studies will be the context of WP6 for the demonstration of the performance modelling framework developed by SIMBAD.

Additionally, the criteria for the selection of proper case studies as framework for the development of SIMBAD goals are explained. Within this criteria, five main foundations are considered: (1) Compatibility with SIMBAD developments; (2) Matureness of the performance assessment; (3) Potential gap between the expected and the actual benefits; (4) SIMBAD simulator capabilities and; (5) Data availability. Also, and according to the added value that SIMBAD may imply, a complementary comment is considered: the existence of a mature report of the performance after the deployment.

The document shows a detailed revision of the current air traffic simulation methodology, as well as of the indicators used to evaluate the results, which will be based on the SESAR Performance Framework for consistency. Furthermore, it also highlights the research questions that will be assessed in the different case studies, aimed at capturing the specific added value delivered by the proposed metamodeling methods.

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1 Executive Summary

The aim of the deliverable is to specify the **set of cases studies** that will be used to test the proposed SIMBAD technical developments aimed at providing state of-the-art ATM microsimulation models with the level of reliability, tractability and interpretability required to effectively support **performance evaluation** at ECAC level. A **methodological framework** has been developed as a selection criterion to define and chose the final case studies and scenarios. In other words, the metamodeling and data-driven methodology will be assessed and refined during the demonstration of SIMBAD Performance modelling with the case studies serving as framework for the developments. Thus, the selection of the solutions and their detailed specification is based on the content, approach, and objectives of the different work packages, to ensure that the proposed case studies are suitable to be tackled by the data-driven and metamodeling approach built upon on an active learning[1] strategy.

The deliverable aims to **gather**, **consolidate,** and **analyse information from different sources** to provide a state-of-the-art review in the latest achievements in SESAR Industrial Research and deployment phases. The main sources of information used for this purpose are collected from:

1. SESAR Solutions Catalogue 2019 (third ed.)
2. Performance Assessment and Gap Analysis Report (PAGAR) 2019 - confidential and non-confidential edition
3. Local Single Sky Implementation documents (LSSIP).
4. Performance Assessment Report (PAR) of individual solutions, if available online.
5. European ATM Master Plan 2020.

The **selection criteria** developed for the decision on the SIMBAD case studies to use is based on three fundamental pillars:

- **CRT-001: Compatibility with SIMBAD developments**.
- **CRT-002: Mature performance assessment**.
- **CRT-003: Potential gap between the expected and actual benefits**.

[1] One of the applications of active learning is the development of metamodels: when dealing with complex simulation models for which each simulation run is computationally demanding, a possible solution is to approximate the microsimulation model itself through a metamodel, i.e., a more parsimonious representation of the relationships between the inputs and outputs of the model. In these situations, the role of active learning is to optimally select the points that need to be simulated in order to build a metamodel that acceptably replicates the model itself. Different approaches might be followed to build the metamodel itself, including Gaussian Processes, Dynamic Bayesian Networks, and Influence Diagrams, among others.

An extra condition is also defined for setting a 'ground truth' that would allow to measure how close are the SIMBAD performance modelling framework to the actual benefits of the deployment of the solutions:

- **CON-001: Assessment report after the deployment in terms of performance**. This criterion allows setting the ground truth, especially with regards to the metamodeling development proposed by the project.

Having in mind both the criteria and the extra considerations, two **solutions** are chosen from an initial list that originally contained six mature solutions:

- **Advanced Demand-Capacity Balancing (DCB)** solution proposes to consider the needs of the network as a whole, as well as local factors, in order to avoid overloads in a seamless process, by creating a powerful distributed network management function that takes full advantage from the SESAR Layered Collaborative Planning, Trajectory Management principles and SWIM Technology. Within DCB, there are different areas, some of them already deployed. This latter aspect is the reason why the following specific topics are selected:
    - Dynamic Airspace Configuration (DAC) is part of the wider DCB and is fully integrated in DCB processes for all phases at local, sub-regional and regional levels. Dynamic Airspace Configurations are a "packaging" of all manageable airspace elements e.g., ATC sectors, airspace reservations (ARES), associated restrictions into Airspace Configurations which are designed and dynamically managed to respond flexibly to different performance objectives which vary in time and place.
    - Short-Term ATFCM measures (STAM) consists of a system supported approach to smooth sector workloads by reducing traffic peaks through short-term application of minor ground delays, appropriate flight level capping, timing and modalities of ATC re-sectorisation, exiguous re-routings to a limited number of flights. These measures are capable of reducing the traffic complexity for ATC with minimum curtailing for the airspace users.
- **Free Route (FR)** concept seeks **Airspace Users being able to** plan flight trajectories without reference to a fixed route network or published directs, so they can **optimise their associated flights** in line with their individual operator business needs or military requirements. It is a transversal operational concept that affects many ATM activities at regional, sub-regional and local level.

From the solutions selected, relevant **scenarios** are identified. With regard to that, some feedback from the 1st SIMBAD Stakeholder Workshop has been collected and included in this document, although further details will be provided and considered as inputs for the corresponding work packages of the project. Close related to the identified scenarios, the data required to successfully implement the case studies will be also provided.

Finally, two set of **research questions** (RQs) are designed to address the benefits of the simulation metamodels proposed in SIMBAD - the first set of RQs aims at estimating the overall operational benefit of the metamodeling approach at a system level, whereas the second one encompasses the research questions tailored to address its benefits for each specific solution identified.

2 Introduction

2.1 Purpose of the document

The main objective of this document is to present a detailed description of the case studies and potential research questions that will be addressed within the SIMBAD project.

In particular, this document covers:

- a high-level ATM performance assessment and modelling state-of-the-art,
- the description of the case studies selection approach and selection criteria, and
- the detailed specification of the case studies selected based on an initial list of the SESAR solutions included in the SESAR Solutions Catalogue.

The output of the work reported under this deliverable will be used as the operational basis to guide the development of SIMBAD subsequent work packages.

2.2 Intended Readership

This document is intended to be used by:

- SJU programme manager.
- SIMBAD project members.
- SESAR2020 and international research community addressing automation in Air Traffic Management and Artificial Intelligence / Machine Learning.

2.3 Document Structure

This document is structured into the following sections:

- Section 1 is the Executive Summary and provides an overview of the SIMBAD Case Studies.
- Section 2 is the Introduction that provides the purpose of the document, the intended readership, the document structure and the terminology and acronyms used throughout the document.
- Section 3 presents the current state-of-the-art in terms of ATM performance assessment and modelling, the reference Performance Framework used in SIMBAD, and an overall description of the project approach.
- Section 4 contains the details on the selection criteria used for the selection of SIMBAD case studies, as well as a summary of the initial list of SESAR solutions identified as potential case studies. Research questions at SIMBAD project level are also included in this section.

- Section 5 describes the first case study selected (i.e., Demand and Capacity Balancing), including the description of the solution, the performance assessment results available, the potential case study scenarios and research questions tailored to the case studies to be addressed by the project.
- Section 6 presents the description of the second case study selected (i.e., Free-Route).
- Section 7 contains the relation between the case studies selected and the available data sources.
- Section 8 presents the list of references used along the document.

2.4 Terminology and Acronyms

Term	Definition
AAM	Advanced Airspace Management
AB	Airspace Block
ACC	Air Control Centre
A-CDM	Airport Collaborative Decision Making
ADS-B	Automatic Dependant Surveillance-Broadcast
AMAN	Arrival Manager
ANS	Air Navigation Services
ANSP	Air Navigation Service Provider
APACHE	Assessment of Performance in current ATM operations and of new Concepts of operations for its Holistic Enhancement
API	Application Programming Interface
ARES	Airspace Reservation
ARN	ATS Route Network
ASP	Air Navigation Service Providers (Civil & Military providing services to GAT)
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management

Term	Definition
ATM	Air Traffic Management
ATS	Air Traffic Service
AU	Airspace User
BADA	Base of Aircraft Data
CAP	Capacity
CASA	Computer-Assisted Slot Allocation
CEF	Cost Efficiency
CHMI	Collaboration Human Machine Interface
CTA	Controlled Time of Arrival
CTOT	Calculated Take-Off Time
DAC	Dynamic Airspace Configuration
DCB	Demand-Capacity Balancing
DDR	Demand Data Repository
DMA	Dynamic Mobile Area
DYNAMO	Dynamic Optimiser
E-AMAN	Extended-Arrival Manager
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Weather Forecasts
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ES	Elementary Sector
EUROCONTROL	European Organisation for the Safety of Air Navigation
EvoATM	Evolutionary ATM
FAB	Functional Airspace Blocks
FB	Flexible Boundary
FCM	Flow and Capacity Management
FEFF	Fuel Efficiency

Term	Definition
FIR	Flight Information Region
FMP	Flow Management Position
FR	Free Route
FRA	Free Routing Airspace
G2G	Gate-to-gate
HC	High Complexity
IFR	Instrumental Flight Rules
INTUIT	Interactive Toolset for Understanding Trade-offs in ATM Performance
KEA	Key performance Environment indicator based on Actual trajectory
KPA	Key Performance Area
KPI	Key Performance Indicator
LSSIP	Local Single Sky Implementation
M1	Initial Trajectory
M2	Regulated Trajectory
M3	Actual Trajectory
MC	Medium Complexity
METAR	Meteorological Aerodrome Reports
NM	Network Manager
NOAA	National Oceanic and Atmospheric Administration
NOP	Network Operations Portal
NPV	Net Present Value
PAGAR	Performance Assessment and Gap Analysis Report
PAR	Performance Assessment Report
PI	Performance Indicator
PRB	Performance Review Board
PRD	Predictability

Term	Definition
PUN	Punctuality
R&D	Research and Development
RBT	Reference Business Trajectory
R-NEST	Research network strategic monitoring tool
ROT	Runway Occupancy Time
RQ	Research Question
SAF	Safety
SAB	Shareable Airspace Block
SAM	Shareable Airspace Module
SBB	Sector Building Block
SDM	SESAR Deployment Manager
SES	Single European Sky
SESAR	Single European Sky ATM Research Programme
SIMBAD	Combining Simulation Models and Big Data Analytics for ATM Performance Analysis
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SLoA	Stakeholder Lines of Action
STAM	Short-Term ATFCM Measures
SWIM	System-Wide Information Management
TEFF	Time Efficiency
TMA	Terminal Manoeuvring Area
TOW	Take-off Weight
UDPP	User Driven Prioritisation Process
VHC	Very High Complexity
VSAB	Vertical Sharable Airspace Block
WP	Work Package

3 ATM Performance Assessment and Modelling

3.1 State-of-the-art

In the current SESAR 2020 programme, project PJ.19 “Content Integration, Performance Management and Business Case Development” aims at providing steering guidance by coordinating and integrating the different SESAR Solutions. A dedicated performance assessment and consolidation process is performed to ensure the alignment of the SESAR programme with the expectations and performance ambitions established in the European ATM Master Plan and supported by the SESAR 2020 Concept of Operations [1]. This challenging activity presents, however, some drawbacks susceptible of improvement [2]:

- many validation exercises are heavily focused on local environments, making it difficult to extrapolate results into a broader European context. The aggregation of results at ECAC level is based on assumptions regarding the potential Operating Environments applicability and eligible traffic, thus the expected benefits are handled in a static and deterministic way.
- Reference Scenarios are not always homogeneous or consistent.
- KPAs dependencies, if they are not correctly considered, might originate double counting of benefits.
- there is no method to aggregate the results taking into account concept and benefit dependencies apart from expert judgment, unless a validation exercise that addresses several concepts at the same time is performed.

Considering the limitations previously stated, in the past decade, a number of studies have tried to understand and quantify interdependencies between ATM KPAs/KPIs. Two techniques have been mainly used: Bayesian networks [3] and influence diagrams [4]. These techniques are two types of probabilistic graphical models widely used for building decision support systems. Both of them consist of acyclic directed graphs and probability distributions. The main difference is that Bayesian networks only contain chance nodes, each representing a random variable, while influence diagrams also contain decision nodes, which represent the options available to one or several decision makers, and utility nodes, which represent the decision makers’ preferences. An integrated set of influence diagrams was constructed within the Episode 3 project to show the influences between the SESAR steps and the capacity, efficiency, predictability, environment, flexibility, safety, and cost effectiveness KPAs [5]. However, the combined effects of causal factors on several KPAs are not considered by the study. An ATM performance model based on Bayesian networks was developed by [6]. The main objective of this study is to identify and assess the magnitude of interdependencies between performance indicators. The model focuses on two of the four KPAs included in the SES Performance Scheme, capacity, and cost-efficiency. Among the advantages of the proposed approach, the authors mention the intuitive representation of the cause-effect relationships between variables and the possibility to incorporate past information about a parameter and form a prior distribution for future analysis; the drawback is that this requires the translation of subjective prior beliefs into a mathematically formulated prior, and thus relies heavily on expert judgment.

Another drawback is the need to transform original variables to maintain computational complexity to a manageable level, as Bayesian Networks only deal with discrete values.

Additionally, several SESAR Exploratory Research projects have also addressed ATM performance modelling. APACHE proposed an ATM simulation system used to perform what-if assessments and to provide advanced models and optimisation tools that support the preliminary impact assessment of long-term ATM concepts and the analysis of interdependencies between KPAs and SESAR Solutions [7]. EvoATM focuses on the definition of a framework that allows a better understanding and modelling of how architectural and design choices influence the ATM system and its behaviours, and how the expected ATM performance drives the design choices; the proposed framework is based on the combination of agent-based modelling with evolutionary computing [8]. Vista and Domino also used an agent-based modelling approach to address different performance modelling problems. Vista examined how the effects of market forces, technologies and regulatory factors influence the ATM performance, considering the trade-offs between different periods and stakeholders [9], while Domino focuses on the analysis of the impact of deploying solutions in different manners (e.g., harmonised vs. local/independent deployment), from both a flight and passenger perspective looking at network effects [10]. Finally, INTUIT developed a set of machine learning and visual analytics approaches for the analysis of ATM performance and the exploration of trade-offs between different KPAs [11].

3.2 Reference Performance Framework

SIMBAD will consider, as the reference Performance Framework, the set of Key Performance Areas (KPAs), Key Performance Indicators (KPIs) and Performance Indicators (PIs) applied within the development of the technological and operational pillars of the European Commission's Single European Sky Air Traffic Management Research programme (SESAR) [12].

The following table summarises the reference KPAs and KPIs.

KPA	Focus Area	KPI	KPI Definition
Safety	ATM system safety outcome	SAF1	Total number of estimated accidents with ATM Contribution per year.
Operational Efficiency	Environment-Fuel Efficiency	FEFF1	Actual average fuel burn per flight.
	On-time Performance	PUN1	Average departure delay per flight
	Flight Times	TEFF1	Gate-to-gate flight time
	Predictability	PRD1	Average of Difference in actual & Flight Plan or RBT durations
Capacity	Airspace Capacity	CAP1	TMA throughput, in challenging airspace[2], per unit time.

[2] Airspace where the current operating concept and technology is close to the limit of throughput that can be sustainably handled (typically VHC, HC and MC under period of high traffic demand).

KPA	Focus Area	KPI	KPI Definition
		CAP2	En-route throughput, in challenging airspace[3], per unit time.
	Airport Capacity	CAP3	Peak Runway Throughput (Mixed mode).
Cost-Efficiency	G2G ANS Cost Efficiency	CEF2	Flights per ATCo-Hour on duty.
		CEF3	Technology Cost per flight.

Table 1. Reference Performance Framework

3.3 SIMBAD concept and approach

In a system like ATM, with few opportunities for large-scale experimentation, modelling and simulation is often the only way to evaluate the performance impact of new concept/solutions at network-wide level.

The ATM system is composed of a large number of heterogeneous components that interact with each other, giving rise to emergent behaviours and properties that cannot be understood by analysing the actions of its components in isolation [13]. The propagation of delay, the safety impacts produced by failures of interacting elements and the performance resulting from collaborative network management are some relevant examples. Reductionist modelling approaches are ill-suited to deal with these emergent phenomena, which call for modelling paradigms that explicitly incorporate the actions and interactions of the ATM components with a view to assessing their effects on the system as a whole. When assessing the performance of a certain ATM concept/solution at a network-wide level, this translates into the need for complex simulation models involving a high number of variables and parameters and a significant computational effort.

Despite being the only reliable way to analyse certain ATM performance problems, the complexity of large-scale, bottom-up microsimulation models are often a barrier for their effective use to support decision-making. In particular, this kind of simulation tools have to deal with the following problems:

- Among the large number of parameters required to construct the simulation model, some can be easily extracted from publicly available databases. On the contrary, other parameters are more difficult to obtain, especially if they provide information considered as business-sensitive by ATM stakeholders. Particularly relevant, especially for those models looking at flight efficiency indicators, are certain parameters that are critical for trajectory modelling and prediction, such as AUs' cost functions and aircraft TOW and thrust setting.
- For many applications, a realistic representation of traffic demand patterns is an essential condition for a comprehensive evaluation of new concepts, which may deliver very different performance gains depending on the level of traffic density and complexity. However, since the execution of each simulation can sometimes take minutes or even hours, many projects end up exploring a reduced number of traffic scenarios that are usually selected based on

[3] Idem as above.

expert judgement and/or simple rule-of-thumb criteria (e.g., simulate the day with the highest number of scheduled flights), without any evidence that they are representative of the variety of traffic patterns that will be encountered when the concept under study is implemented in real-world operations.
- More generally, computational cost is a barrier for the comprehensive exploration of the model input-output space. Simulations are necessarily restricted to a limited number of scenarios, often insufficient to obtain conclusive results. The problem becomes even more evident when the goal is to find the combination of input variables and parameters that optimise a certain output, as the size of the search space grows exponentially with the size of the problem's input (e.g., what is the optimal sequence in which different SESAR solutions should be implemented in different parts of the network to maximise the benefit-cost ratio?).
- Finally, the complexity of the model also comes at the cost of less interpretability, which is however of critical importance for decision-makers to understand, trust and communicate the conclusions of the simulation exercises. What makes these models accurate is what makes their predictions difficult to understand: they are very complex. So, the question arises of how to improve interpretability while retaining reliability and accuracy.

These problems are not exclusive of ATM but, appear also in other areas where large-scale microsimulation models are used to inform decision-making, such as transport planning and traffic engineering. In the last decade, with the rising interest in artificial intelligence, transport and traffic modelers have begun to apply a variety of machine learning techniques for hidden parameter estimation, traffic pattern classification and simulation metamodeling that are proving successful in improving the capabilities of microsimulation models [14][15][16]. However, the exploration of these techniques in the field of ATM is only very recent. The starting point for the research proposed by SIMBAD is the belief that machine learning can also enable substantial improvements in ATM simulation.

Based on the above premises and assumptions, SIMBAD proposes to investigate how machine learning can contribute to bringing state-of-the-art ATM microscopic modelling approaches to the point where they can be effectively used for performance evaluation at ECAC level. The project will deliver the following outcomes, which address the objectives presented in section 1.1:

- A set of machine learning techniques for the estimation of hidden variables from historical air traffic data that allow a more accurate modelling of aircraft trajectories.
- A set of classification and pattern recognition algorithms that support the task of selecting a sufficiently representative set of traffic demand patterns for a given simulation experiment.
- A methodology for the construction of performance metamodels able to provide a computationally efficient approximation of the input-output function defined by complex microsimulation models.
- A number of case studies enabling the evaluation of the SIMBAD methods and tools and the assessment of their applicability to different ATM decision-making problems.

The overall concept proposed by SIMBAD is summarised in Figure 1.

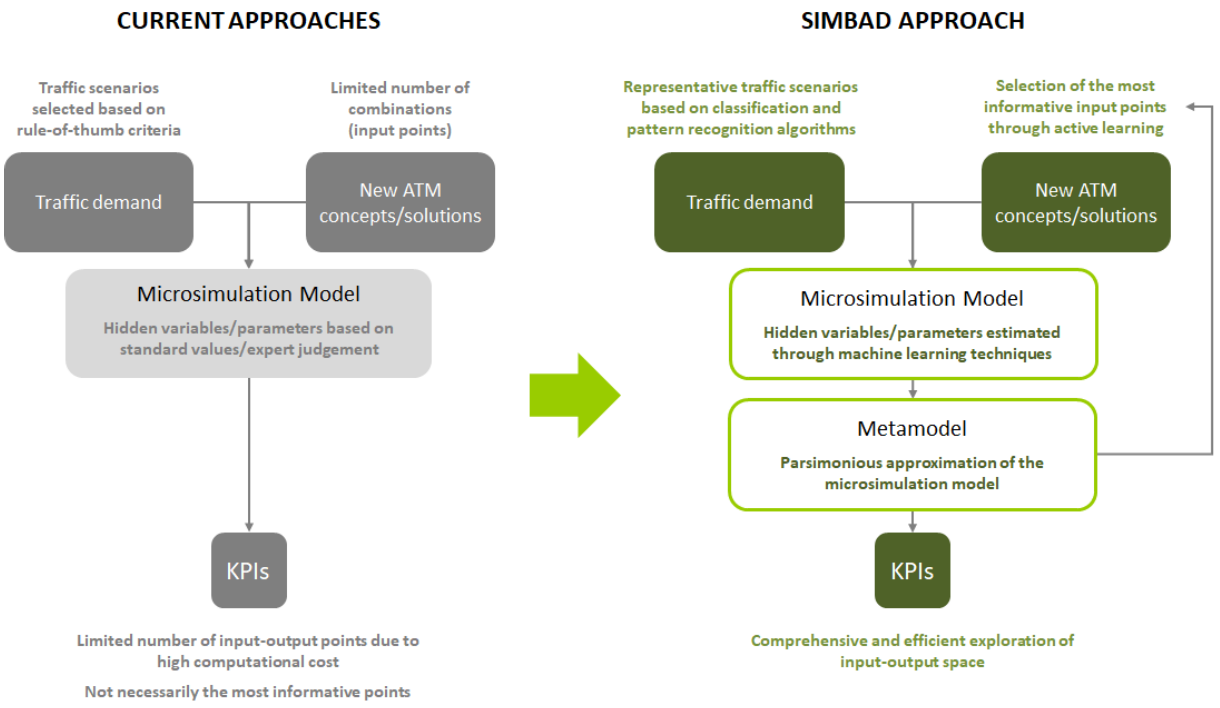


Figure 1. SIMBAD project approach

4 SIMBAD Case Studies selection and Research Questions

This section defines the selection criteria applied by the SIMBAD project for the selection of the most relevant case studies that are to be considered, as well as the initial SESAR solutions considered and the fulfilment of the established criteria.

A high-level identification of the potential research questions at SIMBAD project level is also included in this section.

4.1 SIMBAD case studies selection criteria

Overall, three different criteria (CRT) have been considered that cover both the level of maturity of the potential case study and its suitability bearing in mind the project objectives. On top of that, aligned with SIMBAD purposes, an extra condition (CON), which is not blocking, is considered.

- **CRT-001: Compatibility with SIMBAD developments.** The case studies selected shall serve as a framework for the development and assessment of the work carried out within the SIMBAD project according to the established objectives. Compatibility with SIMBAD developments is assessed considering how the proposed solutions fit in the objectives of the different work packages. Therefore, having in mind SIMBAD goals, the chosen solutions should have a close relationship with trajectories and traffic patterns.

- **CRT-002: Mature performance assessment.** The case studies selected shall have available a mature performance assessment based on the reference Performance Framework, and if possible, the operational and technological solutions covered by the case studies should be already deployed within the ECAC area.

- **CRT-003: Potential gap between the expected and actual benefits.** Since the added value of SIMBAD is focused on the methodology for assessing performances, for the case studies selected there has to exist a gap between the expected benefits and the actual benefits.

- **CON-001: Assessment report after the deployment in terms of performance**. This criterion allows setting the ground truth, especially with regards to the metamodeling development proposed by the project.

The latter condition, which was in the first steps the fourth criterion, is not needed since SIMBAD aims at developing microsimulation models with the level of reliability, tractability and interpretability required to effectively support performance evaluation at ECAC level. Nevertheless, having the actual results of the deployment of either a technology or a concept operation would mean an added value to the project, because of the ability of analysing the results obtained by SIMBAD micromodels with the actual ones.

Beyond that, after the analysis of LSSIP reports, which contains the status of the ATM Master Plan deployment for each of the ECAC States, the difficulty of having the isolated effect of the implementation of the different solution was proven. Therefore, the actual benefits of the implementation of a stand-alone solution is not monitored since it is difficult for the different stakeholders to unbundle the impact of the implementation from the global figures.

Due to the reasons above, the fact of having a performance assessment report after the implementation was discarded but, it was kept as an extra consideration for adding value to the existing objectives.

Finally, simulator capabilities and data availability are not considered as criteria themselves but, they might mean a restriction too. According to that, the chosen solutions should fit in both the capabilities of those simulators planned to be used in SIMBAD and the data framework described in section 7.Case Studies and Data Sources.

4.2 Initial list of candidates SESAR Solutions

This section presents a brief description of the candidate SESAR Solutions identified at an early stage of the project as potential solutions to be analysed in SIMBAD Case Studies. These solutions are then mapped to the case studies selection criteria defined in section 4.1.

4.2.1 User Driven Prioritisation Process (UDPP)

The User-Driven Prioritisation Process (UDPP) is intended to give more flexibility to Airspace Users to reschedule their flights in order to keep their business-driven schedule priorities on track when facing capacity constraints and delays.

UDPP allows Airspace Users to request flight prioritisations to readjust their operations in a more cost-efficient manner in the presence of unforeseen demand and capacity imbalances (airport or En-route) that require the application of delays to flights.

The expected benefits are:

- reduced airline delay costs in case of disrupted situations, without jeopardising airport and network performance;
- increased flexibility for airlines;
- improved environmental performance.

From SIMBAD's perspective, the UDPP concept is highly compatible with SIMBAD development and can be used to tackle all three different aspects of the projects including trajectory prediction, traffic pattern classification and metamodeling. However, the major drawback of using this concept emerges from the fact that its implementation requires an extensive "behavioural model" needed to mimic airlines' priorities/preferences when solving the demand/capacity imbalance.

4.2.2 Demand and Capacity Balancing (DCB)

The Advanced Demand and Capacity Balancing solution proposes to consider the needs of the network as a whole, as well as local factors, in order to avoid overloads in a seamless process, by creating a powerful distributed network management function that takes full advantage from the SESAR Layered Collaborative Planning, Trajectory Management principles and SWIM Technology.

The expected benefits are:

- optimised En-route, TMA, and airport capacity;
- enhanced predictability and punctuality;
- improved operational and cost-efficiency;
- reduced fuel consumption and emissions.

4.2.3 Free-Route (FR)

The Free-Route solution proposes that, between a particular origin and destination, flights could follow as direct routes as possible, so users can freely plan a route between defined entry and exit points. This should be enabled by the introduction of higher levels of automation.

The expected benefits are:

- increased airspace capacity;
- improved operational efficiency;
- reduced fuel burn and emissions.

4.2.4 Airport Collaborative Decision Making (A-CDM)

The Airport Collaborative Decision Making (A-CDM) aims to improve the efficiency and resilience of airport operations by optimising the use of resources and improving the predictability of air traffic. This is achieved through the transparent and close collaboration between airport partners (airport operators, ground handlers and ATC), Network Manager and Airspace Users, exchanging relevant accurate and timely information. A-CDM focuses, mainly, on aircraft turn-round and pre-departure processes.

The expected benefits are:

- improved resilience and efficiency of airport operations;
- optimisation of the use of resources;
- improved predictability.

4.2.5 Extended – Arrival Manager (E-AMAN)

The Extended-Arrival Manager (E-AMAN) allows for the sequencing of arrival traffic much earlier compared to the current AMAN, by extending the AMAN horizon from the airspace close to the airport to further upstream sectors. Therefore, a smoother traffic management can be performed, by providing upstream sector controllers system advisories in support of an earlier pre-sequencing of aircraft.

The expected benefits are:

- improved operational efficiency and quality of service by reducing holding times;
- improved operational efficiency by reducing fuel burn and emissions;
- improved safety and quality of service.

4.2.6 Runway Occupancy Times (ROT)

This solution comprises the application of machine learning techniques to develop more accurate predictions of arrival runway occupancy time (ROT) and runway exit times based on aircraft characteristics such as aircraft type, weight, equipage, and weather.

The expected benefits are:

- increased runway throughput capacity and resilience;
- improved safety linked to accurate runway exit prediction.

4.3 SIMBAD case studies selection criteria mapping

The solutions or concepts that have been briefly described in the section above must be further analysed with respect to the selection criteria defined in section 4.1.

It should be highlighted that the capabilities and characteristics of the tools available to the consortium (i.e., R-NEST and DYNAMO) play a relevant role in the final selection of the solutions which will be modelled in the project, although they are not considered as criterion themselves. Both tools demonstrated their broad capabilities in assessing ATM performance: R-NEST has been successfully used in the past to evaluate different mechanisms (inspired and aligned by SESAR solutions) and the impact of exogenous factors, while DYNAMO is able to simulate a massive number of trajectories in the entire ATM network under nominal, sub-nominal or enhanced conditions.

Although broad and successful in their applications, the tools still have some restrictions and limitations with respect to specific solutions and their respective operational aspects, as their assessment may require the development of the additional modules that are currently not available.

Table 2 summarises, for each SESAR solution identified, the assessment of the different SIMBAD case studies selection criteria.

SESAR SOLUTION	CRT-001	CRT-002	CRT-003
UDPP	Y	N	Y
DCB	Y	Y[4]	Y
FR	Y	Y	Y

[4] Only some concept elements are being deployed.

SESAR SOLUTION	CRT-001	CRT-002	CRT-003
A-CDM	N	Y[5]	Y
E-AMAN	N	Y[6]	Y
ROT	Y	N	Y

Table 2. Initial candidates SESAR solutions vs. SIMBAD Case Studies selection criteria

Therefore, based on the above-mentioned results, the SIMBAD case studies selected, which will be further described in the following sections, are Demand and Capacity Balancing and Free-Route.

4.4 SIMBAD Research Questions

Two set of research questions (RQs) are designed to address the benefits of the metamodels proposed in SIMBAD:

- The first set of RQs aims at estimating the overall operational benefit of the metamodeling approach at a system level. These research questions can be addressed by most of the scenarios considered in SIMBAD as they tried to address the advantages of the metamodels with respect to microsimulation models (i.e., APACHE and R-NEST). Therefore, each question will be validated with as many scenarios as possible (i.e., using large number of combinations of the model input parameters). Objective and quantifiable success criteria will be defined for each RQ to validate or refute the corresponding hypothesis.

- The second set of RQs is tailored to address the benefits of metamodeling approach for each specific solution identified. The aim is to evaluate the added value delivered by the new methods and tools developed by SIMBAD in each solution in comparison to the micromodels approach.

Table 3 summarises the research questions for assessing the overall operational benefit of the developed metamodels. The validation activities will aim at quantifying some of the metamodel results of the different planned scenarios.

[5] The expected benefits assessed cannot be isolated for the conceptual elements deployed.

[6] The expected benefits assessed cannot be isolated for the conceptual elements deployed.

Research Question ID	Rationale	Research Question (RQ)	Hypothesis	Success criteria
RQ-01	Validate that the metamodeling methodology will allow for a more efficient exploration of the simulation input-output space	Will the results obtained by the metamodel methodology provide more informative input-output data in a timelier manner than the respective microsimulation tools?	Once the metamodel has been trained, it will allow the exploration of solutions not directly executed in the micromodel tool.	The number of input-outputs data obtained by metamodels will be larger than with micromodels and will constitute a reasonably good approximation for the real simulated data. Note that the concern for a balanced trade-off between minor accuracy loss and the metamodel's computational performance should always be present
RQ-02	Validate the benefit of the metamodel ability to find extreme cases for each KPI	Will the information on the extreme cases for each KPI impacted be more valuable than information obtained solely by microsimulation model	The efficient input space exploration underpinning the metamodels will enable and enhance the identification of the inputs, and their corresponding values, for which one can expect the worst and best performance for each KPIs.	The extreme cases for each KPI will be found for each specific scenario run by the metamodels. This feature might not be available by micro modelling approach.

Research Question ID	Rationale	Research Question (RQ)	Hypothesis	Success criteria
RQ-03	Validate the benefit of the metamodeling methodology when deployed as part of an optimisation process	Will the active learning method show benefit of driving the optimisation search in the space of targeted KPIs?	With a selective search combining exploration and exploitation, the active learning can be considered as a heuristic to drive the optimisation search in the space of solutions.	If feasible, metamodels will provide the result of the process that aims to optimise the inputs to obtain targets to KPIs. This feature might not be available by the micro modelling approach
RQ-04	Validate the benefits of the metamodels to provide the information on uncertainty on their predictions	Will the information on uncertainty (lower and upper bounds, variance, quantiles, etc.) help to take a more informed decision on specific KPAs and their respective targets?	The information on uncertainty provided by metamodels will be supportive and informative enough in the decision-making process.	The statement will be validated based on the feedback obtained from the experts from the Advisory Board who will assess the benefits.

Table 3. DCB – Project Research Questions for validation of the metamodels at a system level

5 Case Study #1: Demand and Capacity Balancing

5.1 Brief description of the solution

According to [17], research projects of SESAR programme, which are included in PJ.09, aim at evolving the existing DCB process to a powerful distributed network management function which takes full advantage from the SESAR Layered Collaborative Planning, Trajectory Management principles and SWIM Technology to improve the effectiveness of ATM resource planning and the network performance of the ATM system in Europe. The needs of the network are considered as a whole, as well as local factors, to avoid overloads in a seamless process.

On the other hand, within the DCB process, capacity measures, specifically Dynamic Airspace Configuration (DAC), have been considered separately from the PJ.09 in Wave 1 because of the significance of the solution. PJ.08 Advanced Airspace Management (AAM) [18] pursued the efficient management of the airspace considering the various defined AU's performance targets, operational requirements, and military activities through the DMA type 1 and 2 design principles.

Therefore, under the umbrella of the entire Demand Capacity Balancing process within SESAR programme, four solutions were considered in SESAR 2020 Wave 1:

- PJ.09-02 Integrated Local DCB Processes.
- PJ.09-03 Collaborative Network Management.
- PJ.08-01 Management of Dynamic Airspace Configurations.
- PJ.08-02 Dynamic Airspace Configuration supporting moving areas.

In addition, within SESAR 2020 Wave 2, the following solution addressing DCB aspects is under development:

- PJ.09-W2-44 Dynamic Airspace Configurations (DAC)

In particular, SIMBAD will consider for the analysis of this first case study two conceptual elements of the Advanced Demand and Capacity Balancing concept: the use of Dynamic Airspace Configurations and the application of Short Term ATFCM Measures (STAM), both of them already deployed to some extent.

On the one hand, the use of DAC aims at improving the use of airspace capacity by increasing the granularity and flexibility in the airspace configurations that can be used by the Air Navigation Service Providers to better accommodate the traffic demand for both civil and military users.

On the other hand, STAM measures are defined as an approach to smooth ATCo workload by reducing sector complexity and traffic peaks through the application, in short-term (on the day of operation, from several hours to a few minutes in advance in tactical) of minor ground delays, horizontal re-routings and vertical re-routings (flight level capping) to a limited number of flights.

5.1.1 Dynamic Airspace Configuration

As previously mentioned, the main objectives of Dynamic Airspace Configurations are to develop airspace designs and sector opening schemes optimised for the traffic demand preferred routes; to better balance ATCo workload among sectors; and to reduce as much as possible the need for tactical interventions on traffic flows.

In a DAC environment, where the number of controlled sectors and their shape can be dynamically adapted, the following processes are identified:

- **Airspace Design** (from long-term to medium-term planning phases). This process, supported by automation, consists in the definition of the different airspace structures that will be part of the sector configuration management process.
- **Sector Configuration Management** (from short-term planning phase to tactical phase). This process aims at determining the optimum sector configuration for a given traffic demand and time period, considering several optimisation criteria and constraints (e.g., ATCo workload, underloads and overloads period, minimum transition time, number of active sectors, available workforce, etc.).

In support of the dynamic sector configuration concept, three different axes have been defined:

- **Design and Configuration Axis**

This axis introduces the airspace design elements that can be used when building the Configured Sectors (CS).

  - Elementary Sectors (ES), which are ATC 3D airspace volumes (i.e., they can be controlled by ATCo, but they cannot be split further down into controllable sectors).
  - Airspace Blocks (AB), which are primary volumes of airspace that have to be configured to build workable sectors.
  - Shareable Airspace Blocks (SAB), which are non-workable volumes (i.e., they cannot be controlled by ATCo) of airspace that can be dynamically configured in a pre-defined way to any adjacent Elementary Sector or Airspace Block to build a Configured Sector.
  - Flexible Boundaries (FB), which are sector boundaries that can be modified or refined to facilitate and optimise Free Routing trajectories.
  - Vertical Sharable Airspace Modules (VSAM), which are non-workable volumes of airspace vertically split in 1000 feet layers.

The combination of one or more of the previous airspace elements results into the so-called Configured Sectors, in which the ATCo provide Air Traffic Services.

- **Automation Axis**

This axis is considered as a fundamental driver of the performance of the Dynamic Airspace Configuration process. The automation will increase the range of possibilities in organising and managing the airspace, the efficiency of sector solutions by using optimisation algorithms, and the overall efficiency of the DCB decision-making process.

- **Human and Training Axis**

This conforms the last pillar of the dynamic airspace configuration process and refers to the interdependency of training requirements as the airspace configuration dynamicity increases. This axis also considers the different levels of automation.

5.1.2 Short Term ATFCM Measures

The short term ATFCM Measures, commonly known as STAM, are demand and capacity balancing measures aiming at increasing Flow Managers flexibility to handle overloads.

When a sector presents a demand and capacity imbalance, the problem is usually addressed by applying ATFM regulations (i.e., delaying the departure of flights) through the Network Manager who issues for each flight involved in the demand and capacity imbalance a Calculated Take-Off Time (CTOT). CTOTs should be typically allocated and notified at least two hours before the flight is originally scheduled to take-off. This means that the effectiveness and efficiency of these measures are limited as the demand continuously evolves over time. On the other hand, FMPs can act on traffic flows by applying route availability restrictions or ATFM scenarios to separate traffic flows and reduce complexity. Even though these measures provide significant safety benefits, they are usually too penalising in terms of delay and flight efficiency due to the flight stage at which they are applied.

In this way, the application of STAMs, that can be applied at later stages targeting the specific flows and flights creating the demand and capacity imbalance, has led to improved efficiency and increased predictability. In addition, the impact of STAMs is less penalising than the application of a standard CASA regulation as it usually affects a small number of flights, and depending on the kind of STAM, the measure can be just temporary.

Following, some of the most common Short Term ATFCM measures are described:

- **Flight Level Capping**: this measure consists in the application of flight level restrictions for flights that meet certain conditions (e.g., flights departing a particular airport or set of airports and crossing a particular Traffic Volume). The objective of this measure is to protect from overloads the upper sectors by delaying the climb of one or more flights to their requested cruise flight level or by advancing their descent phase.

- **Horizontal Re-Routing:** this measure is applied through the horizontal diversion of certain flights or traffic flows to offload certain areas.

- **Minimum Departure Interval:** through this measure, sequential departures from certain aerodromes are spaced by X minutes if they proceed in a specific direction. Although this measure could be similar to the application of CTOTs, the main difference resides on the fact that the application of these measures is temporary.

- **Miles in Trail:** with the application of this measure, successive flights following a specific flow or route are regulated by applying minimum miles-in-trail separation between aircraft.

- **Mandatory Cherry-Picking regulations**: these measures are used to solve short peaks of traffic (e.g., less than 1h 30') created by a limited number of flights in congested areas. The measure consists of selecting the flights creating complexity and applying delays only to those flights. In any case, the delay for the cherry-picked flights should not exceed 20 minutes.

5.2 Performance Assessment available

This section gathers the performance benefits available for the conceptual elements of the Demand and Capacity Balancing process described in the previous sections. The performance benefits include both the expected benefits coming from the SESAR programme and the actual benefits where the solutions have been already deployed.

5.2.1 Expected benefits

During SESAR 2020 Wave 1, a series of human-in-the-loop validation activities addressing the dynamic airspace configuration solution and the integration of airspace management and short-term ATFCM measures were conducted under PJ.09-02 and PJ.08-01.

Considering the results of these validation activities, the expected performance benefits for the different Key Performance Areas impacted were computed and extrapolated at ECAC level for 2035, taking into account the forecast traffic for En-Route Very High Complexity and High Complexity sub-operating environments (i.e., the 59,31% of the total traffic for 2035 at ECAC level).

Table 4 presents the performance benefits expected for each Key Performance Area and Key Performance Indicator for both Dynamic Airspace Configuration and STAM solutions [19][20].

Key Performance Area	Key Performance Indicator	Dynamic Airspace Configuration	STAM
Airspace Capacity	En-Route throughput	+ 3.5% (local)	+ 7.2% (local)
Operational Efficiency	Fuel Efficiency – Actual Average Fuel Burn per Flight	- 0.510 kg fuel burn / flight (positive impact)	+ 4.789 kg fuel burn / flight (negative impact)
	Punctuality - % Flights departing within +/- 3 minutes of scheduled departure time due to ATM and weather-related delay causes	No impact expected	+ 1.186% (positive impact)
	Predictability – Average of difference in actual and flight plan or RBT durations	No impact expected	- 0.136 min2 (positive impact)

Key Performance Area	Key Performance Indicator	Dynamic Airspace Configuration	STAM
Cost-Efficiency	Flights per ATCo-hour on duty	+ 0.42% flights/ATCo-hour (positive impact)	+ 4.211% flights/ATCo-hour (positive impact)

Table 4. DCB expected benefits (SESAR)

5.2.2 Actual benefits

The amount of solutions deployed by a single stakeholder hinders the analysis of the actual benefits once the technology and/or the operational concept is deployed. In fact, stakeholders work on annual reports about the traffic and capacity evolution but, the deployment of several solutions within that period prelude the apportionment and the allocation of the benefits to a single solution.

Despite the previous comment and those in section 4.2, strong assumptions can be posed on top of the Local Single Sky Implementation (LSSIP) reports for getting some figures about the results of the deployment of a specific solution. LSSIP provides relevant information about, on one hand, the situation of Air Traffic, Capacity and ATFM delay per ACC and, on the other hand, the main implementation projects.

With respect to STAM measures, FCM04 addresses the deployment of both phases: Figure 2 and Figure 3 show the implementation status of STAM phase 1 and phase 2; while Table 5 summarises the content of the two phases.

	FCM04.1 - STAM Phase 1	FCM04.1 - STAM Phase 2
Basic Content	Initial version of STAM already deployed in some FMPs	The tactical capacity management procedures can be supported by a Network Tools (system based STAM with the hot-spot detections in the network view, the "what-if" function and capabilities of promulgation and implementation of STAM measures, including CDM) or by local tools.
Objectives	Availability of CHMI	Enhanced monitoring techniques (including hotspot management and complexity indicators)
	Capacity balancing tool via CHMI	Coordination systems (including B2B with local tools)
	STAM network view for the AUs	What-if function (local measures, flight based, flow based and multiple measure alternative)

	FCM04.1 - STAM Phase 1		FCM04.1 - STAM Phase 2	
	Dynamic Demand and Capacity balancing tools via NOP		Network impact assessment	
	Integration of ANSPs sector and traffic occupancy parameters data into NM systems		-	
Expected benefits	Safety	Some enhancement through the prevention of overloads.	Safety	Small enhancement through the resolution of some conflicts through STAM measures.
	Capacity	Some enhancement through the prevention of overloads.	Capacity	Effective capacity is globally optimised thanks to replacement of some ATFCM regulations with the STAM measures, hotspot reduction and its more efficient management
			Operational Efficiency	Improved through the proposition of the most appropriate measures according with the type of flight.
SLoA ref.	FCM04.1-ASP01	Availability of demand-capacity balancing tools via CHMI	FCM04.2-ASP01	Develop STAM procedures and upgrade the local systems
	FCM04.1-ASP02	Provision of ANSPs sector and traffic occupancy parameters data to NM	FCM04.2-ASP02	Use of STAM phase 2
	FCM04.1-ASP03	Implement FCM Procedures to enable application of flow management techniques	FCM04.2-ASP03	Train the personnel

FCM04.1 - STAM Phase 1		FCM04.1 - STAM Phase 2	
FCM04.1-ASP04	Develop, and deliver as necessary, a safety assessment of the changes imposed by the implementation	FCM04.2-USE01	Airspace Users to deploy the appropriate tools and associated procedures
FCM04.1-USE01	Availability of demand-capacity balancing tools	FCM04.2-NM01	Update the NM systems and develop the associated procedures
FCM04.1-NM01	Develop and implement demand-capacity balancing tools via CHMI	FCM04.2-NM02	Train the personnel
FCM04.1-NM02	Integration of ANSPs sector and traffic occupancy parameters data into NM systems	FCM04.2-NM02	Train the personnel

Table 5. Summary of STAM Phase 1 and Phase 2 content

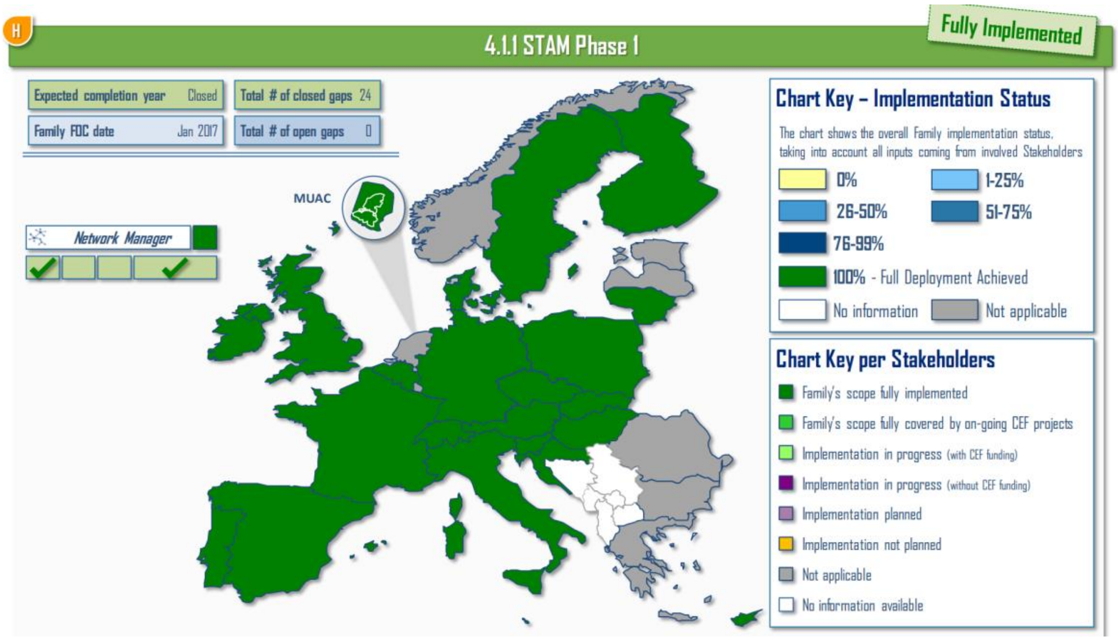


Figure 2. SDM Monitoring View 2019 – STAM Phase 1 implementation

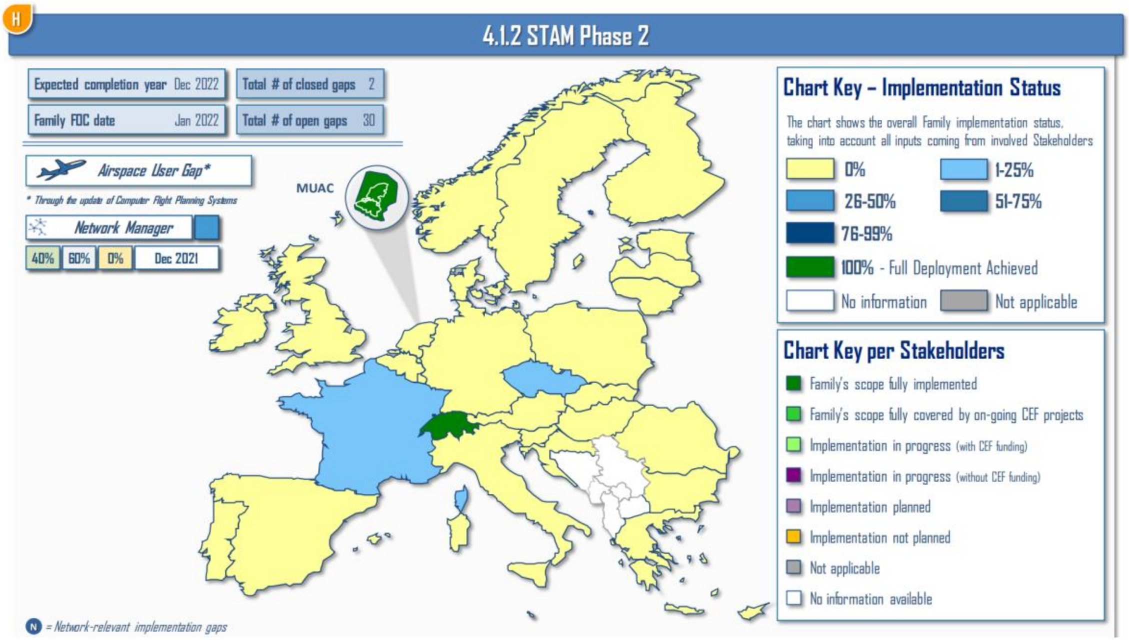


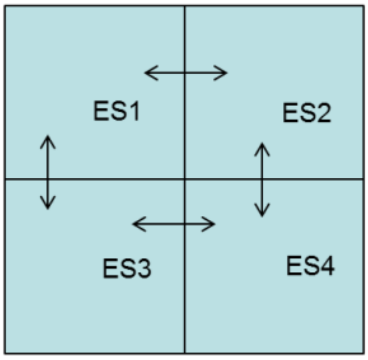
Figure 3. SDM Monitoring View 2019 –STAM Phase 2 implementation

5.3 Potential case study scenario

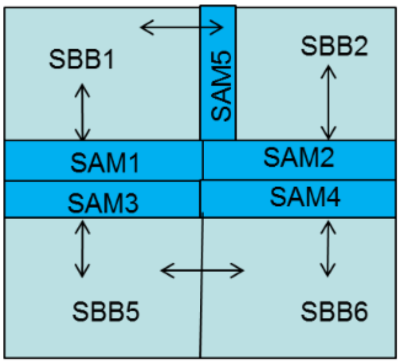
In the current operations, the most similar practice to DAC is the selection of the opening scheme among a set of predefined configurations. In the context of SESAR, the DAC concept is divided into four different levels depending on the airspace structures used for the generation of the new controllable sectors and configurations [21]:

- Level 1. The airspace is divided into elementary sectors (ES) and no predefined configurations are used. Dynamically computed configurations are provided by an automated optimisation process based on the combination of the existing elementary sectors.
- Level 2. The airspace is divided into sector building blocks (SBB) and shareable airspace modules (SAM). Typically, SBBs are delineated capturing high traffic areas while SAM are linked with less busy regions (with eventually some demand peaks). In this level, SBBs can be controllable by themselves (i.e., they are sufficiently big) but SAMs need to be collapsed to be workable. A SAM can be collapsed laterally and vertically to the neighbouring areas with the purpose of being adapted to the changes of traffic patterns.
- Level 3. The airspace is still organised in SBBs and SAMs. The number of SAMs and SBBs is much greater than in Level 2 which leads that now the SBBs are not operable by themself. The controllable sectors are obtained by collapsing SAMs and SBBs.
- Level 4. The airspace is divided into only SAMs not related with the traffic patterns.

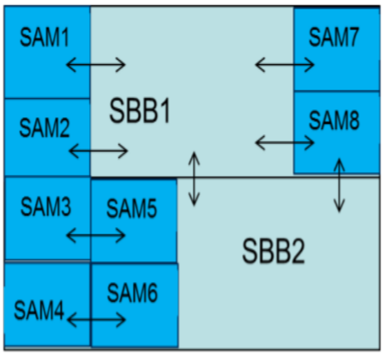
In Figure 4, an illustrative example of the four levels of DAC is provided. For SIMBAD purposes, DAC solution will be modelled following the principles of Level 1 or Level 2, depending on the availability of the data. In other words, if the definition of SAMs and SBBs is provided, Level 2 will be conducted. If not, and only the elementary sectors are given, the DAC model will be based on Level 1.



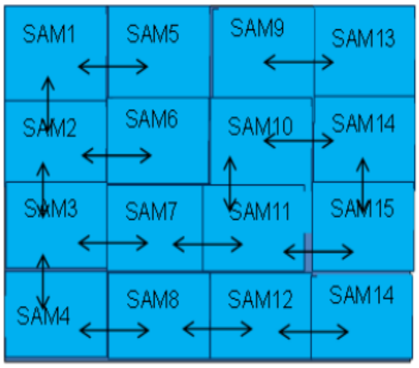
DAC level-1. Elementary sectors components (top/lateral view)



DAC Level 2. SBBs and SAMs components (lateral view)



DAC Level-3. SBBs and SAMs components (top view)



DAC Level 4. SAMs components (top/lateral view)

Figure 4. DAC levels

Regarding the time horizon of the scenarios, SIMBAD will be focused on the ATFCM pre-tactical phase, which is basically when the sector opening scheme is defined. With respect to the geographical location of the scenarios, aligned with CON-001, SIMBAD will be focused on those European regions where a first approach to DAC has been already deployed:

- French airspace - Bordeaux (LFBB)
- MUAC airspace - MUAC (EDYY)
- Swiss airspace – Geneva (LSAG)

Depending on the availability of the data, the project will cover one, some or all the indicated regions.

From the 1st Workshop with the Advisory Board, the potential link with PJ.09-W2-44 'Dynamic Airspace Configuration (DAC)' was highlighted. Cooperation opportunities (e.g., use the same scenarios) were posed and further coordination will be needed in order to take advantage of that link. On the other hand, two topics were raised:

- From the ANSP perspective, SIMBAD should consider that openings are chosen during the day, based on short-term forecasts, which change every minute.

- Regarding the Bordeaux scenario, that might be a nice case study, since an algorithm to propose the optimised sector configuration is currently used in operations.

5.4 Case Study #1 - Research Questions

Table 6 presents the set of research questions to be addressed for the conceptual elements of the DCB case study.

Concept addressed	A set of RQs addressed
Dynamic Airspace Configuration	What are the overall benefits of an optimal airspace adjustment to traffic demand on airlines operations and En-route capacity in contrast to other ATFCM measures?
	What are the traffic features (e.g., average flown distance) that have a direct impact on the identification of traffic patterns in a DAC context?
The application of Short Term ATFCM Measures (STAM).	What is the trade-off between sector complexity (i.e., a measure of the difficulty that a particular traffic situation will present to an air traffic controller) and traffic peaks through the application of, on one hand, an excessive fuel consumption due to horizontal re-routings and vertical re-routings (flight level capping) on the other hand?

Table 6. Research questions – Case Study #1

6 Case Study #2: Free-Route

6.1 Brief description of the solution

One of the objectives of the Single European Sky is to enable airspace users to plan flight trajectories without reference to a fixed route network to optimise flights in line with their business needs. Free routing allows airspace users to plan a route along segments of the great circle, which connect any combination of published waypoints and is due to become available above 31,000 feet from 2022 under European regulations. In the context of SESAR, the free route airspace concept is tackled by the project PJ.06 which assessed and delivered two solutions [22]:

- Solution PJ06-01 "Optimized traffic management to Free Routing in high and very high complexity environments". This solution consolidates R&D activities to support the implementation of a Free Routing Airspace (FRA) in all complexities, where Airspace Users can fly as close as possible to their preferred trajectories.
- Solution PJ06-02 "Management of Performance Based Free Routing in Lower Airspace". This solution assesses the possibility and benefits of extending FRA in lower airspace and TMA.

Free routing is already available in a number of low to medium complexity environments following validation work completed under SESAR 1 (i.e., PJ.06-01) paving the way for the latest SESAR research, which is focused on high and very high complexity cross-border environments.

6.2 Performance Assessment available

This section aims at displaying the information on the performance benefits available for the conceptual elements of the Free Route Airspace process described in the previous section. The performance benefits include both the expected benefits coming from the SESAR programme and the actual benefits where the solutions have been already deployed.

6.2.1 Expected benefits

During SESAR 2020 Wave 1, a series of the validation exercises addressing the operational concept description of free route airspace in high and very high complexity environments were conducted under PJ.06-01.

Considering the results of these validation activities, the expected performance benefits for the different KPAs impacted were computed and extrapolated at ECAC level for 2035, taking into account the forecast traffic for En-Route Very High Complexity and High Complexity sub-operating environments (i.e., the 59,31% of the total traffic for 2035 at ECAC level).

Table 7 presents the performance benefits expected for each Key Performance Area for the implementation of structurally limited Free Route concept [23].

KPA/KPIs	Performance Assessment Results
Fuel efficiency	A reduction of 26,57kg per flight
Predictability	The validation results did not allow to confirm or infer any possible benefits in term of local variance of flight times between planned and flown trajectories. However, the mean difference between flown and planned flight durations is improved in both validation exercises
Safety	The Solution contributes to not adversely affecting the Safety and the Airspace KPAs with the implementation of structurally limited cross-border FRA in En-Route High and Very High Complexity operating environment
Capacity	There is a high probability that capacity will be reduced during a transition phase from ARN (ATS Route Network) airspace to Structurally Limited Free Route Airspace, until ATCo have gained high proficiency in the new environment.

Table 7. Free-Route expected benefits (SESAR)

Human Performance is not included in this table above as no quantitative Ambition Targets were set for HP. Nevertheless, the outcomes of the HP assessments demonstrated that ATCo situational awareness and cognitive workload were considered adequate to perform their work both in high and in very high complexity environments.

Finally, the PJ.06-01 Solution would bring significant benefits to the Airspace Users and great improvement to the network performance. The overall cost benefit analysis results of the PJ.06-01 show that the Net Present Value is positive with a gain estimated at 797 M€. This result is supported by flight efficiency benefits evidenced in Validation Exercises and Fast Time Simulations performed by the Network Manager [24].

6.2.2 Actual benefits

Free route operations can be implemented in one of the following forms:

- Time limited (e.g., at night) – this is usually a transitional step that facilitates early implementation and allows field evaluation of the FRA while minimising the safety risks.
- Structurally or geographically limited (e.g., restricting entry or exit points for certain traffic flows, applicable within CTAs or upper airspace only) – this could be done in complex airspaces where full implementation could have a negative impact on capacity.
- Implemented in a Functional Airspace Block environment – a further stage in the implementation of FRA. The operators should treat the FAB as one large FIR.
- Within Single European Sky airspace – this is the ultimate goal of FRA deployment in Europe.

The introduction of FRA in Europe is a step-by-step process rather than a single act. Most states have decided to start with a limited implementation (e.g., during night hours) and then gradually expand it.

By the end of 2020, 46 ACCs had implemented FRA at least partially (but mostly on H24 basis). Also, there are many cross-border implementations, i.e., more than one ACC participating in a FRA initiative. This is shown on Figure 5.

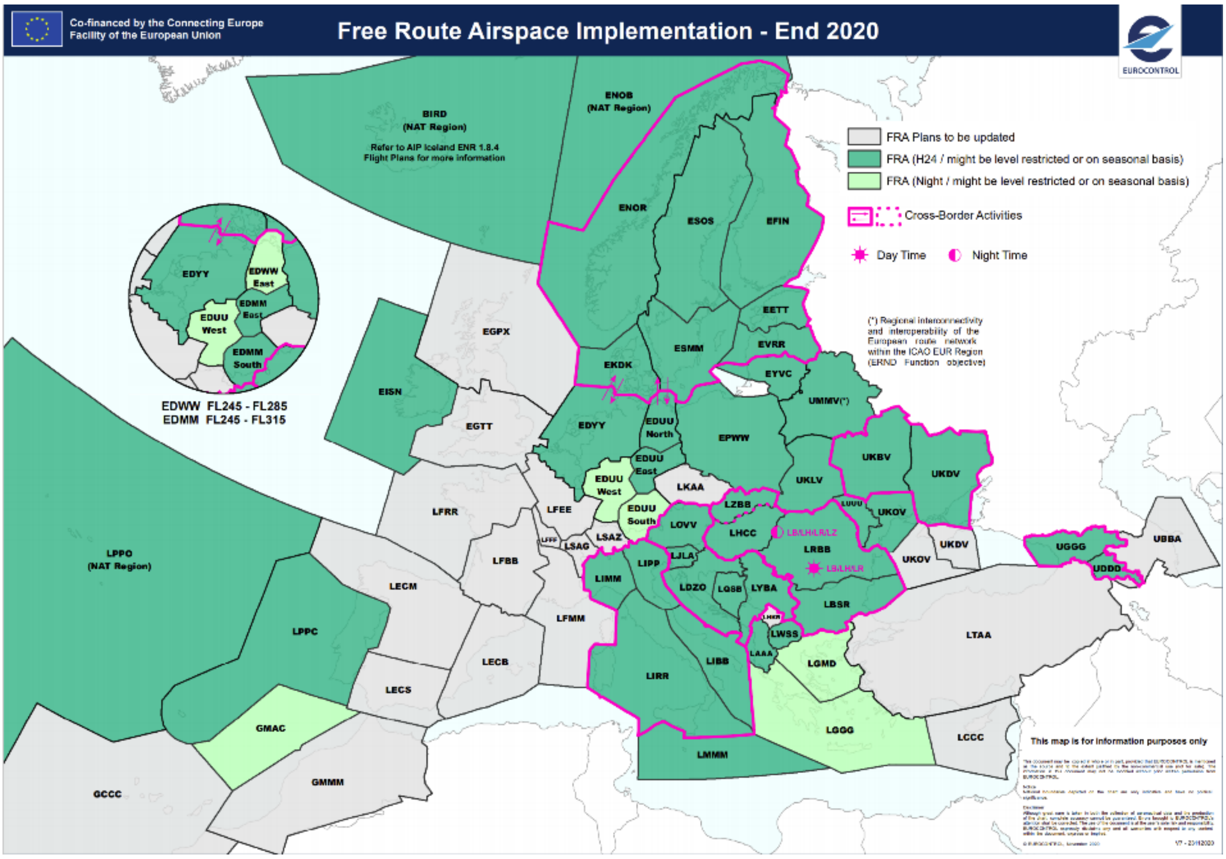


Figure 5. Free route airspace implementation at the end of 2020 (EUROCONTROL)

As observed, FRA has been successfully implemented in much of northern, south-east, and central south-east Europe, as well as in Portugal – the first country to introduce full free route airspace in 2009. With free route airspace projects now in place across three quarters of European airspace, the region's flight efficiency targets are closer to the target ambitions. European flights reached a record low in terms of En-route flight extension at the end of 2017. The key performance indicator KEA (key performance environment indicator based on actual trajectory - KEA) which essentially measures the route extension - the difference between the flight flown and the corresponding portion of the great circle distance - reached an average of 3.17% in 2012. In 2017, the KEA fell to 2.77%, very close to the Europe-wide performance target of 2.6% by 2019 as set by the SES Performance Scheme (SES PRB Monitoring Report 2018, 2019), thanks in part to initiatives like free route airspace (EUROCONTROL).

As mentioned, the move from structured airspace to free route airspace availability offers significant opportunities to AUs. Thus, once fully implemented, the FRA concept should allow the following savings, compared with the current situation:

- 500,000 Nautical Miles per day
- 3,000 tonnes of fuel per day
- 10, 000 fewer CO_2 tonnes per day
- € 3 million in fuel cost saving per day

6.3 Potential case study scenario

As already discussed, the FRA have been extensively implemented across the ECAC area, which enable us to select the particular portion of airspace which will be further analysed within the project. However, the availability of the data will be a decisive factor which will determine the final selection and specification of the case study. Irrespective of the case study which will be eventually modelled, the set of input parameters will be required to particularise the given scenario:

- traffic demand,
- definition of the network structure with FRA for the whole ECAC area, and
- network structure prior to the implementation of FRA for the airspace portion which corresponds to the current FRA.

The special consideration should be focused on the creation of the following two scenarios:

- baseline scenario - One of the key elements to capture the benefits of the FRA is to validate them against baseline network which does not contain the FRA.
- some new scenarios assuming that FRA has been already implemented at specific part at the ECAC area.

The comparison of the new scenario containing the FRA area with the baseline scenario is useful to evaluate expected benefits but should be done with caution as misinterpretations could arise. One has to consider that different models used for the estimation of the two scenarios may result in potential discrepancy in results. In order to ensure the consistency in the results and enable the fair comparison, the same model (i.e., DYNAMO) will be used to simulate the baseline scenario as well as new scenario.

However, the network of both scenarios must be chosen and designed properly in order to maintain the consistency of the results. The structure routes outside the FRA areas must be the same in both scenarios. This is especially important to guaranty that the differences in the results are only due to the effect of the Free Route and not to the changes in the network. Thus, the only differences in the network between the scenarios must be located only inside the FRA area. Another important remark is that the structure route network inside the FRA area in the baseline scenario must be connected with the rest of the airspace network.

Regarding the time horizon of the scenarios, SIMBAD will be focused on the pre-tactical and tactical phase, to model the filing flight plan process. With respect to the geographical location of the scenarios, SIMBAD will try to analyse European regions where a first approach to FRA is already deployed:

- FRAIT (Free Route Airspace Italy, 2014-2017).
- FRAL (Free Route Airspace Lisbon FIR, 2009).
- FRASAI (Free Route Airspace Santiago & Asturias, 2015).
- MUAC (Free Route Airspace Maastricht, 2019).

With regard to the scenario selection and according to the 1st Advisory Board Workshop held on July 2nd, the FRA deployment in Italy might be an interesting case considering the definition of several implementation levels, which mean interesting transition phases. Therefore, within the FRAIT case, three different scenarios are proposed:

- Baseline scenario (no FRA).
- Implementation of Direct shortcuts (DCT).
- Full operational FRA.

Beyond the scenario selection itself, extra comments about the FRA implementation were posed in the 1st Advisory Board Worksop:

- FRA implementation is not usually a ‘single shot’ and, in some cases, ATS routes are kept so AUs can still plan flights via airways.
- The implementation varies from one country to another, so considering the local specificities is needed.

Aligned with these latter comments and bearing in mind the relationship between data availability and the need of defining the local specificities, the project will cover one, some or all the indicated regions.

Moreover, the methodological framework containing a novel set of fuel-based PI proposed in the APACHE project can be of special interest in the context of capturing the actual benefits of the FRA implemented in the given portion of airspace. Namely, the framework is particularly designed for the post-operational analysis which enables the comparison of fuel consumption between the actual/planned trajectory with different types of optimal trajectories as baseline. Additionally, the proposed methodology can be used to separate the different sources of flight inefficiency, either at trajectory level (vertical/horizontal inefficiency) or by capturing the contribution of different ATM layers separately (e.g., strategic, tactical) [25].

In the context of SIMBAD, the similar approach can be followed in order to capture the actual benefits of FRA implementation at a given portion of airspace in more efficient way, by comparing the fuel consumption in the period prior to the FRA implementation within the actual network with FRA already implemented. This trigger the need of data acquisition and preparation which must be performed in order to calculate the fuel efficiency metrics and some capabilities developed in the APACHE project can be particularly useful.

6.4 Case Study #2 - Research Questions

Table 8 presents the set of research questions to be addressed for the conceptual elements of the Free Route case study.

Concept addressed	A set of RQs addressed
Free Route	How are the performance benefits of the Free Route concept impacted by the hidden or latent variables associated to the Airspace Users' behaviour?
	What are the traffic features that have a direct impact on the identification of traffic patterns in a Free Route context?
	What is the improvement that Free Route solution provides in terms of flight efficiency?

Table 8. Research questions – Case Study #2

7 Case Studies and Data Sources

According to the needs explained in the previous sections, the data presented in Table 9 is foreseen as needed for achieving SIMBAD goals.

With regard to the access of the consortium to SIMBAD database, a document named D2.2. Data Repository has been created linked to the data repository creation.

Data Source	Availability	Project needs by work package	Type of data
DDR2		**WP4**: Traffic data & ATFCM Measures & Env. data	Flight information (M1, M2, M3) Environmental data (e.g., airspace data) ATFCM Measures (only Regulations & ATFCM scenarios)
ADS-B	OpenSky free license, limited to research use	**WP3**: high-sampling trajectory data for latent variables estimation	Surveillance data
NOAA	Limited data		Wind, temperature, pressure, climate variability and a wide range of meteorological indicators
EUMETSAT	Limited data	Interesting for **WP4**: European range is essential (national data is not relevant enough). Regarding the temporal scope, a year of data is sufficient.	Convective weather/storms

Data Source	Availability	Project needs by work package	Type of data
ECMWF			Wind, temperature, pressure, historical model data, weather data and a wide range of meteorological indicators An API is available for extraction
BADA	Limited data	**WP3**: Needed to run dynamo (model-based trajectory generator).	Aircraft performance data
METAR			Wind strength and direction, temperature, pressure

Table 9. Data source table

According to the outcome from the 1st Advisory Board Workshop, some of these data sources were discarded and classified according to the potential case studies. For instance, weather data was regarded as a too microscopic variable, since the use of ATFM regulations due to meteorological reason might be sufficient. Table 10 summarizes the data classification from the Advisory Board Workshop.

FREE ROUTE	DYNAMIC-CAPACITY BALANCING
Average flown distance per flight Gate-to-Gate flight time Actual average fuel burnt per flight Average of difference between flown trajectories and flight plans Direct ANS Gate-to-gate cost per flight (mainly route charges)	Number of IFR movements Average departure delay per flight ATFM regulations (MET reason) Non-nominal regulation causes
Estimated/Actual Time of Arrival Average minutes of En-route ATFM delay per flight because of Air Navigation Services ATFM Regulations info Sectorisation & Opening Schema Convective phenomena Other weather variables	

Table 10. Data classification from the 1st Advisory Board Workshop.

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Annex A – SIMBAD Simulation Tools

Following, a high-level description of the microsimulation tools available within SIMBAD, in support of the case studies described in the previous section, is presented.

- **DYNAMO**

The core 4D trajectory generation module is provided by UPC with DYNAMO, an aircraft trajectory prediction and optimisation engine capable to rapidly compute trajectories using realistic and accurate weather and aircraft performance data. DYNAMO is based on an aircraft point-mass model (3 degree of freedom) and its design enables it to be used on real-time applications and/or when a large set of trajectories needs to be rapidly generated for simulation or benchmarking purposes. Moreover, DYNAMO is highly flexible and configurable and allows the user to easily specify a great variety of constraints and objective functions. DYNAMO decouples the generation of the lateral and vertical profiles. The lateral trajectory (route) prediction/optimisation module is in charge of generating the sequence of waypoints from origin to destination (i.e., the route), starting from some guessed altitude and speed profiles. Subsequently, the vertical profile prediction/optimisation module is launched assuming a fixed and known route. This process is iterated several times until an acceptable (optimal) trajectory is found. For the lateral optimisation DYNAMO uses an A* algorithm, a well-known method to find the optimal path in a graph. For the vertical optimisation, an optimal control problem is formulated and can be solved with two different methods: discretizing the problem and solving it by using commercial-off-the-shelf nonlinear programming (NLP) solvers; or using pre-computed look-up tables, which can be generated with DYNAMO as well or taken from an external source. The former approach allows more flexibility to define complex optimisation constraints but might present algorithm stability issues due to the problem non-linearities. In this context, the latter approach is much more stable and robust allowing as well to speed-up the computation time making it appealing for on-board real-time applications. However, defining constraints might be complex. Depending on the application, DYNAMO can be configured to use one method or the other, or even a hybrid approach. The required inputs for DYNAMO are grouped and summarised as follows:

  - **Aircraft performance data:** DYNAMO can accept different aircraft performance models, such those developed by EUROCONTROL in the BADA v3.x or BADA v4.x models (Nuic et al., 2010); data derived by performance tools provided by aircraft manufacturers (such as Airbus PEP or Boeing BCOP); or data directly coming from flight tests. In this context, a virtue of DYNAMO is that it accepts performance data in tabular form, and it automatically and transparently handles these data to generate numerically friendly continuous and differentiable functions (using splines), which are required by most NLP solvers.

  - **Weather data:** DYNAMO can predict/optimise aircraft trajectories using weather models of various complexity, from the International Standard Atmosphere (ISA) or Hellmann wind power-law models, useful for initial assessments or benchmarking; to real weather data provided in GRIdded Binary (GRIB) format, which is also handled automatically to generate continuous and differentiable functions for the NLP solvers.

- **Aircraft operator (airline) parameters/constraints:** including basic parameters such as the cost index, payload, or flight plan restrictions/preferences; or more complex structures such as a user-defined objective function.
- **ATM concept of operations:** specifying how the route and the vertical trajectory can be generated, allowing to model (current) realistic operational procedures taking into account the coexistence of structured route networks with free route areas, flight level allocation and orientation schemes, heterogeneous constraints on speeds and altitude profiles, route or altitude availability/constraints, etc.; or alternative (and futuristic/hypothetical) concepts, such as unconstrained continuous cruise climbs and/or full free route concepts.

- **R-NEST**

R-NEST is a stand-alone desktop application dedicated to research projects (Research NEtwork Strategic Tool) used by EUROCONTROL and partners of the SESAR programme.

R-NEST shares the same basis as the Network Manager operational tool for capacity planning, NEST, combining dynamic Air Traffic Flow and Capacity Management (ATFCM) simulation with airspace design and capacity planning functionalities.

R-NEST dynamically simulates network operations and allows the prediction of different types of delays, enabling the measurement at network level of the improvements generated by the local implementations of new ATM concepts.

More specifically, R-NEST allows:

- Innovative and improved airspace design processes
    - Creation of new elementary sectors balancing the workload inside one ACC
    - Re-routing of civil trajectories around Dynamic Mobile Areas
    - Building of Mission Trajectories using BADA performances
    - Estimation of fuel consumption using BADA performances
    - Analysis of the predictability of traffic counts with ETFMS Flight Data messages
- Innovative capacity management processes
    - Analysis of the complexity of traffic crossing an airspace
    - Estimation of the workload based on potential conflicts and crossing durations
    - Creation of new collapsed sectors that minimise the overload
    - Creation of new configurations that minimise the overload
    - Optimisation of the Opening Scheme allowing the exchange of sharable airspace modules between sectors
    - Analysis of the network effect generated by ATFCM delay propagation

- Assessment of innovative algorithms for advanced ATFCM concepts
    - Simulation of ATM actors interacting dynamically through parameterized roles
    - Generation of non-ATFCM delays based on statistical models
    - Calculation of ATFCM delays with the CASA implementing auto-linked regulations
    - Propagation of reactionary delays on same registered flights
    - Detection of hotspots overloading entry, occupancy counts or estimated workload
    - Implementation of Short Term ATFM measures of Opening Scheme or Flight Level Capping
    - Resolving multiple constraints optimising the global impact