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Abstract

This Exploratory Research Report (ERR) provides an overview of the key findings for the Green Route Charging (GRC) Solution, which aims to develop environmentally friendly route charging mechanisms. This final ERR highlights the outcome of validation exercises focused on en-route charges, addressing climate impact, economic effects on air navigation service providers (ANSPs) and airspace users (AUs), overall network efficiency, and capacity constraints.

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Green-GEAR

GREEN OPERATIONS WITH GEOMETRIC ALTITUDE, ADVANCED SEPARATION AND ROUTE CHARGING SOLUTIONS

Green-GEAR

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1 Executive summary

The objective of this Experimental Results Report (ERR) is to analyse and discuss the results of the validation exercises for the GRC Solution. This initiative concerns en-route charges, taking into account the economic impacts on Air Navigation Service Providers (ANSPs), Airspace Users (AUs), the overall network, and capacity constraints. The proposed approach involves extending and adapting existing network models to simulate the implementation of these mechanisms.

Given the complexity of the task, the GRC Solution is being developed in two stages: the Initial and Full Solutions. The Initial Solution focuses on reducing horizontal inefficiencies caused by differences in unit rates, while the Full Solution aims to incentivise the use of climate-friendly trajectories by considering both CO_2 and non-CO_2 emissions.

The validation objectives for these exercises were primarily based on the Digital European Sky performance framework [AD6], with additional criteria introduced to better evaluate the proposed solutions. The objectives were aligned with research and innovation needs. The first objective addressed feasibility, ensuring that the solutions are compliant with stakeholder needs by verifying the underlying model assumptions. The second objective focused on the climate impact of the solutions, which is at the core of the project. The main KPI in this respect is ENV1, which measures the CO_2 emissions associated with the solution. In addition, the validation aimed to assess the impact of non-CO_2 emissions on climate.

The success criterion for the Initial Solution is a reduction in ENV1, while for the Full Solution, it is the reduction of total climate impact. The issue of air traffic congestion was also addressed. This included measuring en-route and airport capacity violations, as well as total aircraft movements per airspace volume during peak hours (CAP2). The overall performance of the proposed models was assessed by comparing these KPIs between the reference and solution scenarios.

The validation scenarios used in the exercises were based on a set of representative days of European air traffic, carefully selected to reflect the dynamics of the air traffic network throughout the year.

At the beginning of the project, the maturity level of the mechanisms was assessed at TRL 1 for the Initial Solution and TRL 0 for the Full Solution. By the end of the project, the Initial Solution had reached TRL 2, while the Full Solution had progressed to TRL 1.

2 Introduction

2.1 Purpose of the document

The final ERR aims at reporting the outcome of the GRC Solution (#0408), detailing, and analysing experimental results. More in detail, the outcome of validation exercises defined in the ERP will be shown.

2.2 Intended readership

This document is primarily intended for all Green-GEAR consortium members involved directly in Solution research or related work packages within the project (Airbus, Airbus OPS, DLR, EUROCONTROL, NATS, NLR, UNITS, UoW), as well as to inform the SESAR 3 JU programme representatives, who serve as final approvers of this document, about the Solution's progress.

In addition, potential readers of this document are all those involved in research in the field of ATM, particularly regarding route charging projects and projects mitigating the climate impact of aviation, as well as all industry professionals, such as ANSPs, CRCO members, and more in general anyone with an interest in the topic.

2.3 Background

The project bases on the context of exploratory research activities from both within and outside SESAR, aligning with the European Union's climate neutrality goal by 2050 [1], emphasising emissions reduction across various sectors, like aviation. Prior work relevant to this project's aims has provided valuable insights and methodologies, helping to develop environmentally friendly route charging mechanisms. Notably, past projects have laid crucial groundwork.

SATURN (Strategic allocation of traffic using redistribution in the network – [2]) focused on modulating en-route charges to redistribute European traffic, forming the basis for Green-GEAR's model development. ADAPT (advanced prediction models for flexible trajectory-based operations – [3]) instead explored advanced prediction models aimed at enhancing flexible, trajectory-based operations, providing a basis for adaptive decision-making in air traffic management. Pilot3 (from Clean Sky 2 – [4]) contributed by integrating environmentally focused initiatives under the Clean Sky 2 umbrella, emphasising sustainability in aviation through innovative approaches and technologies. COCTA (coordinated capacity ordering and trajectory pricing for better-performing ATM – [5]), provided an in-depth examination of coordinated capacity ordering and trajectory pricing, aiming to improve air traffic management (ATM) performance through strategic pricing and capacity management. Within the ClimOP (climate assessment of innovative mitigation strategies towards operational improvements in aviation – [6]) project one of the considered concepts was related to charging climate sensitive areas (e.g. modulation of charges). Finally, CADENZA (advanced capacity and demand management for European network performance optimization – [7]) focused on reducing air traffic emissions and improving overall network performance through enhanced demand-capacity balancing strategies. ATM4E (air traffic management for environment – [8]) instead explored the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace. The project aimed at integrating existing methodologies for assessment of the environmental impact of aviation, in order

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to evaluate the implications of environmentally optimised flight operations to the European ATM network, considering climate, air quality and noise impacts. FlyATM4E (flying air traffic management for the benefit of environment and climate – [9]) project aimed at advancing climate-assessment methods and optimising aircraft trajectories to identify effective mitigation options for reducing aviation's overall climate impact. It developed a concept for climate-optimised trajectories, ensuring a robust and eco-efficient decrease in climate impact. The project pinpointed weather situations and trajectories that consistently reduce climate impact, leveraging ensemble probabilistic forecasts despite atmospheric uncertainties.

In parallel with Green GEAR, several other currently ongoing projects are also trying to provide different solutions for a more sustainable ATM. The CONCERTO project (dynamic collaboration to generalise eco-friendly trajectories – [10]), aims to make eco-friendly flight trajectories an everyday occurrence, thereby reducing both CO_2 and non-CO_2 emissions from aviation. The project focuses on integrating green air traffic control (ATC) capacities with the appropriate level of automation, supporting stakeholders in balancing operational regularity and environmental performance at both local and network levels. To achieve this, CONCERTO leverages state-of-the-art climate science and data, enabling ATM stakeholders to elevate their “eco-responsibility” to new heights. The GEESE (gain environmental efficiency by saving energy – [11]) project aims to develop an initial concept of operations (CONOPS) for enabling weather-efficient routing (WER) from Europe to the North Atlantic. It will analyse the safety aspects and impacts on legacy systems associated with these operations. Additionally, GEESE will investigate the potential non-CO_2 benefits associated with aircraft formations, building on the more well-known CO_2 reduction benefits. The CICONIA (climate effects reduced by innovative concept of operations - needs and impacts assessment – [12]) project focuses on reducing aviation's climate effects through an innovative CONOPS. It will closely examine non-CO_2 effects and explore methods to measure them. By collaborating with airlines, the network, and air traffic control, CICONIA aims to ensure that these effects are taken into account in operational planning and design. The project will blend cutting-edge AI techniques and climate science to better predict and understand the non-CO_2 impact of aviation on global warming, thereby reducing uncertainties as an essential step towards greener aviation.

These preceding and currently on-going projects contribute valuable insights and methodologies that inform the development of this project's route charging mechanisms. They illustrate the use of pricing mechanisms to effectively manage air traffic and foster environmentally sustainable operations.

2.4 Structure of the document

The document is organised as follows:

- This introduction outlines the purpose of the document, its objectives and illustrates the scientific background from which the project started.
- Section 3 delves into the context of the ERR, defining its research scope, and introducing the validation exercises, the underlying assumptions and their objective.
- Section 4 presents a general overview of the results of the validation exercises, as well as several considerations about the lesson learned during the project.
- In Section 5 the conclusions regarding the progress of the validation exercises are discussed.
- The scientific details of the validation exercises are given in appendices A and B.

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2.5 Glossary of terms

Table 1 Glossary of terms

Term	Definition	Source of the definition
En-route charging zone	A volume of airspace that extends from the ground up to - and including - upper airspace, where en-route air navigation services are provided and for which a single cost base and a single unit rate are established.	SES Performance & Charging Scheme
Unit rate	The unit rate of charge is the charge applied in a charging zone to a flight.	EUROCONTROL 2022
Route charge	The route charge is a levy that is designed and applied specifically to *recover the costs* of providing facilities and services for civil aviation.	ICAO Doc 9082
Modulation of charges	"Member States may, on a non-discriminatory and transparent basis, modulate air navigation charges for airspace users to: (a) optimise the use of air navigation services; (b) reduce the environmental impact of flying; (c) reduce the level of congestion of the network in a specific area or on a specific route at specific times; (d) accelerate the deployment of SESAR ATM capabilities in anticipation of the time period set out in the common projects referred to in Article 15a(3) of Regulation (EC) No 550/2004,… Member States shall ensure that modulation of charges in respect of points (a) to (c) of this paragraph does not result in any overall change in annual revenue for the air navigation service provider compared to the situation where charges would not have been modulated. Over- or under recoveries shall result in an adjustment of the unit rate in year n+2."	SES Performance & Charging Scheme
Performance & Charging Scheme	Commission Implementing Regulation (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky and repealing Implementing Regulations (EU) No 390/2013 [13] and (EU) No 391/2013 (Text with EEA relevance) [14].	SES Performance & Charging Scheme
Environmental impact	The total emissions, CO_2 and non-CO_2, produced by a flight or a set of flights, measured in general in nK of increase of temperature at the 20 years horizon (called also ATR20).	Using CLIMaCCF ATR calculations.
Environmental impact rate	The rate (euros per nK) at which the emissions at taxed in the full solution. This rate is set by a central agent – Central planner in the document.	

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2.6 List of acronyms

Table 2 List of acronyms

Term	Definition
A*<no.>*	Assumption *<no.>*
aCCF	algorithmic climate change function
AIC	Akaike information criterion
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATM	Air Traffic Management
BIC	Bayesian information criterion
CBA	cost-benefit analysis
CLIMaCCF	[Python library for computing individual and merged non-CO_2 algorithmic climate change functions]
CONOPS	concept of operations
CORDIS	Community Research and Development Information Service
CP	Central Planner
CRCO	Central Route Charges Office
D*<no.>*	Deliverable *<no.>*
DDR	Demand Data Repository
DES	Digital European Sky
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Economic Area
ENV	environment [performance indicator]
ERA5	ECMWF Reanalysis v5
ERP	Exploratory Research Plan
EU	European Union
FLL	Final log likelihood
FL	Flight Level
GDPR	General Date Protection Regulation
G2G	gate-to-gate
GR*<no.>*	Grant risk *<no.>*

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Term	Definition
GRC	Green Route Charging
Green-GEAR	Green operations with Geometric altitude, Advanced separation & Route charging Solutions
Green RC	Green Route Charging
HE	Horizon Europe
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ID<*no.*>	Identifier <*no.*>
JU	Joint Undertaking
KPA	Key Performance Area
KPI	Key Performance Indicator
M<*no.*>	project month <*no.*>
MRC	Modulation of Route Charges
MTOW	maximum take-off weight
OBJ<*no.*>	objective <*no.*>
OD	Origin-destination
ODA	Origin-destination-aircraft type
ODC	Origin Destination Charging
OPS	operational efficiency [performance indicator]
OSED	Operational Service and Environment Description
PI	Performance indicator
PU	Public
R&I	research & innovation
RP	Reference Period
SES	Single European Sky
SESAR	Single European Sky ATM Research
S3JU	SESAR 3 Joint Undertaking
SJU	SESAR Joint Undertaking
SP	stated preference
T<*no.*>	task <*no.*>

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Term	Definition
TRL	Technology Readiness Level
UK	United Kingdom [of Great Britain and Northern Ireland]
UKRI	UK Research and Innovation
V<*no.*>	version <*no.*>
VA<*no.*>	Validation assumption <*no.*>
VoT	Value of time
VFR	Visual Flight Rules
WA	Working Area
WER	weather-efficient routing
WP<*no.*>	Work package <*no.*>
WTP	willingness to pay

3 Context of the exploratory research report

3.1 Project / SESAR solution #0408: a summary

The third Solution developed under Green-GEAR is the "Green Route Charging" (Green RC) Solution, aimed at incentivising airspace users to reduce the environmental impact of aircraft operations, specifically through en-route charges, excluding terminal charges. Currently, the European charging system has limited impact on the environmental behaviour of aviation stakeholders. Although EU states are required by the Single European Sky (SES) Performance and Charging Scheme to develop Performance Plans targeting average horizontal en-route flight efficiency, there is no mandate for incentive schemes for air navigation service providers (ANSPs) to meet this target. Similarly, the SES scheme allows for the possibility of modulating air navigation charges to encourage reduced environmental impact, but no such mechanisms have been implemented. The framework for establishing, calculating, and collecting route charges in the EU and beyond is established by the Multilateral Agreement on route charges, signed by 41 contracting states and administered by EUROCONTROL’s Central Route Charges Office (CRCO). This agreement aligns with the International Civil Aviation Organisation’s (ICAO's) policies on charges but lacks an explicit environmental provision. It does, however, conform to EU rules under the Single European Sky framework, meaning any changes within this scheme would automatically be reflected in the route charging. With the ambitions of the Green Deal, there is an urgent need to enhance the environmental focus of the route charging system and address its current limitations. Furthermore, the SES2+ regulation, adopted in October 2024, opens a possibility for environmental route charge modulation to incentivise reduction of non-CO_2 emissions.

3.2 Summary of the exploratory research plan

3.2.1 Exploratory research plan purpose

The Green Route Charging (GRC) [0408] Solution is being developed in two steps: the Initial and Full Solution. The Initial Solution proposes a novel route charging mechanism aimed at reducing the horizontal inefficiency due to difference in unit rates. It is intended to remove the incentive of flying detours to avoid more expensive airspace along the shorter route, and thus reduce the environmental impact of CO_2.

The GRC Full Solution aims to incentivise the use of climate-friendly trajectories, when considering both CO_2 and non-CO_2 emissions. The mechanism “rewards” avoidance of climate-sensitive areas (i.e., climate hotspots[3]), while leaving the flexibility of using the said areas, against a higher charge. In this framework, the Solution proposes novel charging mechanisms, changing how the route charges are **strategically** determined and charged through the modulation of unit rates.

[3] A 'climate hotspot' is a volume of airspace where the atmospheric conditions are such that flying through it creates much higher climate impact than in the other areas.

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The *operational environment* for the GRC Solution encompasses the 41 EUROCONTROL contracting States adhering to the Multilateral Agreement on Route Charging, specifically for *en-route charges*.

The *geographical scope* is limited to en-route airspace. It is assumed that traffic, airspace, and airport characteristics are the same as today, as the GRC Solution can apply irrespective of the operational environment. The en-route charges in practice do not apply to flights with a maximum take-off weight (MTOW) below 2000 kg, military flights, flights in Visual Flight Rules (VFR) airspace, and circular flights.

The existing framework of the SES Performance and charging scheme, SES2+ and the principles set forth in the International Civil Aviation Organisation's (ICAO's) policies on charges for airports and air navigation services are taken as a starting regulatory framework, and the validation exercises will assess the needed changes.

3.2.2 Summary of validation objectives and success criteria

Validation objectives and success criteria are as described in D5.2 - ERP - Green RC [AD26].

3.2.3 Validation assumptions

Table 3 Validation assumptions overview

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
VA1	Route charges	EU and ICAO rules and regulations hold. Route charges are calculated according to the current system.	Required as the baseline of the models.	Level of reliability of the validation.
VA2	Traffic	Historical traffic from DDR2 is similar to the current one and represents the current behaviour in the European airspace.	Required to set models' inputs.	FEFF1, TEFF1.1, capacity violations

3.2.4 Validation exercises list

[EXE 5.1]

Identifier	TVAL.07.01-Green-GEAR 0408-TRL1
Title	Modelling of Green Route Charge schemes
Description	Validate on a reduced-scale scenario the correct functioning of the GRC implementations with respect to expected results of the theoretical models. Monitoring the behaviour of the GRC models and checking for their feasibility.

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KPA/TA addressed	N/A
Addressed expected performance contribution(s)	N/A
Maturity level	TRL1
Use cases	MRC, ODC+MRC, Full GRC
Validation technique	Reduced-scale optimisation modelling and computation
Validation platform	Python software package
Validation location	Trieste, Italy – London, United Kingdom
Start date	01/12/2023
End date	30/04/2025
Validation coordinator	UNITS
Status	Completed
Dependencies	

[EXE 5.2]

Identifier	TVAL.08.01-Green-GEAR 0408-TRL2
Title	Execution of Green Route Charge schemes
Description	Validation of the GRC Solution by assessing the performance in respect to capacity, cost efficiency, operational efficiency and environment.
KPA/TA addressed	A1. Capacity, cost efficiency G2G, operational efficiency, environment
Addressed expected performance contribution(s)	Demand capacity imbalance decreases. Fuel consumption reduction for Initial Solution. CO_2 emissions reduction for Initial Solution, climate impact reduction for Full Solution.
Maturity level	TRL2
Use cases	MRC, ODC+MRC, Full GRC
Validation technique	Large-scale optimisation modelling and computation
Validation platform	Python software package

Validation location	Trieste, Italy – London, United Kingdom
Start date	01/06/2024
End date	30/04/2025
Validation coordinator	UNITS
Status	Completed
Dependencies	TVAL.07.01-Green-GEAR 0408-TRL0

3.3 Deviations

3.3.1 Deviations with respect to the S3JU project handbook

There are no deviations with respect to the S3JU project handbook.

3.3.2 Deviations with respect to the exploratory research plan (ERP)

A number of changes has been made as suggested during review of the intermediate ERR document [AD28]:

- The description of TVAL.07.01 has been modified by including the validation of the models on the reduced-scale scenario; the maturity level has been changed from TRL0 to TRL1.
- A clearer distinction has been made between Validation assumptions (Table 3) and the justification of the choice of input data.
- Modelling assumption A4 has been modified as requested, by including a tolerance for the revenue neutrality principle for ANSPs (Appendix A.1.1). The additional success criterion has been added to the "exercise success criteria" (Table 7).

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4 Validation results

4.1 Summary of project / SESAR Solution #0408 validation results

Table 4 Summary of validation exercises results

Project / SESAR solution validation objective ID	Project / SESAR solution validation objective title	Project / SESAR solution success criterion ID	Project / SESAR solution success criterion	Project / SESAR solution validation results	Project / SESAR solution validation objective status
OBJ1	Feasibility	#1.FEAS	Each constraint should be fully satisfied.	Feasibility has been fully satisfied by exercise#01. The exercise #02 just confirmed the findings.	Achieved
OBJ2	Environmental impact	#2.ENV	The success criteria are different for Initial and Full Solutions. For the Initial one the success would be achieved with the reduction of ENV1, while for the Full Solution, the success is the reduction of the climate impact of CO_2 and non-CO_2.	OBJ2 has been achieved and validated via exercise #02.	Achieved
OBJ3	Congestion reduction	#3.CAP	The overall number of capacity violations show an improvement from the reference scenario to the solution scenario.	OBJ3 has been achieved and validated via exercise #02 for Initial Solution and partially achieved for the Full Solution, due to the assumptions and constraints applied.	Achieved for Initial / Partially achieved for Full Solution

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The validation exercises defined in the ERP are two and cover three main objectives: feasibility, congestion reduction and environmental impact. The first exercise covers the first objective, as it aims at verifying that the theoretical models developed address the required tasks, respecting the identified validation assumptions. The second exercise instead, aims at finalising the project effort, so all other objectives will be considered.

4.2 Detailed analysis of project / SESAR solution validation results per validation objective

The validation activities for the GRC solution (Exercise #01 and Exercise #02) focused on the assessment of feasibility and the performance (measured with the appropriate KPIs) of the Green RC Solution. The solution has two components, each representing a different level of ambition and complexity: the Initial and Full solutions. The Initial solution aims to reduce CO_2 emissions and congestion, while the Full solution builds on this goal by also addressing the mitigation of non-CO_2 effects.

With a slight abuse of terminology, in the Initial Solution we use the term *congestion* to refer to demand–capacity imbalances at the strategic level. These imbalances were assessed by comparing the number of capacity violations between the reference case and two newly developed models. Although capacity is generally managed at the tactical level, this study has also investigated the effect that strategic-level actions may have on mitigating demand–capacity imbalances, since previous research has highlighted their potential benefits [2] [15]. Specifically, it has been observed that a distribution of traffic aligned with the declared nominal capacities of airports and sectors across the entire network can reduce the amount of ATFM delay imposed on the day of operations in two ways. First, by eliminating the need to impose ATFM delay to respect nominal capacities, as these are already balanced through the mechanism. Second, by reducing the amount of delay resulting from other types of regulations that impose stricter limitations than the declared nominal capacity. The causes of such regulations can typically only be identified on the day of operations (e.g., weather-related restrictions). Even in these cases, however, strategic traffic redistribution could lead to smaller delays, as the number of flights exceeding imposed capacity would be lower than under current conditions, given that nominal capacity is practically not enforced. Therefore, a strategic redistribution of air traffic has the potential to reduce the number of ATFM interventions on the day of operations, and the Initial solution has shown very promising results in this direction.

The Initial Solution consists of two models: Modulation of Route Charges (MRC) and Origin Destination Charging with Modulation of Route Charges (ODC+MRC). The Full Solution explores different ways in which full emissions reduction incentivisation could be applied. The design and formulation of the models to test the GRC solution was successfully completed: as well as their implementation, and all experiments have been conducted. The Stated-preference survey has been concluded, and a detailed analysis of exercise results can be found in Appendix A and Appendix B.

In the following subsections we will present a summary of the results obtained with the various models, activities and exercises, which detailed discussions can be found in Appendix, Sections A.3 and B.3.

4.2.1 OBJ1 results

4.2.1.1 Initial solution

The main objective of Exercise #01 was assessing the models' feasibility (OBJ1) on a small-scale scenario (a statistically representative sample of the real traffic). Feasibility in this context is defined as the compliancy of the model with the stakeholders' requirements, which are defined in two different ways depending on the Solution. We summary here only the assumptions related to the Initial Solution, particularly the MRC model, leaving the discussion of the Full Solution assumptions in the appendix A.3.2.2:

A1. Given a set of routes with the same origin-destination, the shortest is the one with the lowest CO_2 environmental impact.

A2. Given a set of routes with the same origin-destination, each flight operates the one with the lowest cost.

A3. In case of predicted capacity imbalance at the strategic level, the central planner (CP) can propose a time shift to some flights and/or modulate the route charges on a route basis in order to minimise the violation of the capacity constraints.

A4. The modulation of route charges must be comply with the revenue neutrality principle. This means that each ANSP receives the same revenue for the same amount of workload (measured in service units), within a predefined tolerance. While this approach preserves the unit price of the service, it does not guarantee that the total revenue remains unchanged, since the Solution may lead to an increase or decrease in the amount of traffic served by the same ANSP.

The data used for the small-scale optimisation have been taken from the real European air traffic of 20th September 2019, considering 995 flights covering 563 origin-destination (OD) pairs.

OBJ1 has been achieved since a complete test has been conducted on the MRC model resulting in a full satisfaction of the above-mentioned assumptions. In fact, the model ensured that flights operated at minimum cost, as all routes selected adhered to the optimisation constraints established (A2). In addressing capacity imbalances, the MRC via an average modulation factor of 0.945 on selected routes and 0.983 on alternative routes, provided a reorganisation of the traffic for which no violations occurred (A3). Regarding the modulation factors, on average, route charges of chosen routes have been reduced by 5.5% and route charges of all possible routes have been decreased by 1.7%.

The unit price of the service has been maintained for each ANSP, within a tolerance of ±10%, thereby ensuring compliance with the revenue neutrality principle (A4).

Finally, in accordance with A1, the optimisation led to a reduction in the global distance flown from 1,700.3 thousand kilometres to 1,669.6 thousand kilometres, resulting in a 1.81% decrease in global distance flown, demonstrating that the shortest routes were indeed chosen when possible, and aligned with the lowest CO_2 impact.

OBJ1 has been verified also for the ODC+MRC mechanism.

4.2.1.2 Full solution

Similarly to the initial solution, the objective of exercise #01 was to assess the soundness of the model on a small-scale scenario. Feasibility in this context was to be understood as the compliance of the model to a few core ideas, the feasibility of the implementation itself, including the analytical derivation of the core equations, and an assessment of the computational time for the model to run.

The constraints were all met:

- The internal constraints like capacity violations and ANSP revenue neutrality were all shown to be solvable by the model.
- The model behaved as expected, showing a reduction of EI when the EI rate was increased.
- The analytical derivation was done on simple cases and was shown to work. Analytical work on more complex cases was proven to be very difficult, thus highlighting the limits of the model.
- The assessment of the computational time of the implementation of the model was satisfactory on small case but deemed too high for bigger scenarios. This triggered a round of heavy optimisation of the code, leading to some good gains for the model overall.

4.2.2 OBJ2 results

4.2.2.1 Initial solution

The objective OBJ2 is evaluated by reducing KPI ENV1, which measures CO_2 emissions per flight based on fuel consumption. The environmental impact of the MRC model was assessed over two AIRAC cycles: a high traffic period (1910) and a low traffic period (1902). The analysis has been conducted on two different scales: the first, the global one, considered all flights to or from ECAC (and adjacent) states; the second, the *local* one, focused only on flights with both departure and arrival within ECAC (and adjacent) states.

The MRC led to consistent reductions in all KPI compared to the reference scenario. For AIRAC 1910, the distance flown decreased by 0.661%, fuel consumption by 0.412%, and ENV1 by 0.412%. For AIRAC 1902, the reductions were smaller but still meaningful, with distance flown reduced by 0.435%, fuel consumption by 0.249%, and ENV1 by 0.249%.

Focusing on flights entirely within ECAC and adjacent states, the results show even greater benefits. For AIRAC 1910, distance flown decreased by 1.384%, fuel consumption by 1.364%, and ENV1 by 1.364%. In the low traffic period of AIRAC 1902, the reductions were slightly lower but still significant: distance flown decreased by 1.009%, fuel consumption by 0.972%, and ENV1 by 0.970%.

These results confirm that the MRC model effectively reduces emissions and fuel use, particularly during high traffic periods and for flights fully within the ECAC region.

When extending the assessment to the ODC+MRC model for the high traffic AIRAC 1910, the reductions in environmental indicators are similar. For all flights involving ECAC and adjacent states, distance flown decreased by 0.696%, fuel consumption by 0.435%, and ENV1 by 0.435%. The effect is more pronounced for flights entirely within ECAC, where distance dropped by 1.457%, fuel by 1.440%, and ENV1 by 1.442%.

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Table 5 Summary of results (see Appendix B for details).

Scenario	AIRAC	KPI/PI	Value
Reference	1902	ENV1 [tonne/flight]	31689
Solution (MRC)	1902		31610
Reference	1910	ENV1 [tonne/flight]	30316
Solution (MRC)	1910		30191
Reference	1910	ENV1 [tonne/flight]	30316
Solution (ODC+MRC)	1910		30184

4.2.2.2 Full solution

The OBJ2 is evaluated for the Full Solution by reducing the total emissions, including non-CO_2 ones.

Exercise #01 showed mathematically that an increase of the EI rate always converts into gains in EI emissions. On top of that, the application of the model to the small scenario showed the magnitude of the savings that can be expected in terms of non-CO_2 emissions, for various EI rates, but also for the optimal EI rate, keeping all the other constraints in check (capacity violations and ANSP revenue). This exercise also showed the differences of magnitudes that can be expected from slightly different flavours of the full solution.

Exercise #02 showed the same kind of behaviour, with total emissions decreasing with the EI rate, and optimal solutions found at different states of the system (in terms of capacities), with decreased emissions overall (14% in a typical scenario).

Table 6 Summary of results (see Appendix B for details).

Scenario	KPI/PI	Value
Exercise #01	ATR20	Shows reduction.
Exercise #02		
Reference	FEFF1 [kg fuel/flight]	3496
Solution		3596
Reference	ATR20 [nK/flight]	9.9
Solution		8.6

4.2.3 OBJ3 results

4.2.3.1 Initial solution

Congestion was assessed by comparing the number of capacity violations between the reference and MRC scenarios. The results show a significant reduction in violations for both traffic periods. For the high traffic AIRAC 1910, violations decreased by 91.2%, while in the low traffic AIRAC 1902, the reduction reached 94.1%. This indicates a substantial improvement in network congestion.

The combined ODC+MRC model also delivers a substantial reduction in congestion. For the high traffic AIRAC 1910, capacity violations drop by 90.9% compared to the reference case closely matching the reduction achieved by MRC.

4.2.3.2 Full solution

For the full solution, the results show that the capacity violations do not always decrease with the application of the full solution. In general, capacity violations are solved by the full optimiser, but they are a part of the optimisation process in the same way as the environmental impact, which means that sometimes the optimiser favours one of the other.

Furthermore, in the course of the exercises, it emerged that for a more comprehensive analysis, better capacity data would be needed, and the higher traffic scenario, to be able to fully investigate the Full Solution impact.

4.3 Confidence in validation results

4.3.1 Limitations of validation results

Initial GRC Solution. The sample selected for the exercise #01 has been chosen to be small enough for easy monitoring and accurate calibration, yet representative of a typical real-world scenario, to ensure a robust assessment of the Solutions. However, two main limitations must be noted: firstly, the selection, while significant, only represents a sample of the real scenario, making the estimated impact an approximation of the actual impact. Secondly, the data available for these exercises is from 2019. Although the methodology as such is valid regardless of the input data, as it is not case-specific, the resulting impact may differ annually due to its strong correlation with the traffic patterns analysed.

Regarding the exercise #02, the sample used includes two full AIRAC periods—one representing high traffic and the other low traffic—chosen to be broadly representative. However, it still reflects only a limited portion of the year, covering just 8 out of 52 weeks. As a result, the modelling of system behaviour has inherent limitations. Furthermore, the estimated fuel and delay costs are key factors in the evaluation, and even minor changes in these estimates can lead to significant shifts in the results.

Full GRC Solution. Regarding exercise #01: The sample for this exercise was very small, as the intention behind the exercise was to test the feasibility of the model itself and the data integration. The behaviour of the model was tested as well. The results of this exercise are limited to feasibility and behaviour testing.

Regarding the exercise #02: The results significance is limited by the size of the Solution scenario applied – traffic between 10 busiest airports in Europe. The route charging mechanism is applied to

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the entire CRCO network, for all flights, not only for this selection, however significant it is. Furthermore, these are the assumptions used in the exercise that are somewhat limiting the representativeness of results:

- the information on the airspace capacity used is limited in scope, and should be extended for a fuller analysis,
- having only two routes per OD pair to choose from is also a limitation, which should be addressed in the future,
- the choice of the EI threshold needs to be discussed with a wider community and decided on the value/percentage that makes environmental and operational sense,
- the reduction of the route charges experimented is done through the optimisation, but it should also be tested with the ANSPs, CRCO and AUs, in terms of operational implementation.

4.3.1.1 Quality of validation results

Initial GRC Solution. The validation exercises conducted provided meaningful insights into on all models' performance, but the quality of these results must be assessed in light of methodological constraints and data limitations. Although the exercises were designed to ensure representative and robust evaluations, several factors might influence the accuracy and confidence in the outcomes. The validation relied on carefully selected but limited datasets Exercise #01 used a small yet representative sample to facilitate monitoring and calibration, but the results remain an approximation of real-world impact due to the partial coverage of actual operational scenarios. Additionally, the use of 2019 data introduces a temporal limitation—while the methodology itself is sound, traffic patterns and operational conditions may vary annually, affecting result generalizability.

For Exercise #02 instead, the analysis included two full AIRAC cycles (high and low traffic), and this certainly enhanced representativeness. However, these periods cover only 8 out of 52 weeks, meaning seasonal variations or atypical traffic conditions outside this timeframe are not captured. Consequently, while the model demonstrates consistent performance within the tested scenarios, extrapolating results to an entire year carries uncertainty. The validation outcomes are also particularly sensitive to fuel and delay cost estimates, which play a critical role in cost-benefit assessments. Adjustments in these parameters could lead to variations in the results, affecting conclusions on cost efficiency and environmental impact. This sensitivity underscores the need for continuous refinement of input assumptions to improve result reliability.

Despite these limitations, the structured approach to validation/testing across different traffic conditions and benchmarking against reference scenarios strengthens confidence in the model's consistency and accuracy. The observed reductions in CO_2 emissions, congestion, and operational costs align with theoretical expectations, reinforcing the validity of the solution rationale. However, the magnitude of these improvements should be interpreted as indicative rather than absolute, given the constraints of the validation scope.

Full GRC Solution. For exercise #01: As mentioned in previous section, the objective of the exercise was to test the feasibility and behaviour of the model, which was achieved. The quality of results is limited to this purpose.

For exercise #02: The results obtained in the exercise are valuable as they point to the potential benefits. The quality, however, is limited by the same factors described in the section 4.3.1.

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4.3.1.2 Significance of validation results

Initial GRC Solution. For the proposed solutions, the statistical significance of the results can be assessed mainly qualitatively since exhaustive data of high-volume traffic can be found only in the few years pre-covid and the in the recent post-covid periods. Still, several considerations can be made. Exercise #01 used a controlled, representative sample to ensure accurate calibration, but its limited scope means that statistical power is constrained. While the results demonstrate trends, the small sample size reduces the ability to generalize findings with high confidence.

Exercise #02 expanded validation to two full AIRAC cycles (high and low traffic), improving statistical reliability by covering a broader range of operational conditions. However, since only 8 out of 52 weeks were included, the results may not fully capture annual traffic variability. The consistency of improvements (e.g., reduced emissions, congestion, and costs) across different scenarios strengthens confidence in the model's effectiveness, but additional repetitions or larger datasets would further enhance statistical significance.

On the operational significance perspective a few considerations can be made to evaluate whether the validation exercises realistically reflect real-world conditions and constraints. The selected AIRAC cycles (high and low traffic) provide a reasonable approximation of different demand scenarios, but the absence of extreme or atypical conditions (e.g., disruptions, irregular operations) limits the assessment of model robustness under all possible operational environments. The reliance on 2019 data also introduces uncertainty, as traffic patterns, fuel costs, and airspace usage may have evolved since then. While the methodology remains valid, operational impacts could differ in current or future contexts. In fact, the model's performance is highly dependent on fuel cost and delay assumptions, which directly influence cost-benefit outcomes. Minor changes in these parameters could alter conclusions, suggesting that operational significance is contingent on accurate, up-to-date input data. Finally, the focus on ECAC and adjacent states ensures relevance for European air traffic management, but results may not fully translate to other regions with different traffic flows or regulatory conditions.

Full GRC Solution. For exercise #01: The results obtained in this exercise are not statistically significant, as the model and the novel charging mechanism were tested just for feasibility and behaviour.

For exercise #02: The highest significance can be given to analysing additional climate considerations. Due to the dynamical nature of the non-CO2 emissions, the project needed to clarify whether a concept based on the concept of a climate hotspot could be applied, and then what would be the impact on aviation emissions. The results demonstrate that the hotspot concept could be used in route charging scheme, as the environmental impact diminishes. However, these results should be further analysed to account for limitations mentioned above.

5 Conclusions and recommendations

5.1 Conclusions

The validation exercises for the GRC Solution, encompassing both Exercise #01 and Exercise #02, have demonstrated significant progress in assessing the economic and environmental impacts of performance-based en-route charging. The GRC Solution is being developed in two stages: the Initial Solution, addressing horizontal inefficiencies related to unit rates, and the Full Solution, aimed at encouraging climate-friendly trajectories by considering both CO_2 and non-CO_2 emissions.

The **Initial Solution**, comprising the MRC and ODC+MRC models, has now been thoroughly validated across multiple operational scenarios, confirming its feasibility and effectiveness in reducing horizontal inefficiencies while maintaining stakeholder requirements. Exercise #01, conducted on a representative small-scale instance of European air traffic, successfully verified the Initial Solution's compliance with key assumptions, including cost efficiency, capacity balancing, and revenue neutrality. The model achieved a 1.81% reduction in global distance flown, demonstrating its ability to incentivize shorter, more fuel-efficient routes. Exercise #02 expanded validation to two full AIRAC cycles (high and low traffic), reinforcing these findings with broader operational data. The MRC model consistently reduced CO_2 emissions (ENV1) by 0.249–1.364%, with the most pronounced improvements observed for flights entirely within ECAC airspace. Congestion was significantly alleviated, with capacity violations decreasing by 91.2–94.1% across both traffic periods. The ODC+MRC model exhibited similar performance, although only one AIRAC cycle (high traffic) was considered: 0.435-1.442% CO_2 emissions (ENV1) reduction, 90.9% congestion reduction.

While these results are promising, the validation scope has inherent limitations, including reliance on 2019 data and partial coverage of annual traffic variability. The sensitivity of outcomes to fuel cost assumptions and the absence of extreme operational conditions underscore the need for continued refinement and expanded testing. Nevertheless, the consistent performance across different scenarios strengthens confidence in the model's operational applicability. These validation exercises marked a critical milestone in implementing performance-based charging mechanisms aligned with the Digital European Sky framework, demonstrating tangible benefits in environmental efficiency, congestion reduction, and cost-effectiveness for European air traffic management.

Full GRC Solution. This solution adds full climate considerations. Due to the complexity of non-CO_2 emissions, the project first assessed whether a climate hotspot-based approach was viable, requiring a simplified new model. Initial exercise results show that: airlines can be incentivized to choose environmentally friendly routes by avoiding hotspots; flight level changes could greatly improve effectiveness of the solution on environmental impact; and airspace congestion reduces the mechanism's efficiency. Exercise #02 tested the mechanism on a larger sample, where it was demonstrated that most of KPIs were slightly or neutrally affected, except the PI on full emissions, which shows 14% reduction of full emissions impact (measured by ATR20). The inclusion of CO_2 emissions in the total impact led to less marked changes in fuel consumption, and thus impacts airlines much less in terms of cost. Detailed conclusions can be found in the following subsections.

5.1.1 Conclusions on project/ SESAR solution maturity

As an outcome of the project, all mechanisms under development marked a significant step in maturity level. For the Full solution, starting from TRL 0, the level reached is TRL 1. The Initial Solution started at TRL 1 and reached TRL 2 (see self-maturity assessment in D5.6 ECO-EVAL) [AD31].

5.1.2 Conclusions on concept clarification

The validation exercises have successfully clarified the operational concept and demonstrated the feasibility of the GRC Solution within the SESAR framework. The two-stage development approach (Initial Solution addressing horizontal inefficiencies and Full Solution incorporating climate-friendly trajectory optimization) has proven conceptually sound through rigorous testing.

The **Initial Solution**'s core concept - modulating route charges to incentivise optimal routing while maintaining revenue neutrality - has been experimentally validated. The model successfully demonstrated its ability to maintain compliance with stakeholder requirements and operational constraints, and it achieved measurable performance improvements across many key metrics measured. The results show that the solution is capable of balancing multiple objectives including efficiency, capacity and environmental benefits.

Exercise #02, in particular, confirmed consistent performance across different traffic conditions, which demonstrated the ability to maintain system stability while achieving performance gains.

The **Full GRC Solution** concept builds logically on these validated principles by incorporating additional climate considerations. Due to the dynamical nature of the non-CO_2 emissions, the project needed to clarify whether a concept based on climate hotspots would be applicable. This required another type of model completely, which had to be heavily simplified due to the complexity of the task (setting the appropriate EI rate). The first exercise showed that:

- Airlines could be incentivised to choose a more environmentally friendly trajectory, thanks to a solution based on hotspot determination,
- Automatic flight level changes to avoid hotspots could greatly enhance the efficiency of the solution,
- A solution based on a full emissions scheme (paying for all emissions along the entire trajectory instead of only hotspot-based) may not be much more efficient when compared to the hotspot avoidance integrated with the flight level changes, in this small experiment,
- Congestion (i.e. lack of airspace capacity) decreases the efficiency of the mechanism.

The second exercise further clarified the following:

- Most KPIs are slightly or neutrally impacted by the full solution, except for a PI on full emissions,
- The inclusion of CO_2 emissions in the total impact leads to less significant changes of fuel consumption, and thus impacts airlines much less in terms of costs.

Note that the Full Solution calculates the modulation of charges strategically. However, the foreseen location of hotspots can only be known 6-12 hours prior to the planned flight, so the exact route

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charges (decreased in case of avoidance, or increased in case of hotspot crossing) would not be known sooner. This implies a change in the way of planning flights, which should be doable as the airlines are already taking into account the weather forecast (i.e. winds) in their flight planning.

The solution has demonstrated strong alignment with Digital European Sky performance objectives while maintaining operational practicality. The validation results provide sufficient confidence in the fundamental concept to proceed with further research, while highlighting specific areas needing additional clarification before full implementation.

5.1.3 Conclusions on technical aspects

The GRC Solution proposes new route charging mechanisms. As such, these are not ATM Solutions per se, as no ATM system would be impacted. However, throughout the duration of the project, several aspects of the concept were clarified and the following new functions needed, were identified:

- A central planner that would determine the environmental modulation (in both Initial and Full Solution), and hotspots in the case of Full Solution, and then communicate the information to the airlines,
- MET provision of forecast for hotspot determination. Forecasts are already being provided in aviation. However, the required forecast might need some specific additional requirements that should be further investigated.
- Flight planning software being able to take new information (e.g. EI rate) to properly optimise trajectories.

5.1.4 Conclusions on performance assessments

Initial GRC Solution. The validation exercises for the GRC Solution have demonstrated measurable performance improvements across key performance areas (KPAs), supporting its potential to enhance European air traffic management. In **capacity**, the MRC and ODC+MRC models achieved substantial congestion reduction, decreasing capacity violations by 91.2–94.1% across both high and low traffic periods. This confirms the models' effectiveness in balancing demand with available resources through optimized routing and charge modulation. For **efficiency**, the results showed consistent improvements in both fuel consumption and flight distance. The MRC model reduced global distance flown by 1.81% in Exercise #01, while Exercise #02 demonstrated fuel savings of 0.249–1.361% depending on traffic conditions. Flights operating entirely within ECAC airspace saw the greatest efficiency gains, validating the model's ability to incentivize optimal trajectories. **Predictability** improvements were indirectly observed through the reduction in capacity violations, suggesting more stable traffic flows. However, further validation is needed to assess the models' impact on schedule adherence and delay propagation. The validation did not identify any negative impacts on **safety** or **security**, as the solutions operate within existing operational and regulatory frameworks. However, these aspects will require continuous monitoring during implementation. From a **cost-efficiency** perspective, the models maintained revenue neutrality for ANSPs while reducing overall airline costs through fuel savings. Route charge modulation remained within ±10% tolerances, ensuring financial stability for service providers.

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Full GRC Solution. The exercises demonstrated the initial feasibility of the route charging mechanism that takes into account all emissions. Regarding **capacity**, the Full Solution shows that traffic flows move, but the capacity with the Full Solution could become slightly more saturated. Furthermore, an important finding is that when there is a lack of capacity, it is much less possible to reduce the environmental impact of flights, as there is no space for manoeuvre left. For **efficiency**, FEFF1 and TEFF1 are slightly higher (less than 1%) in the solution scenario than in the reference one (see Figure 17 for details), which is a normal consequence of minimising emissions instead of fuel. The **environmental impac**t for all emissions, as measured by ATR20, is 14% lower in the solution scenario. The incentivisation to minimise the environmental impacts, slightly increases the costs **(cost-efficiency KPA)** to airlines (AUC3), less than 1%. This is due to higher fuel consumption, and EI modulation rate. The ANSP revenues are held constant, which is aligned with only slight increase in capacity saturation. Other KPAs are not impacted by this solution.

5.1.5 Stakeholder feedback

The detailed stakeholder feedback can be found in the Appendix of D5.6 – ECO-EVAL – Green route charging [AD31]. Below is the summary of the feedback received.

The main requirement from the CRCO and ANSP representatives was to propose a system that would be as simple as possible, with the view that any implementation would require a relatively simple system. For example, the current route charging formula is very simple, even if the process behind the calculation of traffic, service unit and cost forecast is much less so. The GRC Solutions would require a slight adjustment of the formula to include modulations for routes, but could essentially stay the same (Initial Solution, cf. the Full Solution would be more complex for implementation). The determination of the modulation factors would require a set up of a new function, and the verification system would also need adjustments.

The IATA representatives participated in the design of the survey that was a part of the work in the development of the Full GRC Solution, and in the workshops. The gist of the IATA provided feedback is the strong opposition to any environmental route charging modulation. For example, regarding the Initial Solution and the levers it employs (CO_2 and congestion minimisation): "Such scenario is biased to focus on changing the customers' behavior without considering behaviors on the providers' side. The economic regulation on monopolistic business should not be turned against the customers, potentially increasing the monopolies' rewards for inefficiencies." Further criticism revolved around the perceived immaturity of science behind the prediction and monitoring of non-CO_2 emissions. Due to that, the non-CO_2 emissions should not be a subject of research on route charge environmental modulation, it was stated.

Even if the IATA position shows strong opposition to the idea of environmental route charge modulation, several of their observations are found to be aligned with the GRC team's description of limitations and the need for further investigation and refinement. For example: the data sample should be more diverse (e.g., more AIRAC cycles, extreme traffic conditions), and to incorporate recent operational data and up-to-date/new aircraft fuel consumption performance data; improve capacity input data and test its impact on the traffic re-distribution and environmental impact values. The assessment of equity for different AUs and ANSPs should be performed to ensure proper cost-benefit analyses. The forecast uncertainties on the proposed mechanisms should be assessed and how those impact the Solution.

5.2 Recommendations

5.2.1 Recommendations for next R&I phase

The validation results demonstrate promising trends in environmental efficiency, congestion reduction, and cost savings, supported by consistent performance across different traffic scenarios. However, the limited sample size and reliance on historical data temper the statistical certainty, while operational realism is constrained by the absence of edge cases, and potential shifts in aviation dynamics since 2019.

When comparing the two models, MRC and ODC+MRC, it is observed that they produce similar results. From these preliminary experiments, limited to the high-traffic scenario, ODC+MRC yields a slightly greater reduction in flown distance, and consequently in fuel consumption and the ENV1 indicator, compared to MRC. However, MRC achieves a slightly higher reduction in the number of capacity violations. Overall, the differences between the two models are minimal.

MRC is, however, simpler to implement and more closely aligned with the current charging mechanism. ODC+MRC requires an additional step, applying the modulation (MRC) only after first calculating the distance factor based on the great-circle distance between origin and destination airports (ODC). More importantly, it departs from the current mechanism in the way route charges are calculated, as they would no longer reflect the number of service units flown within the ANSP's controlled airspace. This would also affect the mechanism for revenue redistribution among states. For these reasons, the use of the MRC mechanism is recommended for future applications.

To strengthen the concept and the significance of results, future validations should:

- Increase sample diversity (e.g., more AIRAC cycles, extreme traffic conditions).
- Incorporate recent operational data to reflect current aviation trends.
- Incorporate up-to-date/new aircraft fuel consumption performance data.
- Conduct sensitivity testing on critical assumptions to assess their influence on model outcomes.
- Include the assessment of equity for different AUs and ANSPs.
- Assess the impact of forecast uncertainties on the proposed mechanisms (see next section for detailed discussion).
- Perform targeted Monte-Carlo simulations with the full solution and/or develop new analytical methods to deal with the dimensionality of problem (many routes, many airlines).
- Requirements analysis (from technical and operational points of view) for the three identified new functions: central planner, MET provision of non-CO_2 forecast and inclusion in flight planning software.

The forecasting for climate impact determination still needs research in terms of uncertainties and setting of the appropriate threshold for minimisation of aviation climate impact. This would need discussions between atmospheric scientists and operational stakeholders (AUs and ANSPs) to understand the climate impact and what can be done operationally to diminish it. Furthermore, given the necessity for transparency in charges, it is crucial that all stakeholders utilise the same information, which would require the establishment of new functions to source, compute, and disseminate this information among all stakeholders (see bullet points above).

5.2.2 Recommendations for future R&I activities

The validation exercises have identified several promising research avenues that warrant further investigation in future SESAR or other R&I programs.

First of all, to consider expanded operational scenarios. Future validation should include more diverse traffic conditions (e.g., extreme weather, major disruptions) to assess robustness under atypical operational environments.

A second relevant objective for future R&I activities is to develop a single mechanism that integrates both CO_2 and non-CO_2 emissions. In the meantime, it is advisable to maintain two parallel models—one considering CO_2 only and one including both CO_2 and non-CO_2 effects—in order to ensure more credible and robust assessments. The modulation could also be tailored to specific aircraft type or engines, if we assume that a central entity will set and communicate these modulations in advance. The modulations in question may be extremely hard to compute, and further research effort in needed. In addition, dynamic pricing could also be the scope of further studies, to investigate the impact of varying charge modulation strategies at the tactical level. This last issue might need the deployment of machine learning enhancements, since AI-driven optimizations might improve real-time decision-making for route and charge adjustments.

Uncertainty is also a big issue, especially for the non-CO_2 emissions. The accuracy of the models, the dynamicity of the atmosphere, and the heterogeneity of the aircraft and engines flying in Europe imply that any mechanism based on these considerations has to make extra effort to determine the acceptable level of uncertainty. A significant research effort in this area, first to reduce the uncertainty and then to manage it more rationally, is needed.

New aircraft types should be included in further research regarding the environmental modulation of route charges, from both emissions (none, or very much reduced) and congestion point of view (which portions of airspace are these more likely to occupy).

5.2.3 Further recommendations

The experience with the execution of the present research activity leads us to recommend that the duration of the validation activities, i.e. the technical phase of the Exploratory Research, should be extended to at least 24 months net (i.e. until the first delivery of the last technical Deliverable to the SJU). The level of modelling that is necessary to guarantee significant results, plus possibly time-consuming execution of simulations cannot be fully parallelised. The time for evaluating the results, including relation to other activities, is perceived as too short, especially in view of the considerable insights this could bring at small additional cost.

6 References

6.1 Applicable documents

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

SESAR solution pack

[AD1] SESAR DES Solution Definitions Green-GEAR V1.0, 3rd June 2024.

[AD2] SESAR Operation Concept Document OCD 2023, 02.00.00, 14th July 2023.

[AD3] SESAR DES & DSD Solutions slides 2023 (1_0).pptx

Content integration

[AD4] Content Integration – Executive Overview, Edition 00.01, 16th February 2023.

[AD5] DES Common Assumptions, Edition 00.02.01, 29th June 2023.

[AD6] DES Performance Framework, Edition 00.01.04, 29th June 2023.

[AD7] DES Performance Framework – U-space Companion Document, Edition 00.01.02, 3rd April 2023.

Content development

[AD8] SESAR 3 Joint Undertaking – Communication Guidelines 2022-2027, Edition 0.03, 23rd November 2022.

System and service development

Performance management

[AD9] Performance Assessment and Gap Analysis Report (PAGAR) 2019 – updated version, Edition 00.01.00, 20th May 2021.

[AD10] SESAR Solution Cost Benefit Analysis (CBA) Quick Start Guide (1_0).docx

[AD11] SESAR ECO-EVAL Quick Start Guide (1_0).docx

[AD12] Performance Assessment and Gap Analysis Report (2019), Edition 00.01.02, 13th December 2019.

Validation

[AD13] DES HE requirements and validation /demonstration guidelines, Edition 3.00, 15th September 2023.

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[AD14] DES SESAR Maturity Criteria and sub-Criteria_01_01 (1_1).xls

System engineering

Safety

[AD15] DES expanded safety reference material (E-SRM), Edition 1.2, 17th November 2023.

[AD16] Guideline to Applying the Extended Safety Reference Material (E-SRM), Edition 1.1, 17th November 2023.

Human performance

[AD17] SESAR DES Human Performance Assessment Process TRL0-TRL8, Edition 00.03.01, November 2022.

Environment assessment

[AD18] SESAR Environment Assessment Process, Edition 05.00.00, 23rd July 2024.

Security

Programme management

[AD19] Green-GEAR Grant Agreement No. 101114789, version 1, signed 11th May 2023.

[AD20] SESAR 3 JU Project Handbook – Programme Execution Framework, Ed. 01.00, 11th April 2022.

[AD21] Common Taxonomy Description (1_0).pdf, Edition 1.0, 7th February 2023.

[AD22] Horizon Europe ethics guidelines – essentials_1 (1_0).pptx

[AD23] Project Reviews 2024_guidance for IR1 & ER1 (1_0).pptx

[AD24] SESAR 2 Joint Undertaking Project Handbook – Programme Execution Framework, 01.00, 11th April 2022.

Project documents

[AD25] «SESAR 3 ER 1 Green-GEAR – D5.1 – Initial OSED – Green Route Charging», ed. 01.00, 29th June 2024.

[AD26] «SESAR 3 ER 1 Green-GEAR – D5.2 – ERP – Green Route Charging», ed. 01.00, 22nd November 2024.

[AD27] «SESAR 3 ER 1 Green-GEAR – D2.2 – Updated data management plan», ed. 02.00, 30th August 2024.

[AD28] «SESAR 3 ER 1 Green-GEAR – D5.3 – Intermediate ERR – Green Route Charging», Ed 01.00, 12th February 2025.

[AD29] «SESAR 3 ER 1 Green-GEAR – D5.4 – Final OSED – Green Route Charging», Ed 01.00, submitted 30th June 2025.

[AD30] «SESAR 3 ER 1 Green-GEAR – D5.5 – FRD – Green Route Charging», Ed 01.00, submitted 30th June 2025.

[AD31] «SESAR 3 ER 1 Green-GEAR – D5.6 – ECO-EVAL – Green Route Charging, Ed 01.00, 9th July 2025.

6.2 Reference documents

[1] E. Commission, «Communication on The European Green Deal,» (europa.eu), 2019.

[2] «SATURN. Strategic Allocation of Traffic Using Redistribution in the Network,» [Online]. Available: https://wikiengagektn.com/E.02.33_Strategic_Allocation_of_Traffic_Using_Redistribution_in_the_Network.

[3] «ADAPT. Advanced prediction models for flexible trajectory-based operations,» [Online]. Available: https://cordis.europa.eu/project/id/783264.

[4] «Pilot3. A software engine for multi-criteria decision support in flight management,» [Online]. Available: https://cordis.europa.eu/project/id/863802.

[5] «COCTA, Coordinated capacity ordering and trajectory pricing for better-performing ATM,» [Online]. Available: https://cordis.europa.eu/project/id/699326.

[6] «ClimOP. Climate assessment of innovative mitigation strategies toward operational improvements in aviation,» [Online]. Available: https://cordis.europa.eu/project/id/875503.

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[10] «CONCERTO. dynamicC cOllaboration to geNeralize eCo-friEndly tRajecTOries,» [Online]. Available: https://cordis.europa.eu/project/id/101114785.

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Appendix A Validation exercise #01 report

A.1 Summary of the validation exercise #01 plan

As in SESAR Solution #0408 ERP (D5.2 - ERP - Green RC) [AD26].

A.1.1 Validation exercise description and scope

Exercise #01 covers the modelling and the feasibility of the Green RC Solution, which has two steps of implementation corresponding to different levels of ambition and complexity: Initial and Full. The former is designed to reduce CO_2 emissions and congestion, the latter extends this objective, aiming to mitigate the non-CO_2 effects as well.

Initial Solution consists of two models:

- Modulation of Route Charges (MRC)
- Origin Destination Charging with Modulation of Route Charges (ODC+MRC)

Full Solution also includes the stated-preference survey.

Once conceptualised, the models will be validated, testing for the feasibility and the compliance to the assumptions described.

For the Initial Solution, the main **modelling assumptions** made in our framework are:

A1. Given a set of routes with the same origin-destination, the shortest is the one with the lowest CO_2 environmental impact.

A2. Given a set of routes with the same origin-destination, each flight operates the one with the lowest cost.

A3. In case of predicted capacity imbalance at the strategic level, the central planner (CP) can propose a time shift to some flights and/or modulate the route charges on a route base in order to minimise the violation of the capacity constraints.

A4. The modulation of route charges must be compliant with the revenue neutrality principle, i.e. each ANSP receives the same income for the same amount of workload (measured in service units), within a predefined tolerance. If on the one hand with this approach the price of the service is preserved, it does not guarantee that the total revenue remains the same, as the Solution might significantly reduce or increase the amount of traffic served by the same ANSP.

For the Full Solution, the ERA5 reanalysis will be used to determine the “forecasted” climate hotspot areas that will influence the route charging scheme.

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

This validation exercise aims at making an initial preliminary test on the functionality of the models, and particularly its feasibility, which in this context means that the solutions provided are compliant with the modelling assumptions.

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Table 7 Validation objectives addressed in validation exercise #01.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
Feasibility	The solution respects all stakeholders' requirements	Fully covered	Check whether the models and the relative solutions are compliant with the stakeholders' requirements, implemented as models' constraints.	Each model assumption (Section A.1.1) has to be fully satisfied. The utility functions and climate hotspots should be obtained and included in the optimisation model. The revenue neutrality principle is respected with a tolerance of ±10%.

A.1.3 Summary of validation exercise #01 validation scenarios

The feasibility of the GRC, both for the Initial and the Full Solutions, will be tested on a set of small instances (about one thousand flights) of real European air traffic data from 2019. Such a choice allows to monitor, potentially calibrate and finally validate the models in order to guarantee their feasibility. In fact, the detailed examination of how the models respond to various air traffic scenarios, helps to identify any potential issues or unexpected behaviours early in the testing phase.

A.1.3.1. Initial GRC Solution

For the validation of the exercise, the reference scenario is simply represented by the FTFM traffic of the selected small samples that is taken from the 20th September 2019 and counts 995 flights involving 563 origin-destination pairs. The flow emerging from data, provides the starting point for calculating the initial benchmark in terms of environmental impact, congestion, delays, and operational costs. We remark that, if on the one hand the congestion level and the delays are directly extracted from the data, on the other hand the environmental effects and operational costs are estimated, since no data are available for these quantities.

The feasibility of the solution is evaluated on the solution scenario, which is represented by the simulated traffic resulting from the implementation of the computed new route charges, on the same samples with respect to the ones of the reference scenarios.

A.1.3.2. Full GRC Solution

For this exercise, the Full Solution is using a small example for the validation scenario, testing the model on only two OD pairs. There are three scenarios applied, as described in Table 8 below.

Table 8 Full Solution exercise #01 scenarios.

Scenario	Description
Benchmark scenario – 'free'	Idealised scenario where airspace capacities are infinite and airlines do not have constraints on their routes, apart from their utilities
Reference scenario – 'cap'	This is an optimised scenario where capacity constraints are enforced through strategic delays, applied on the sectors. This is the closest scenario to the present situation.
Solution scenario – 'full'	This is an optimised scenario where a central planner tries to minimise the environmental impact while capacity constraints are enforced. This represents the closest situation to what the system with the full solution would look like. In this situation, the central planner can play with the EI rate, a multiplicator factor to decrease the revenue of the CRCO charges (to keep revenue neutrality), and delays applied to sectors.

All three scenarios are run on the same dataset, but with different constraints and setting being applied, as requested by the scenario. The data types used are listed below. The detailed explanation of data preparation can be found in section A.3.2.2.4

- Typical trajectories for each OD (obtained via clustering),
- Airspace structure (simplified, we considered only a horizontal slice of sectors),
- Average values for fuel consumption,
- Values of route charges,
- Distributions of EI on each OD pair,
- Distribution of external delays, fitted for each OD,
- Behavioural parameters for airlines (obtained from the survey).

A.1.4 Summary of validation exercise #01 validation assumptions

We remark that the validation exercise #1 is run on a small sample of the whole data set at disposal.

A.1.4.1. Full GRC Solution assumptions for exercise #01

Table 9 lists assumptions used in the exercise #01 for the Full Solution. These are further explained in section A.3.2.2.1.

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Table 9 Full GRC Solution assumptions for exercise #01.

Description
EI distributions are independent on each route
Delay distributions (without ATFM) are the same on both route on a given OD
Each OD pair has only two routes available
Airlines choose route based on a linear deterministic utility function
Fuel consumption and emissions are estimated using a typical engine
Emission estimates are accurate enough to define the hotspots
Delays experienced by flights are exponentially distributed
Behaviour of airlines is bundled in two categories

A.2 Deviation from the planned activities

There are no deviations from the planned activities.

A.3 Validation exercise #01 results

A.3.1 Summary of validation exercise #01 results

Table 10 Validation exercise #01 results.

Exercise #01 validation objective ID	Exercise #01 validation objective title	Exercise #01 success criterion ID	Exercise #01 success criterion	Sub-operating environ-ment	Exercise #01 validation results	Exercise #01 validation objective status
OBJ1	Feasibility	Exercise #01 success criterion #1.1	Each model assumption (Section A.1.1) has to be fully satisfied. The utility functions and climate hotspots should be obtained and included in the optimisation model.			Partially OK

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A.3.2 Analysis of validation exercise #01 results

In the following sections the results of each part of the validation exercise #01 are presented:

- Section A.3.2.1 details Initial GRC Solution results, for both MRC and ODC+MRC
- Section A.3.2.2 details Full Solution results.

A.3.2.1. Initial Solution

A.3.2.1.1. Modulation of route charges

The modulation of route charges (MRC) mechanism aims to reduce the environmental impact of flying, while addressing the congestion. The modulation is expressed as a factor, defined per route, that reduces or increases the total route charge of that specific route. The goal is to reduce CO_2 emissions, for which the global distance flown is taken as a proxy, while trying not to exceed the declared capacity of airports and sectors.

MRC has been software-implemented using Python programming language and Gurobi Optimizer[4] as solver. The feasibility of MRC has been tested on a set of small instances (995 flights) of real European air traffic data from 20th September 2019. 563 origin-destination (OD) pairs were considered.

This small set of data has been used to run the MRC implementation, the results of which are presented later in this section.

First of all, the results show that the modelling and the implementation of MRC are compliant with the stakeholders' requirements, implemented as models' constraints, and the modelling assumptions described in section A.1.1 related to the Initial Solution (A1 to A4) have been properly captured in the model.

Regarding the satisfaction of the modelling assumption, hereafter a detailed evaluation is presented.

A1. Given a set of routes with the same origin-destination, the shortest is the one with the lowest CO_2 environmental impact.

The first term of the MRC objective function (presented in section 5.1.1.1.1 of D5.2 ERP [AD26]) takes into account the global distance flown (i.e., the sum of distances flown for all the flights of the network operating on the day considered), therefore, since the global distance flown is taken as a proxy for the CO_2 emissions, choosing the shortest route over a set of possibilities, for a specific flight, makes this choice the one with the lowest CO_2 impact.

In particular, the reference scenario for this execution had a global distance flown of 1,700.3 thousand of kilometres, while the result of the optimisation shown a global distance flown of 1,669.6 thousand of kilometres, resulting in a decrease of 1.81%.

[4] Gurobi Optimizer, Gurobi Optimization, LLC. https://www.gurobi.com

Regarding the Operational Efficiency (OPS) KPA, the KPI FEFF1.1 (total amount of planned fuel burnt divided by the number of flights [kg fuel/flight]) for the reference scenario was 7393.9, while for the solution scenario was 7275.6, resulting in a reduction of 1.60%.

Regarding the Environment (ENV) KPA, the KPI ENV1 (amount of fuel burnt x 3.15 (CO2 emission index) divided by the number of flights [kg CO2/flight]) for the reference scenario was 23290.8, while for the solution scenario was 22918.1, resulting again in a reduction of 1.60%.

A2. Given a set of routes with the same origin-destination, each flight operates the one with the lowest cost.

Airlines operating flights at minimum cost is a policy enforced in the optimisation model using several constraints (presented in section 5.1.1.1.1 of D5.2 ERP [AD26]), which guarantee that the minimum cost route and time shift is chosen over each possible combination of them.

A3. In case of predicted capacity imbalances at the strategic level, the central planner (CP) may propose a time shift to some flights and/or modulate the route charges on a route base minimise the violation of the capacity constraints.

The second term of the MRC objective function (presented in section 5.1.1.1.1 of D5.2 ERP [AD26]) considers the violation of declared capacity of airports and sectors and has the highest priority over the two terms. The modulation factor for each route of each origin-destination pair and the time shift of each flight taken into account are decision variables of the model.

In this execution the minimum and maximum value of each modulation factor was set to 0.8 and 1.2, respectively. The possible values for the time shift were [-15, 0, 15] minutes.

The resulting modulation factor was, on average, 0.945 on chosen routes and 0.983 on all possible routes. This means that, on average, route charges of chosen routes have been reduced by 5.5% and route charges of all possible routes have been decreased by 1.7%.

Regarding KPA CAP, it has been considered the KPI CAP2: the total number (and percentage) of movements per volume of En-Route airspace per hour for specific traffic mix and density (Very High, High and Medium Complexity) at peak demand hours. In particular, the number of capacity violations has been monitored as a successful criterion. The model perfectly addressed the task of avoiding congestion as its solution presented no violation of capacity constraints.

A4. The modulation of route charges must be compliant with the revenue neutrality principle, i.e. each ANSP receives the same income for the same amount of workload (measured in service units), within a predefined tolerance. If on the one hand with this approach the price of the service is preserved, it does not guarantee that the total revenue remains the same, as the solution might significantly reduce or increase the amount of traffic served by the same ANSP.

Initially, the revenue neutrality principle was designed as a hard constraint, i.e. each ANSP had to receive the exact same income for the same amount of workload (measured in service units). Later, it was decided to relax this constraint, permitting to have a predefined tolerance with respect to that condition. The motivation of this relaxation is due to gain a greater flexibility of the model, without which the possibility of having a different schedule of the traffic, compared to the reference scenario, was extremely low. In the execution of the MRC, it was permitted to have a ±10% tolerance with respect to the price of the service.

A.3.2.1.2. Origin destination charging with modulation of route charges

The origin destination charging with modulation of route charges (ODC+MRC) mechanism is an adaptation of the MRC. The underlying charging mechanism is changed from charging on actual route to origin destination charging.

For the validation of ODC+MRC, see section B.3.2.2.

A.3.2.2. Full Solution

The sections below describe the details of the SP survey, climate hotspot analysis and the Full GRC Solution modelling and results for validation exercise #01. The SP survey results are used in the validation exercise #02 as well.

A.3.2.2.1. Modelling and simulations

The SP survey and the climate hotspots analysis come together in the model that is tasked to implement the Full GRC Solution. The way airlines behave when hotspots appear will drive the efficiency of the policy that could lead to a reduction of CO_2 and non-CO_2 emissions.

The general scientific problem we face here is to forecast the impact of a change of policy, i.e. route charges, when flights are crossing climate hotspots, on the airlines' behaviour when planning/choosing trajectories and their related climate impact. This is crucial to be able to find a policy that may, in fine, lead to a reduction of climate impact.

Such forecast is not easy to form, since 1) traffic patterns can change for various reasons[5] and 2) airlines have intricate and heterogenous decision-making processes that may lead to counter-intuitive results. For Full GRC Solution, we focus on the second issue, leaving the exact traffic forecast to entities with better forecasting capabilities, like STATFOR. Here, we assume that airlines minimise a utility function when choosing their flight plans pre-tactically. This utility function is composed of the parameters shown in section A.3.2.2.3, which can be sorted out in two big categories, delay and cost, with added category for the environmental impact.

Hence, the core policy idea is to identify climate hotspots, either strategically or tactically and put a modulated charge on top of the standard route charges on the trajectories going through hotspots, to de-incentivise their choice. The extra revenues coming from the modulation may then be offset by a decrease of the route charges at a strategic level to ensure revenue neutrality for ANSPs.

[5] The reasons can be strategic, but are mostly tactical/operational, as the trajectory planning takes place about 3 hours before the flight and tends to take the state of the network into account.

Given a modulation scheme and an offset mechanism the task is then to forecast how much airlines will avoid the hotspots, keeping in mind constraints linked to capacity. This can be done via two methods:

- An analytical and semi-analytical model: the mathematical expectations of EI and other metrics are computed explicitly, taking into account the utility functions and the stochasticity of the environment (for instance, the appearance of hotspots). These models are typically very fast to execute, but may struggle to take into account all constraints/behaviours happening in the system. Moreover, the implementation effort may scale badly with the number of routes and different types of airlines.
- A bi-level optimisation model, used within a Monte-Carlo scheme to estimate the expectation from the policy implementation. This type of model can be slow to execute but is able to capture many details that analytical models sometimes cannot. The implementation effort is also fairly low in this case, and does not depend on the number of OD pairs simulated.

The full GRC is interested in setting strategically modulation levels that will be applied tactically, akin to how ANSPs compute their unit rates for the next reference period. Hence, the level of details at the tactical level may be enough in the analytical model to capture most of the impact that we want to see from the mechanism. This the method we are using in both exercises.

A.3.2.2.2. Model scope

Goal

The model presented here is a simple one designed to show the main trends that can be expected when applying the Full Solution. As a reminder, the full solution consists in the following process:

- At the start of a reference period (e.g. every 5 years, or every year), the Central planner decides the ‘environmental impact tax rate’ (EI rate).
- X hours before a flight plan (e.g. 6 hours, typically on the same time scale than weather forecast), the Central planner defines environmental “hotspots”, in the form of 3D volumes.
- Any flight going through a hotspot has to pay an extra charge in the form of the distance flown through the hotspot times the EI rate.

The model presented here aims at answering the following questions:

- Given a traffic forecast at the beginning of the reference period and an EI rate, what is the expected impact of the EI rate on the behaviour of airlines, without considering capacity issues, and what is the resulting impact on the KPIs? (see Table 11). This prediction is called the ‘free’ prediction in the following, because it does not take into account capacity optimisation of EI impact.
- Similarly, what is the impact of the EI rate given capacity constraints? This prediction in the following is called the ‘capp’ prediction. It takes into account various capacity constraints.
- Finally, how much should the EI rate be to minimise the environmental impact? What is the impact of this rate? This prediction in the following is called ‘full’.

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KPIs

The impact of the EI rate has to be measured in several different dimensions. Given the scope of the model, we selected the performance indicators (PIs) in Table 11 as the metrics computable with this class of model and interesting from the system point of view.

Table 11 KPIs description.

Performance indicator	Full description
Environmental impact (EI)	EI estimated using the CLIMaCCF library. It represents the total impact of the emissions of all the flights in the model, measured in nK of increase of the Earth temperature at the 20-year horizon.
ANSP revenues	ANSP revenues are estimated in € 2019. There are composed of two components: the standard route charges from the flights, and the surplus given back by the Central planner via the EI rate collection.
Airline costs	Airline costs are estimated based on fuel consumption, standard route charges, the extra EI rate. Note that the airline costs are distinct from their disutility, see model description.
Fuel consumption	Fuel consumption enters the estimation of EI and airline costs, but we also estimate it independently.
Delays	Measured in minutes, we measure the average minute of delays expected due to capacity limitations. This estimation is very crude due to the level of approximate at which the analytical model operates.

Scope

Ideally, the model should capture the entire ECAC area, to capture all the possible options of the airlines when it comes to avoiding hotspots. Due to the novel approach of the model, it was however decided to start with simple cases and go to more complex ones gradually. In the end, the 'validation scenarios' considered for this deliverable are the following.

Table 12 Overview of validation scenarios used in model evaluation.

Validation Scenarios	Description	Comments
Small scenario	Two OD pairs (Istanbul-Gatwick & Madrid-Stockholm)	To analyse the trends in the model.

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A.3.2.2.3. Model description

The model does not rely on simulations, but rather on the estimation of mathematical expectations for various KPIs described above. Technically, these expectations can be expressed as integrals and sums.

High-level description

The model works in the following way:

- Time slices of one hour are defined throughout the day.
- Each sector has a fixed capacity. Loads are computed based on entry count within each time slice.
- A strategic delay can be applied to one sector.
- For a given route, all flights are submitted to the highest strategic delay across all sectors in the routes (akin to the most penalising ATFM regulation).
- This delay then modifies the distribution of delay of flights on this route, by shifting its mean.
- For each OD, for each time slice, an analytical expression can be obtained to predict the load on each route and the corresponding environmental impact, taking into account a utility maximisation from the airlines to choose the best route. This analytical expression also includes the amount of flights that are 'pushed-over' beyond the time slice due to lack of capacity.
- Subsequent time slices take into account 'pushed-over' flights from previous time slices. Flights pushed over the last time slice are considered cancelled, and disappear from the statistics.

Note that this model is **not stochastic**. Each run of the model will give the same result if the same scenario is run, because it computes **already averaged metrics** using underlying distributions.

Assumptions

The main assumptions used to form the mathematical expressions are presented in Table 13.

Table 13 Main modelling assumptions and their implications.

Description	Why?	Could be relaxed?
Each OD pair has only two routes available	Number of terms grows exponentially with number of routes available. Analytical computations are required in each case	Near impossible to relax with capacity constraints on top. But expression exists for infinite capacity case, so perturbative

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Description	Why?	Could be relaxed?
		approximations[6] may be computed
Airlines choose route based on a linear deterministic utility function	To capture the sensitivity of airlines to delay and costs independently. We use deterministic utility function to simplify the integrals	Linearity could be relaxed via more complex analytical expression. Deterministic aspect could also be relaxed using numerical methods for the integral estimation
Fuel consumption and emissions are estimated using a typical aircraft engine	The CLIMaCCF library offers calculation for three generic types of engine. We decided to use 'single aisle' estimation only, for simplicity, at this TRL level, and for checking the feasibility of the solution.	Hard to relax with the current modelling approach. Different fuel consumptions and emissions for the same trajectory require in general an added integration for each expression, which is computationally very expensive.
Emission estimates are accurate enough to define the hotspots	This is the core assumption of the solution. If this assumption fails, then by definition, ANY solution taking non-CO_2 emissions into account has to fail	We can relax the "absolute accuracy" assumption by introducing an error term.
Delays experienced by flights are exponentially distributed	For technical feasibility. Exponential distributions allow us to compute analytically some of the terms. Note that evidence that delays are either exponential or normal are numerous.	Normal distributions are harder but feasible. Arbitrary distributions require a different approach, at least with numerical integral estimations.
Behaviour of airlines is bundled in two categories	The two categories notionally represent low-cost and network carriers. This allows for higher diversity of choices of routes when faced with high delays (due to congestion) or high costs (due to hotspots)	Same issue as for number of routes, it is very hard to generalise due to combinatorial issues

[6] Perturbative approximations are sometimes used when a full mathematical expression cannot be derived, but a particular case is known. In this case, the mathematical expression for an infinite capacity can be derived, so approximations may be computable for 'near infinite' capacities.

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Additional technical and more minor assumptions are presented in Table 14.

Table 14 Additional modelling assumptions and their flexibility

Description	Why?	Could be relaxed?
EI distributions are independent on each route	For technical feasibility	Yes, to some extent. In particular, correlation coefficients can be introduced between routes
Delay distributions (without ATFM) are the same on both routes on a given OD	Technical feasibility. Very weak assumption	Yes, but no obvious rationale to relax it

Modelling details

The model relies on the semi-analytical estimation of integrals representing the expected PIs, given the known distributions of delays and environmental impacts of flights. For one OD, a typical integral to be computed looks like this:

$$C_e^\star = \int d\mathbb{P}\, c^\star$$

In this equation, dP represents the integration over all probability functions (i.e. an average with respect to all external factors like environmental factors). In this case we want the value of the environmental impact (c), taking into account that airlines are taking the highest utility routes given a sample value of the distributions (*).

Since it is assumed that airlines are basing their decisions only on costs and delay, given any arbitrary values of the latter, one is able to know which routes would be chosen. The utility looks like this:

$$u = \alpha p + (\beta + \alpha\lambda)c + \gamma\delta$$

,

Where α is the sensitivity of airlines to costs, β is the sensitivity to EI, γ the sensitivity to delays, and λ is the EI rate. Given two routes A and B, and a realisation of EI (c) and delays (δ) on each route, then one knows whether the airline will choose route A or route B simply by comparing the utility on each route (if uA > uB, the airline will choose A, otherwise it will choose B). Given that we know the distribution of delay, and that we can easily transform the integral into sum for EI given the small numbers of values, then typically one gets this kind of expression for the integrals:

$$C_e^\star = 2c_e - \sum_j \sum_i w_j w_i c_j \left[W\left(\frac{\alpha}{\gamma}(p_A - p_B) + \frac{\eta}{\gamma}(c_j - c_i)\right) + W\left(\frac{\alpha}{\gamma}(p_B - p_A) + \frac{\eta}{\gamma}(c_j - c_i)\right)\right].$$

In this expression, we can see appearing the average EI (c_e), the probabilities of having certain values of EI (w_i, w_j), the fixed costs or flying A or B (p_A, p_B), and W. The latter is a pure function that depends **only** on the distribution of delay, and which can be pre-computed outside of the model, either analytically or numerically (see section A.3.2.2.4 on data). More complex expressions can be obtained with two airlines and capacity constraints.

These expressions have to be computed for each OD pair, which in general have different parameters (capacities, route costs, etc.). On top of that, we used time slices to represent the potential congestion of the airspace. For each OD and each time slice, an expression like the one above is computed, taking into account the fact that airlines that are too delayed come out of their current time slice to go into the next one.

A.3.2.2.4. Data

This model requires various input data in order to compute the needed expected values. Hereafter we describe the steps required to build the dataset, and the sources of data used to produce the results shown in this deliverable. The following data is needed by the model:

- Typical trajectories for each OD (obtained via clustering),
- Airspace structure (simplified, we considered only a horizontal slice of sectors and one opening scheme),
- Average values for fuel consumption,
- Values of route charges,
- Distributions of EI on each OD pair,
- Distribution of external delays, fitted for each OD,
- Behavioural parameters for airlines (obtained from the survey).

First the results of the SP survey are detailed, which are followed by the explanation of the climate hotspot determination, trajectory and airspace, and other data used in validation exercise.

Stated-preference survey

An SP survey allows to directly collect respondents' preferences, as respondents articulate their choices, rather than researchers inferring preferences from actual behaviour, known as "revealed preference" (see section 5.1.1.3.1 of D5.2 ERP [AD26]). The survey aims to assess airlines' willingness to pay (WTP) for avoiding climate hotspots and their sensitivity to delays and costs. By focusing on four **key attributes**—cost sensitivity, short delay aversion, long delay tolerance, and environmental

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considerations—we gather insights into what matters most to participants in their decision-making processes.

The survey presents the following sets of questions, where the sets 2-3 are adaptive (see Appendix A of D5.2 ERP [AD26] for more details):

1. Introduction and demographics.
2. Screen tasks, which involve screening questions designed to filter out irrelevant choices and ensure that only the most relevant options are considered.
3. Attribute identification: participants identify essential attributes through "unacceptable" tasks.
4. **Choice tasks** where participants choose between different trajectory choices, each characterised by varying levels of key attributes.

Members of the Advisory Board, including representatives from airlines and IATA, assisted in recruiting participants. The survey was distributed via a survey link on September 25th, 2024 and remained open until October 31st, 2024.

We received 13 complete responses. Incomplete responses were removed from the analysis. Since an adaptive SP survey design was used, participants encountered varying numbers of choice tasks, resulting in a total of 128 observations across all responses.

Figure 1 shows the distribution of responses per airline type category. The highest number of responses was received from network carriers, followed by regional and low-cost carriers.

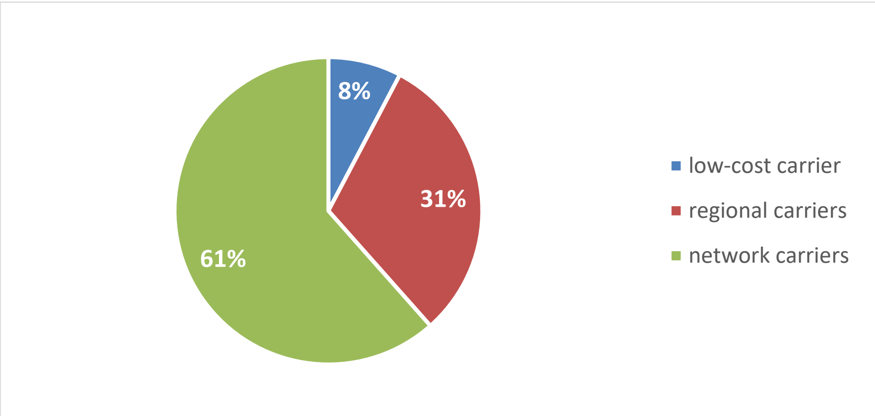

Figure 1 Responses by airline type.

To estimate the utility functions from the SP survey responses, we use Biogeme (BIOlogit GEstimation), an open-source Python package designed for estimating discrete choice models, particularly logit models [16]. 'Utility' refers to the satisfaction or value that a decision-maker derives from choosing a particular alternative and is typically expressed as a linear combination of various attributes, each weighted by a corresponding coefficient. These coefficients quantify the impact of each attribute on the utility derived from the choice.

We consider several types of utility functions depending on the nature of the data and the relationships between variables. For instance, a linear utility function assumes a straightforward additive relationship, while a log-linear utility function addresses multiplicative effects when the outcome variable is skewed. For a quadratic utility function, we model the relationship between the attributes and utility as a second-degree polynomial, allowing for non-linear effects and capturing diminishing or increasing marginal utility, which can provide a more nuanced understanding of decision-making behaviour among different airline types. Also, the choice of different utility functions for various airline types is crucial, as it enables us to tailor our analysis to the specific characteristics and decision-making behaviours of network carriers, low-cost carriers, and regional carriers.

In a typical utility function used for an SP survey, each parameter contributes to the overall utility (U) that a decision-maker derives from selecting a particular option. Identifying the best-fit utility function for our data depends on several factors, such as the nature of the data, the relationships between variables, and the context of our analysis. The standard utility functions are outlined below. The selection of a specific utility function will depend on the insights we aim to extract from the SP survey responses.

- **Linear Utility Function**: The utility is modelled as a linear combination of the explanatory variables. This function is appropriate when we assume a linear relationship between the variables and the outcome:

$$UF_{Linear} = \beta_1 \times cost\_sensitivity + \beta_2 \times short\_delay + \beta_3 \times long\_delay + \beta_4 \times environmental\_consideration$$

- **Log-Linear Utility Function:** This function is used when the marginal effect of the variables on the outcome is multiplicative. It is often applied when the outcome variable is non-negative and right skewed.

$$UF_{Log\_Linear} = exp\,(\beta_1 \times cost\_sensitivity + \beta_2 \times short\_delay + \beta_3 \times long\_delay + \beta_4 \times environmental\_consideration)$$

- **Quadratic Utility Function:** That is a type of utility function that represents preferences in a way that allows for both linear and non-linear relationships between the utility and the characteristics of the alternatives.

$$UF_{Quadratic} = \beta_1 \times cost\_sensitivity + \beta_1^{SQ} \times cost\_sensitivity^2 + \beta_2 \times short\_delay + \beta_2^{SQ} \times short\_delay^2 + \beta_3 \times long\_delay + \beta_3^{SQ} \times long\_delay^2 + \beta_4 \times environmental\_consideration + \beta_4^{SQ} \times environmental\_consideration^2$$

To compare these utility functions, we use three metrics: final log likelihood, Akaike information criterion and Bayesian information criterion. The final log likelihood (FLL) shows how likely the observed data is, given the model parameters. In simpler terms, it tells us how well the model explains the data—higher values mean a better fit. The Akaike information criterion (AIC) is a tool used to compare different models based on the same dataset [17]. It focuses on balancing model complexity with how well the model fits the data, with lower AIC values indicating a better fit. Similarly, the

Bayesian information criterion (BIC) evaluates model quality but gives a stronger penalty for complexity, making it more likely to favour simpler models, especially as the sample size grows. Together, AIC, BIC, and FLL are crucial for choosing and assessing models in statistical analysis. Based on the analysis of the linear, log-linear, and quadratic models, the quadratic utility function stands out as the best choice in terms of fit. It has the highest final log-likelihood of -66.4, indicating a better fit to the data compared to the linear model's -73.8 and the log-linear model's -113.7. Additionally, the AIC for the quadratic model is the lowest at 148.8, suggesting it effectively balances model complexity with goodness of fit. Furthermore, the quadratic model features significant parameter estimates for key variables like cost sensitivity and long delay, with *p*-values indicating strong statistical significance ($p < 0.001$). In contrast, some parameters in the linear and log-linear models show less significance. The structure of the quadratic model allows it to capture nonlinear relationships among attributes, enhancing its performance in optimisation tasks.

Table 15 Different utility functions comparison.

Utility Functions	β_1	β_2	β_3	β_4	β_1^{SQ}	β_2^{SQ}	β_3^{SQ}	β_4^{SQ}	FLL	AIC	BIC
Linear	-6.01	-1.32	-5.2	-0.797	-	-	-	-	-73.8	155.6	167.0
Log-Linear	-6.17	-0.31	-2.77	1.72	-	-	-	-	-113.7	235.5	246.9
Quadratic	-11.9	-1.52	-7.93	-0.851	7.73	0.23	2.76	-0.41	-66.4	148.8	171.6

While the quadratic model is the top choice, the linear utility function can also be considered as a second option. It has a better BIC than the quadratic model, indicating a more favourable balance between model complexity and fit. Also, the linear utility function demonstrates the highest Rho-square value at 0.455, indicating superior explanatory power compared to both the log-linear and quadratic models, which each have Rho-square values of 0. The simpler linear structure can also make it easier to interpret and apply in optimisation contexts, especially when dealing with linear terms. Both models have their advantages, making them valuable depending on the specific requirements of the analysis.

As an example, we illustrate the approach using a linear utility function. We introduce the concept of the value of time (vot), that tells us how much airlines are willing to 'pay' (in terms of cost) to save time (in terms of reduced delays). To calculate the vot for each airline type category, we compare the disutility (negative utility) associated with time-related attributes (delays) against the cost attribute. The typical formula to calculate it is presented here:

$$vot = \frac{\text{coefficient of delay}}{\text{coefficient of cost}}$$

As we use the normalised method to define the utility function and estimate the parameters, the modified method is used to define VoT:

$$vot = \frac{\text{coefficient of delay} \times \frac{1}{(max\ delay - min\ delay)}}{\text{coefficient of cost} \times \frac{1}{(max\ cost - min\ cost)}}$$

Here, the coefficient of delay represents the disutility (or negative utility) associated with the delay and the Coefficient of Cost reflects the disutility related to the monetary cost. Also, Max and Min values are the highest and lowest levels of attributes.

The next important concept is willingness to pay (WTP), which reflects the maximum amount an airline is willing to pay for goods or services. In this case, improvements in various attributes such as cost, delay, and environmental impact. vot is generally used to assess the economic value of time savings across various contexts, while WTP is often used in a more specific context of consumers' preferences for goods and services. vot can be used for broader transport policy decisions and cost-benefit analyses, while WTP is typically focused on how much individuals are willing to spend to avoid specific negative experiences or enhance specific attributes. In our specific analysis, both WTP for attributes yield the same numerical values due to the nature of the coefficients and the calculations involved. Since we look at the cost of delays, both measures focus on the economic value derived from time savings and the avoidance of those delays. Here, we face with the avoidance of disutility rather than WTP. shows the results for the linear utility function and the vot.

Table 16 Estimation of airline preferences: linear utility function analysis of cost, delay sensitivity, and environmental considerations.

Airline type	Number of responses	Observation	Attributes	Coef.	Rob. std err	Rob. t-test	Rob. p-value	Nor m.V.	VoT (€/min)
All	13	128	Cost sensitivity	-6.01	1.15	-5.24	0.00	0.45	
			Short delay aversion	-1.32	0.53	-2.52	0.01	0.10	74.7
			Long delay tolerance	-5.20	1.13	-4.58	0.00	0.39	45.3
			Environmental consideration	-0.80	0.55	-1.45	0.15	0.06	
Network Carrier	8	79	Cost sensitivity	-7.00	1.45	-4.84	0.00	0.49	
			Short delay aversion	-1.42	0.69	-2.06	0.04	0.10	69.0
			Long delay tolerance	-4.61	1.17	-3.93	0.00	0.32	34.4
			Environmental consideration	-1.21	0.66	-1.84	0.07	0.08	

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Airline type	Number of responses	Observation	Attributes	Coef.	Rob. std err	Rob. t-test	Rob. p-value	Nor m.V.	VoT (€/min)
Regional Carrier	4	40	Cost sensitivity	-10.48	3.37	-3.11	0.00	0.26	
			Short delay aversion	-3.38	1.61	-2.10	0.04	0.08	109.7
			Long delay tolerance	-27.98	10.14	-2.76	0.01	0.70	139.7
			Environmental consideration	1.81	1.34	1.35	0.18	-0.05	
Low-Cost Carrier	1	9	Cost sensitivity	-226.72	25.27	-8.97	0.00	0.74	
			Short delay aversion	-15.24	2.67	-5.71	0.00	0.05	22.9
			Long delay tolerance	-33.42	2.73	-12.25	0.00	0.11	7.7
			Environmental consideration	-29.88	2.98	-10.03	0.00	0.10	

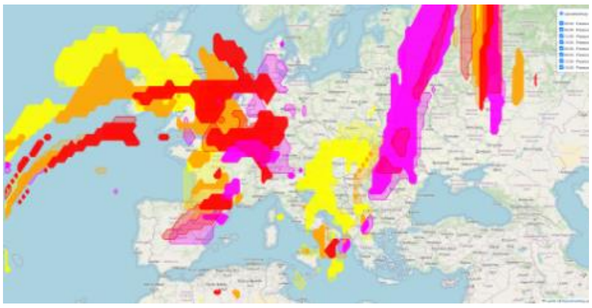
The results from the analysis provide valuable insights into the airlines' preferences. Table 16 summarises the estimated coefficients, beta parameters, for different airline types, revealing how each attribute affects the overall utility in linear utility function derived from the choices presented in the SP survey. The beta parameters show estimated coefficients for each attribute in the linear utility function, indicating the relative influence of each variable on the choice decision. The robust standard error (Rob. std err) measures the variability of the coefficient estimate, accounting for heteroscedasticity or potential misspecification in the model. A smaller standard error implies a more precise estimate. The Robust t-test compares the estimated coefficient to zero, evaluating the hypothesis that the attribute has no effect on the choice. It is calculated as the ratio of the estimated value to its robust standard error. The corresponding Robust p-value provides the statistical significance of the estimate. A p-value below a conventional threshold (such as 0.05 or 0.10) indicates that the attribute has a statistically significant effect on the choice. Finally, the normalised value (Norm. V.) is a scaled version of the estimated coefficient that allows easier comparison across attributes with different units. The analysis reveals that cost sensitivity and long delay tolerance show statistical significance. Short delay aversion is significant for responses in the network carrier and low-cost carrier categories, while environmental consideration is less reliable, particularly within responses in the network carrier and regional carrier categories.

The data for network and low-cost carrier categories from Table 16 are used in both exercises.

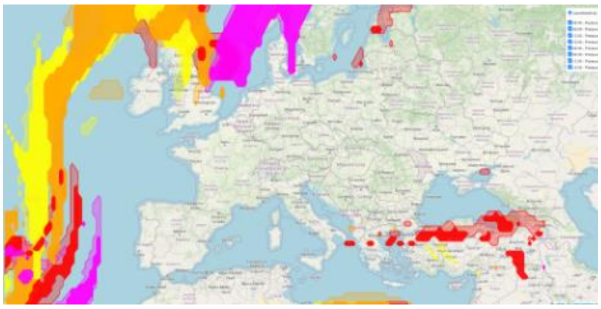
Climate hotspots

To determine the hotspots, we utilised the CLIMaCCF library on ERA5 data. First analysis used ERA5 data for four selected weeks (1st weeks of March, June, September, and December of 2019) to gain insights into the dynamics of climate hotspots. The hotspots are determined as a percentile of the value of aCCF merged (algorithmic climate change function), where the impact of different species is merged, and expressed in K/kg fuel. CO2 is excluded, as CO2 effect does not depend on the state of the atmosphere.

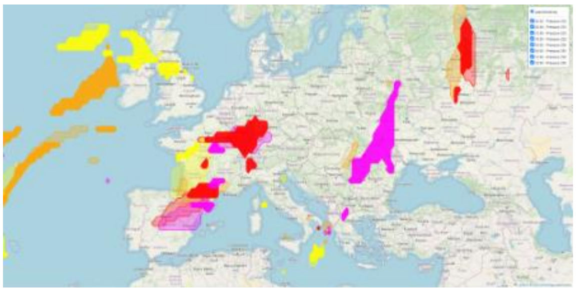
Figure 2 illustrates the progression of the hotspots over two days: one in September 2019 (left-hand side of the Figure 2), and another in December 2019 (right-hand side). The colours represent different times of day—yellow for midnight, orange for 06:00, red for 12:00, and magenta for 18:00—allowing us to observe how these hotspots shift with atmospheric movements. We examined two flight levels—FL340 at 250 hPa and FL360 at 225 hPa, with the hotspots at the latter level appearing more transparent in the depiction. Notably, the hotspot areas differ between levels, indicating that high-altitude avoidance patterns may vary.



Hotspots for 3rd September 2019, 95th percentile



Hotspots for 3rd December 2019, 95th percentile



Hotspots for 3rd September 2019, 99th percentile

Hotspots for 3rd December 2019, 99th percentile

Figure 2 Daily evolution of hotspots, for FLs 340 and 360, at 95th and 99th percentile.

Additionally, it can be noted that the hotspot areas are significantly larger at the 95th percentile, highlighting the need to establish a suitable percentile for a route-charging scheme. Figure 2 depicts a possible seasonal difference in climate hotspots. The hotspots also depend on the **aircraft engine type**. Table 17 shows the percentile values for generic wide-body and single aisle aircraft, across the dataset that contains the month of September 2019 and first two weeks of December 2019.

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Table 17 Percentile values of aCCF merged for generic wide-body and single aisle aircraft.

Percentile	Wide body	Single aisle
0.90	1.584e-13	1.154e-13
0.95	1.955e-13	1.469e-13
0.99	3.677e-13	8.165e-13

The identification of climate hotspots is influenced by weather forecast data (specifically, its resolution) and the selection of various parameters, as detailed in the related manual [18].

In our exercises, we downloaded the ERA5 data for September 2019, along 11 pressure levels, and run the CLIMaCCF library for single aisle aircraft, for 95th percentile of total non-CO_2 impact. The **95th** percentile for September 2019, for single aisle aircraft is **1.96e-13** K/kg fuel. Thus, the hotspots, at each pressure level are identified based on this value. The output of CLIMaCCF library is a netcdf file that contains 4D grid (lat, lon, pressure level for each hour in September), and associated aCCF_merged (total non-CO_2 impact) and aCCF-CO_2 (CO_2 impact, which is constant in all grid points).

Trajectory, airspace, fuel, costs and emissions data

The trajectory and airspace data are sourced from DDR2 data, for AIRAC 1910 (12/09-09/10/2019).

Origin-destination pairs

The first step is to decide which airports will be involved in the model. In this deliverable we selected 2 pairs of airports (so 4 OD pairs) for the exercise #01 validation scenario, and 10 airports (with all possible pairs in between) for the exercise #02 validation scenario, the chosen airports being the 10 busiest airports in Europe, based on our dataset (see below for a description of all sources).

Routes

For each OD pair, we then need routes. For this model, we performed a clustering of planned trajectories in a similar fashion as in [19]. Trajectories have been clustered based on their proximity, using a custom distance measure. Then for each OD, the two routes were selected. The routes are a result of clustering of trajectories, and a trajectory closest to the cluster's centroid represents the chosen cluster. These represent the routes available to the airline for their trajectories between OD.

Airspace

Several pieces of information on the airspace are then needed. First, we build a fixed sector tessellation for the scenario. In order to do this, we select one date and time (12:01 on the 12/09/2019), and select the sectorisation that corresponds to the active opening scheme at this time, across all Europe. We then select a band of altitudes (FL250), and sectors that are active there, and are crossed by at least one route. In the end, we have a complete tessellation of sectors that are encompassing only the relevant routes.

We then extract capacities by considering the maximum between entry counts and nominal capacities, based on NEST saturation files for the chosen sectorisation.

Airlines

The next step is to consider airlines. For each OD, each time slice, and each airline, we consider all flights for a month and divide by the number of days. This gives us an average flow for each OD pair.

We then bundle the airlines in two categories, notionally low-cost (more sensitive to cost) and traditional (more sensitive to delay). This bundling has been done based on past studies, linked to the Mercury and cost of delay models.

Finally, we assign behavioural parameters to each type of airlines, based on the results of the survey described above. For this, we use only linear regression, assimilating the first coefficient of delay to the one of the utility function.

Distribution of delays

The distributions of exogenous delay (i.e. delays which are not strategic) have been obtained by using data from DDR, computing the delays as the difference between the planned and actual departure. We used these delays to fit exponential distributions for each OD pair. The regressions with less accuracy ($R2 < 0.7$) were instead replaced by an exponential distribution with average parameters.

Distributions of environmental impact

In order to use the model, one has to specify either:

- The distribution of the binary variable “flight goes through a hotspot if it takes route A on OD pair X”,
- The distribution of the continuous variable “environmental impact of flight on route A of OD pair X”.

Each correspond to a different flavour of the mechanism: either airline pays based on whether they cross a hotspot, or they pay based on their total emissions.

These distributions have been obtained from the CLIMaCCF output on ERA5 data for September 2019 (as explained above). For each trajectory, environmental impact and hotspot crossing are then obtained from output netcdf file at each 4D point of trajectory. To create a distribution, the trajectory is shifted in time throughout the entire month of climate data. The shift is performed for each day, and each hour in period of 06:00-18:00. Finally, for the environmental impact, expressed in K, the fuel consumption is needed (as aCCFs are expressed in K/kg fuel). We use OpenAP library [20] to determine fuel flow at each trajectory point and fuel consumed, based on aircraft type used and the 0.8 of MTOW. A sample of environmental impact and hotspot crossings is shown in Table 18 below.

Table 18 A sample of environmental impact and hotspot crossing data.

Flight ID	Date	Departure hour	EI [K]	CO_2 impact [K]	Number of trajectory points in hotspots
196766	01/09/2019	6	4.22E-10	4.09E-11	17
196766	01/09/2019	7	4.77E-10	4.09E-11	17
196766	01/09/2019	8	4.13E-10	4.09E-11	9

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Costs

The costs used here cover only fuel and route charges. The price of fuel is assumed to be 1 euro per kg and the route charges are those used today.

A.3.2.2.5. Results

This validation scenario with only two OD pairs allows us to explore the results of the model in a controlled and comprehensive way. Figure 3 shows the geographical scope of the first scenario. As described above, only two OD pairs are considered, and only two routes on each pair. The routes intersect, so we have airspace capacity shared by different routes. We consider only the sectors depicted, and in the following we only act on the crossing sectors, applying strategic delays on the sectors where two routes cross.

For this validation scenario, there are three scenarios (see Figure 3), representing three types of computation modes in the model:

- Benchmark or 'free' results: a simple computation of the indicators when capacities are infinite and airlines can choose freely their preferred route. This represents the ideal world for the airlines. One can play with the application of an arbitrary EI rate with these results.
- Reference of 'cap' results: an optimised scenario where capacity constraints are enforced through strategic delays, applied on the sectors. This represents the closest scenario to the present situation. One can also play with the EI rate to see what the impact would be.
- Solution or 'full' results: an optimised scenario where a central optimiser tries to minimise the environmental impact while capacity constraints are enforced. This represents the closest situation to what the system with the full solution would look like. In this case, the EI rate is set by the optimiser, as well as the strategic delays on sectors, and a multiplicator factor for the route charges, to ensure ANSP revenue neutrality.

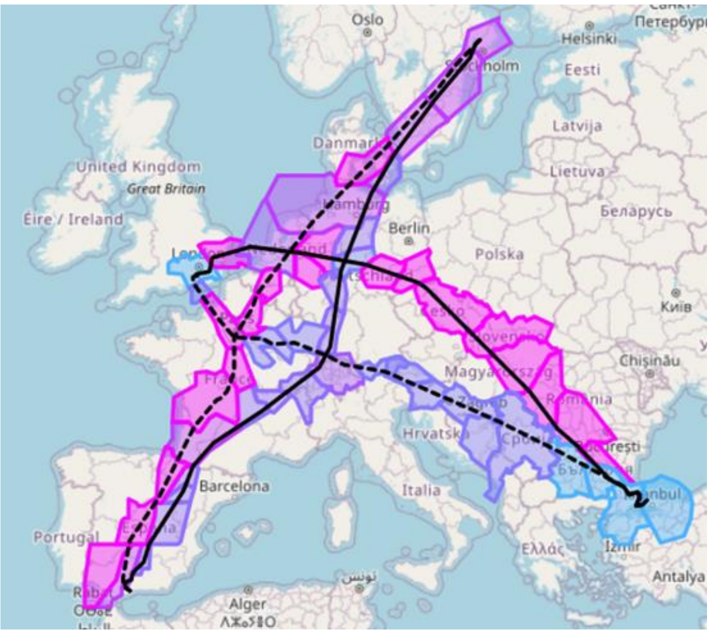

Figure 3 Map for the #01 validation scenario.

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The first results we show in Figure 3 are the environmental impact and the fuel consumption per flight, in the 'free' and 'cap' scenarios as a function of the EI rate. On the left, we see that EI is decreasing monotonously[7] with the EI rate[8]. This is exactly the expected behaviour, and the reason why the project designed this solution. Note that the EI plateaus after a certain value of the EI rate. This represents the fact that all the gains possible have been made already in terms of EI, and increasing the EI rate more does not help. Note also how the environmental impact is always higher in the capacity-constrained scenario, compared to the free one. This represents the fact that lower capacities hinder the possibility of airlines to switch to more environmentally friendly trajectories.

On the right side of Figure 3, we also show the evolution of the fuel consumption with the EI rate. In this case, the consumption increases with the EI rate, because the emissions taken into account are non-CO2. In other words, avoiding hotspots to save on non-CO2 emissions requires to take less efficient routes from the fuel point of view. Note also how the consumption in the capacity constraint case if always smaller than the infinite capacity case. This is counter-intuitive but to be expected: when the capacity is lower, flights have less opportunities to avoid hotspot, so they are more efficient fuel-wise.

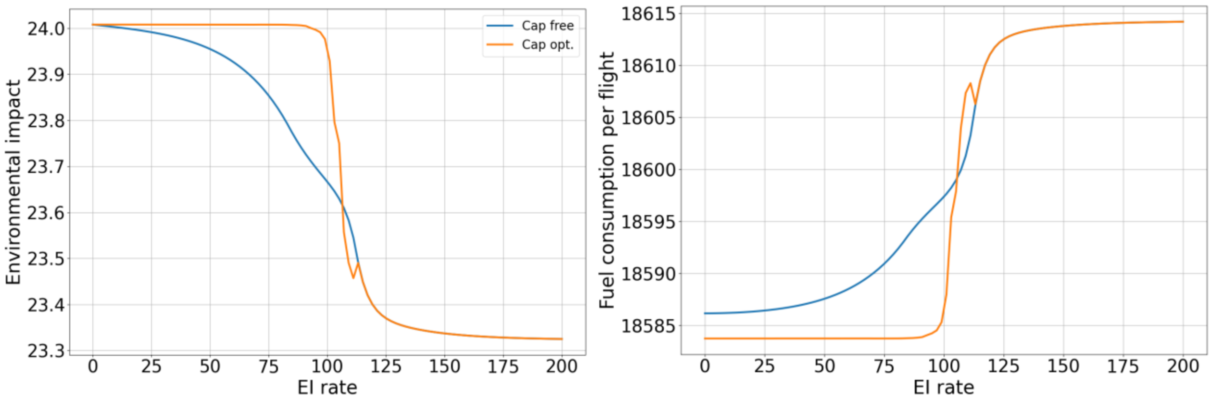

Figure 4 Environmental impact (nK) and fuel consumption as a function of the EI rate (€) in the 'free' scenario (cap free) and the 'cap' scenario (cap opt.).

Results in Figure 5 show the evolution of the ANSP revenues and the airline costs still in the 'free' and 'cap' scenarios, and still with the EI rate. As expected, the revenues of the ANSPs increase with the application of higher EI rates. This is the reason why we apply to reduction of the route charges in the full optimisation, in order to keep revenue neutrality. Conversely, the costs of the airlines increase with the EI rate. However, it is important to note that it is not only due to the EI tax. Indeed, when plotting the costs without the EI rate, we see an increase with the EI rate too. This is simply due to the fact that

[7] Note that in these results there is a small artefact in the middle due to a rounding error in the computation. We fixed this error for the exercise #02.

[8] It can be shown that it is always the case in the "one time slice one OD pair case".

the EI rate distorts the choice of the airlines, and that they choose route which would have been deemed too expensive otherwise (without EI rate).

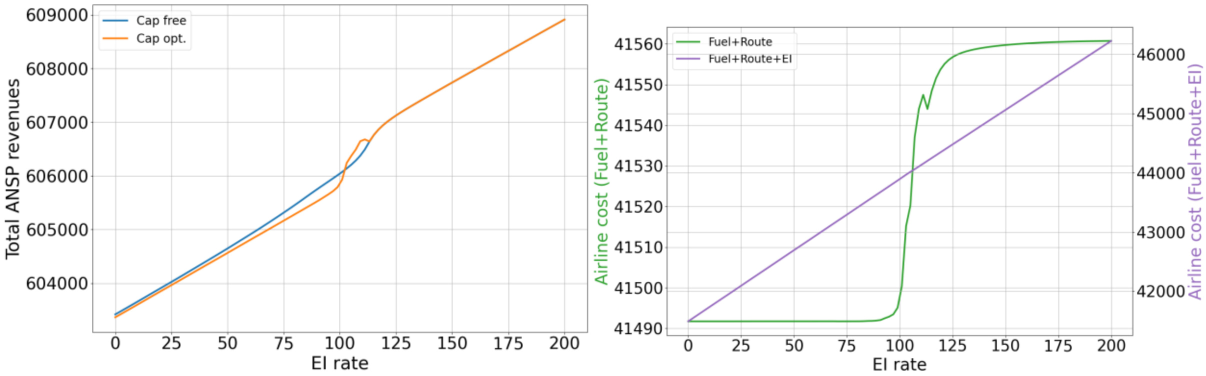

Figure 5 ANSP revenues and airline costs in 'free' computation mode (€).

Still using the 'cap' scenario, we show more explicitly how a capacity decrease hinders the mechanism. In Figure 5 we see indeed that when reducing nominal capacity, the plateau reached by the EI when the EI rate is high changes. In the limit case, no gain can be made from applying an EI tax, because the system is completely constrained.

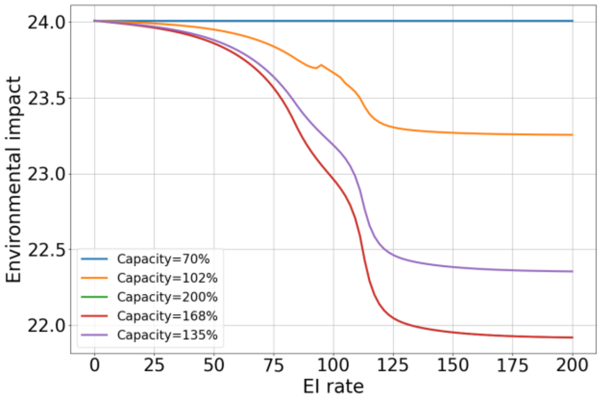

Figure 6 Environmental impact (nK) as a function of the EI rate (€) in 'cap.' computation mode.

Next, we show in Figure 7 results when the full optimisation is applied. On the left, we show the optimal EI rate and route charges multiplier found by the optimisation, again as a function of capacity modulation. It is interesting to note that in this case the multiplier switches very quickly from 1 to 0, effectively removing all route charges from the system. Instead, the system uses exclusively the EI tax to fund itself and keeps revenue neutrality.

This has some non-trivial impact on the average EI. On the right, we show that from a very high point (which is not good), the EI drops linearly and monotonously, a regime that matches the slow increase of the EI rate. When the capacity is large enough, the system keeps the EI rate constant, because all possible gains have been made.

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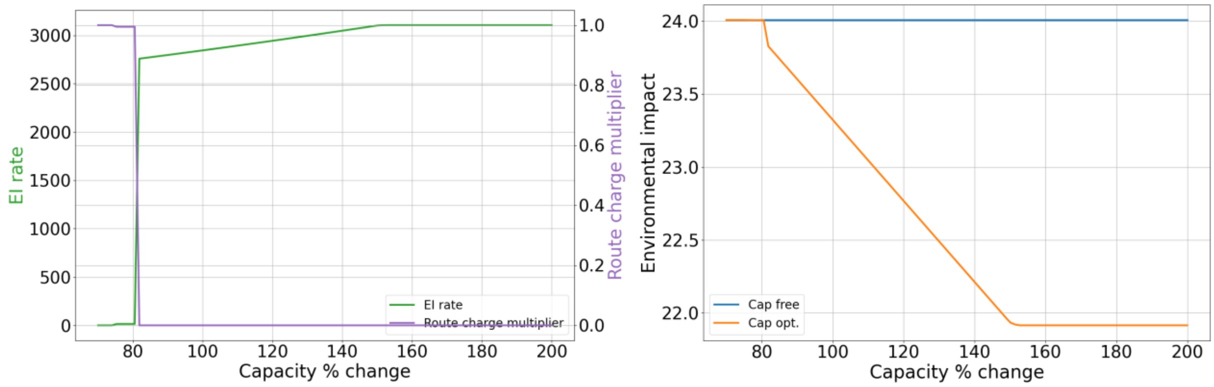

Figure 7 Optimal EI rate and EI as functions of a capacity modulation factor in 'full' computation mode.

Finally, we show in Figure 8 a comparison of different flavours of the Full Solution. We compare the different cases by computing the 'efficiency' of the mechanism, which is defined as the percentage of reduction of EI in the 'full' scenario, compared to the 'cap' one. The different flavours are the following:

- The 'hotspot detection': in this case, the mechanism only takes into account flights that cross a hotspot and puts a price on the corresponding route that depends on the OD pair.
- The 'env. impact detection': in this case, the mechanism takes into account the full emissions of each flight. In theory, the reduction of EI should be bigger in this case than in the previous one, because the information on the EI is more accurate.
- The 'hotspot detection + FL changes': in this case, if the flight would cross a hotspot, we assume that it tries to change its trajectory 2FL up or down, and select one or the other if they do not cross a hotspot.
- The 'env. impact detection+ FL changes': in this case, the flight always takes the least impactful trajectory, within 2FL.

As shown in the Figure 7, changing flight levels can be very beneficial to the mechanism, and may save twice as much emissions as in the simple case. Moreover, it is interesting to note that the 'env. impact detection', although more efficient in theory, does not seem to perform a lot better than the hotspot detection. This is a strong argument in favour of the latter, given its operational simplicity.

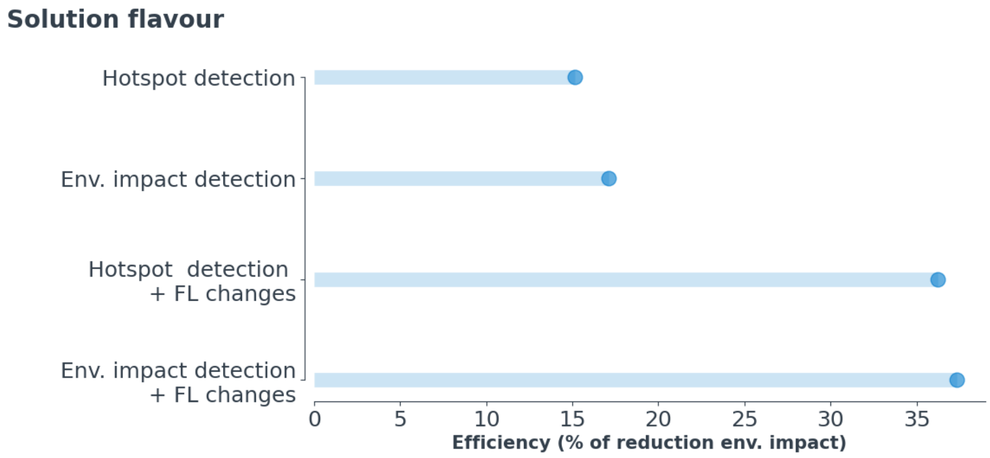

Figure 8 Efficiency of full solution in different cases.

A.3.3 Unexpected behaviours/results

No unexpected behaviours have been reported.

A.3.4 Confidence in results of validation exercise #01

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

Initial GRC Solution. The sample selected for this exercise has been chosen to be small enough for easy monitoring and accurate calibration, yet representative of a typical real-world scenario, to ensure a robust assessment of the Solutions. However, two main limitations must be noted: firstly, the selection, while significant, only represents a sample of the real scenario, making the estimated impact an approximation of the actual impact. Secondly, the data available for these exercises is from 2019. Although the methodology as such is valid regardless of the input data, as it is not case-specific, the resulting impact may differ annually due to its strong correlation with the traffic patterns analysed.

Full GRC Solution. The sample for this exercise was very small, as the intention behind the exercise was to test the feasibility of the model itself and the data integration. The behaviour of the model was tested as well. The results of this exercise are limited to feasibility and behaviour testing.

A.3.4.2. Quality of validation exercises results

Initial GRC Solution. Exercise #01 employed a limited yet statistically significant sample for easier monitoring and calibration, inevitably providing only an approximation of real-world operational impacts. The reliance on 2019 data creates temporal limitations, as while the underlying methodology remains valid, evolving traffic patterns and operational realities may affect the generalizability of findings.

Full GRC Solution. As mentioned in previous section, the objective of the exercise was to test the feasibility and behaviour of the model, which was achieved. The quality of results is limited to this purpose.

A.3.4.3. Significance of validation exercises results

Initial GRC Solution. The statistical assessment of Exercise #1's results presents inherent limitations due to its deliberately constrained scope. The validation employed a carefully selected but limited dataset representing just one day of operations (September 20, 2019), comprising 995 flights across 563 origin-destination pairs. While this sample was designed to be statistically representative, the restricted timeframe and traffic volume necessarily limit the power of quantitative conclusions. The results demonstrate clear directional trends in performance improvement, particularly regarding route optimization and charge modulation effectiveness, but the small sample size prevents definitive statistical generalization to broader operational contexts. From an operational perspective, the exercise successfully validated core model functionality under controlled conditions, proving the concept's technical feasibility. However, the absence of real-world operational variability - including different weather conditions, traffic mixes, or network disruptions - means the exercise could not fully assess robustness across the complete spectrum of daily operations. The pre-pandemic data also introduces questions about current applicability, as traffic patterns changed significantly since 2019.

Full GRC Solution. The results obtained in this exercise are not statistically significant, as the model and the novel charging mechanism were tested just for feasibility and behaviour.

A.4 Conclusions

A.4.1 Conclusions on concept clarification

Initial GRC Solution

Exercise #01 focused on a representative but limited dataset (995 flights across 563 OD pairs from September 2019), demonstrating the Initial Solution's ability to modulate route charges while maintaining revenue neutrality. Key achievements included:

Proof of concept: The model reduced global distance flown by 1.81%, validating its route optimization capability

Stakeholder compliance: All operational constraints and requirements were maintained, including ±10% revenue neutrality for ANSPs

Traffic management: Achieved full resolution of capacity violations through strategic charge modulation

However, the exercise's limited scope (single-day dataset) prevented assessment of seasonal variability or atypical operational scenarios. The pre-pandemic data also raises questions about current applicability given evolving traffic patterns.

Full GRC Solution

The exercise helped clarify some aspects of the concept, and showed that there are different possibilities that can be explored and further addressed in exercise #02: the type of environmental modulation (flat rate, or rate based on EI – see [20]), and the type of scenario to compare to (benchmark, reference and solution).

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A.4.2 Conclusions on technical feasibility

The Exercise #01 validation successfully confirmed some of the essential criteria for the operational feasibility of the GRC Solutions' core concepts. Here, it should be remarked that such an exercise was meant to test initial capabilities of the selected models to respect minimal feasibility standards within a controlled environment, mandatory request to proceed with the large experiments of Exercise #02.

A.4.3 Conclusions on performance assessments

Initial GRC Solution. The validation exercises demonstrated consistent performance improvements across key metrics. Exercise #01 confirmed the Initial Solution's feasibility, achieving a 1.81% reduction in global distance flown and resolving all capacity violations while maintaining revenue neutrality (±10%). Exercise #2 expanded validation across high/low traffic periods, showing 0.249–1.361% fuel savings and 91.2–94.1% congestion reduction, with stronger benefits for intra-ECAC flights. Environmental KPIs (ENV1) improved by up to 1.364%, aligning with CO_2 reduction goals. While results are statistically and operationally significant, limitations include 2019 data vintage and partial annual coverage. The models proved robust under tested conditions but require further validation for edge cases and updated traffic patterns to ensure scalability. Overall, the solution meets SESAR objectives for efficiency, capacity, and environmental performance.

Full GRC Solution. The exercise demonstrated that the data needed in the concept can be integrated and that the envisioned performance assessment PIs can be assessed.

A.5 Recommendations

Since Exercise #01 covered an initial assessment of the proposed models, detailed and complete recommendations are discussed within the analysis of Exercise #02.

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Appendix B Validation exercise #02 report

B.1 Summary of the validation exercise #02 plan

As in D5.2 - ERP - Green RC [AD26].

B.1.1 Initial solution – MRC model refinement

Although the model presented in 5.1.1.2.1 of the ERP proved its effectiveness in successfully achieving all objectives of exercise #1, its initial implementation struggled to scale when tested on larger instances. For this reason, the MRC model has been revisited in order to significantly improve its computational performance. In particular, following a divide-and-conquer approach we decomposed the problem into three sequential optimization stages:

- M1: expected traffic flow optimization – a continuous linear programming model analyses historical demand patterns and system capacity to redistribute air traffic in a way that minimizes congestion and reduces emissions.
- M2: dynamic modulation adjustment – a second linear programming model computes trajectory-specific pricing incentives, encouraging airlines to adopt the optimal routes identified in the first stage while ensuring air navigation service providers (ANSPs) maintain fair revenue relative to their workload (measured in service units).
- M3: day-by-day Flight Management – an integer linear programming model refines daily operations by assigning individual flights to optimal routes and/or adjusting departure times, ensuring compliance with real-time constraints.

B.1.1.1. Mathematical details

M1

The first optimization stage, M1, is formulated as a linear programming model that analyses each origin-destination-aircraft (ODA) combination by considering the average annual demand, available routes, and sector capacities. Its primary goal is to determine the optimal traffic flow distribution by calculating the proportion of flights (x_t) assigned to each route t while minimizing two key factors: overall congestion, measured as the sum of capacity violations (e_s) across all flight sectors, and the total distance flown.

Table 19 M1 Notation.

Symbol	Description
S	Set of sectors
O	Set of ODA
T	Set of all trajectories

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Symbol	Description
T_o	Subset of trajectories corresponding to the ODA o
T^s	Subset of trajectories that cross sector s
T_o^s	Subset of trajectories corresponding to the the ODA o that cross sector s
O_s	Set of ODAs which have at least a trajectory crossing sector s
ρ_o	Average daily demand for ODA o
$g: T \to O$	function that maps each trajectory with its unique ODA
$\bar{c}_s$	Average capacity of sector s
d_t	Length (in kilometres) of trajectory t
x_t	Portion of traffic flow assigned to trajectory t
e_s	Capacity violations at sector s

The model ensures complete demand fulfilment by requiring that the sum of traffic proportions equals 1 for each ODA. It also incorporates relaxed capacity constraints, allowing minor exceedances (e_s) when necessary. A weighting factor prioritizes congestion reduction while still accounting for flight efficiency. This approach provides a balanced traffic distribution that optimizes airspace utilization and operational performance at a strategic level.

$$min\ M \sum_{s \in S} e_s + \sum_{t \in T} d_t x_t$$

$$s.t.:$$

$$\sum_{t \in T_o} x_t = 1 \qquad \forall\, o \in O$$

$$\sum_{o \in O_s} \sum_{t \in T_o^s} \rho_{g(t)} x_t \leq \bar{c}_s + e_s \qquad \forall\, s \in S$$

$$x_t \in [0,1] \qquad \forall\, t \in T$$

$$e_s \geq 0 \qquad \forall\, s \in S$$

The constant M in the objective function is designed to prioritise minimising congestion (first term) over reducing the total flight distance (second term). Its value can be set to the maximum possible total flown distance. The first equation establishes the flow constraint and the second the relaxed capacity constraints.

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M2

Given the solution from M1, the role of the linear programming model M2 is to compute the modulation factors γ_t that adjust route prices. These factors incentivize each flight in each ODA (Origin-Destination-Airline) to follow the routes identified by M1—specifically, those for which $x_t>0$.

It is important to note that in M2, x_t is not a variable but a fixed parameter, as its value is determined by M1's solution.

For each ODA, the trajectories carrying a portion of the flow should have nearly identical costs, ensuring they are all more cost-effective than unused alternatives. Here, the Route Charge (RC) and Overflight Charge (OC) costs for each trajectory t are calculated as averages across all flights in the same ODA.

Table 20 M2 Notation.

Symbol	Description
A	Set of ANSPs
T_o^u	Subset of trajectories t corresponding to the ODA o for which some traffic has been assigned by M1 ($x_t > 0$)
$T_o^{\hat{u}}$	Subset of trajectories t corresponding to the ODA o for which no traffic has been assigned by M1 ($x_t = 0$)
ac_t^a	RC cost of ANSP a for trajectory t
T_a	Subset of trajectories crossing ANSP a
RC_t	Average RC total (sum of all ac_t^a components) costs of trajectory t
OC_t	Average operational costs of trajectory t
γ_t	Modulation factor for trajectory t
γ_t^+, γ_t^-	Deviations (positive and negative) from 1 of modulation factor γ_t

Since this stage involves price adjustments, M2 must also ensure that the modulation factors γ_t maintain revenue neutrality, meaning total revenues remain unchanged despite the price modifications.

$$min \sum_{o\in O, t\in T_o} (\gamma_t^+ + \gamma_t^-)$$

$$s.t.:$$

$$\gamma_t \, RC_t + OC_t \leq (\gamma_{\hat{t}'} \, RC_{\hat{t}'} + OC_{\hat{t}'}) \cdot (1 + \varepsilon_1) \quad \forall \, o \in O, \quad t, t' \in T_o^u, \quad t \neq t'$$

$$\gamma_t \, RC_t + OC_t \leq \gamma_{\hat{t}} \, RC_{\hat{t}} + OC_{\hat{t}} \qquad \forall \, o \in O, \quad t \in T_o^u, \quad \hat{t} \in T_o^{\hat{u}}$$

$$\sum_{t\,\in\,T_a} \gamma_t\, ac_t^a\, \rho_{g(t)} x_t \leq \sum_{t\,\in\,T_a} ac_t^a\, \rho_{g(t)} x_t \cdot (1 + \varepsilon_2) \qquad \forall\, a \in A$$

$$\sum_{t\,\in\,T_a} \gamma_t\, ac_t^a\, \rho_{g(t)} x_t \geq \sum_{t\,\in\,T_a} ac_t^a\, \rho_{g(t)} x_t \cdot (1 - \varepsilon_2) \qquad \forall\, a \in A$$

$$1 - \gamma_t \leq \gamma_t^- \qquad \forall\, t \in T$$

$$1 - \gamma_t \leq -\gamma_t^+ \qquad \forall\, t \in T$$

$$\gamma_t \geq 0 \qquad \forall\, t \in T$$

$$\gamma_t^+, \gamma_t^- \in [0, \varepsilon_3] \qquad \forall\, t \in T$$

The first constraint ensures that all trajectories chosen by M1 have (approximately) equal costs, within a tolerance of ε_1. The second constraint enforces that the selected trajectories (set T_o^u) remain cheaper than unused alternatives ($T_o^{\hat{u}}$). The third and the fourth constraints relax the strict implements the revenue neutrality, considering a small tolerance ε_2 which adds flexibility to the solution. The fifth and sixth constraints quantify the deviation of modulation factors γ_t from 1, and the last constraint set permissible bounds.

The objective is to minimise these deviations, ensuring that to achieve the desired routing incentives, price adjustments are made only when necessary, and as minimal as possible.

M3

M1 and M2 generate solutions based on average traffic patterns, delivering long-term benefits. However, daily operations often deviate significantly from these averages, and relying solely on modulation factors (γ_t) may not adequately address all demand-capacity imbalances.

To ensure robust daily operations, we introduce a third mixed-integer optimization model. Building on M1's framework, M3 processes individual flight data for each day of operations to determine optimal route assignments and calculate precise time shifts when needed.

Table 21 M3 Notation.

Symbol	Description
F	Set of flights
T_f	Subset of possible trajectories for flight f
I	Set of possible time shifts, also including the original time (no shift)
H	Set of hours
FTI_s^h	Set of tuples (flight, trajectory, time shift) for which flight f if assigned trajectory t with time shift i would cross sector s in the hour h

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Symbol	Description
RC_t^f	RC total (sum of all ac_t^a components) costs of trajectory t for flight f
OC_t	Operational costs of trajectory t for flight f
IC_i^f	Strategic cost of time shift i for flight f
y_{ti}^f	Binary variable which determines if flight f is assigned to trajectory t with time shift i
e_{sh}	Capacity violation at sector s in hour interval h
z_{ti}^f	Binary variable that preclude flight f to be assigned to trajectory t with time shift i

This approach maintains consistency with M1's objectives while providing the granularity needed for daily traffic management.

$$\min M \sum_{s \in S, h \in H} e_{sh} + \sum_{f \in F, t \in T_f, i \in I} d_t y_{ti}^f + \sum_{f \in F, t \in T_f, i \in I} z_{ti}^f$$

$$s.t.:$$

$$\sum_{t \in T_f, i \in I} y_{ti}^f = 1 \qquad \forall f \in F$$

$$\sum_{(f,t,i) \in FTI_s^h} y_{ti}^f \leq c_{sh} + e_{sh} \qquad \forall h \in H, s \in S$$

$$y_{ti}^f \left(\gamma_t RC_t^f + IC_i^f + OC_t^f\right) \leq \gamma_{t'} RC_{t'}^f + IC_j^f + OC_{t'}^f + Z\, z_{ti}^f \qquad \forall f \in F, i, j \in I, t, t' \in T_f$$

$$e_{sh} \geq 0 \qquad \forall s \in S, h \in H$$

$$y_{ti}^f, z_{ti}^f \in \{0,1\} \qquad \forall f \in F, t \in T_f, i \in I$$

The first constraint ensures complete flight assignment, while the second tracks capacity violations at each sector-hour. The model maintains a cost-optimization principle through the third constraint, which guarantees that flights will automatically select the minimum-cost trajectory and time shift combination when no Network Manager intervention occurs. The Network Manager may selectively restrict certain options for specific flights when such action would reduce sector congestion or decrease total distance flown. This decision mechanism is implemented through binary variable z_{ti}^f in the fourth constraint, where setting $z_{ti}^f = 1$ allows bypassing the constraint. The parameter Z is set to the maximum value of $\gamma_t RC_t^f + IC_i^f + OC_t^f$ across all flights and options to ensure proper constraint activation. The objective function closely mirrors that of M1, with the addition of a term to minimize Network Manager interventions, ensuring flight options are only restricted when absolutely necessary for system optimization.

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B.1.2 Validation exercise description and scope

The goal of the second validation exercise is to access the effectiveness of the proposed Solutions according to the selected KPIs. In both cases, Initial and Full, the procedure as such is identical, but different KPIs will be adopted for the comparison. Once a reference period of historical air traffic is defined, the exercise flow can be summarised as follows:

- The performance of the network is measured according to each KPI. This is done by considering the actual traffic flow (taken from the historical data).
- The models described in D5.2 ERP [AD26], Section 5.1.1.1 and Section 5.1.1.2 will be separately run to obtain two new route charging schemes.
- According to the models' assumptions (described in Section A.1.1) the traffic is simulated considering the new route charging schemas (separately for each solution).
- The KPIs of the network are computed considering the simulated traffic (separately for each solution).
- A comparison between the actual traffic and the simulated ones is performed, i.e. comparison between reference and solution scenarios.

B.1.3 Summary of validation exercise #02 validation objectives and success criteria

Table 22 Validation objectives addressed in validation exercise #02.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
Feasibility	The solution respects all stakeholders' requirements	Fully covered	Check whether the models and the relative solutions are compliant with the stakeholders' requirements, implemented as models' constraints	Each constraint should be fully satisfied.

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SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
Environmental impact	Improvement of all KPIs relative to environmental impact	Fully covered	The KPIs relative to environmental efficiency are computed for the reference scenario. Once applied the models, the same KPIs are computed for the solution scenarios obtained.	The success criteria are different for Initial and Full Solutions. For the Initial one the success would be achieved with the reduction of ENV1, while for the Full Solution, the success is the reduction of the climate impact of CO_2 and non-CO_2.
Congestion reduction	Capacity violations are minimised	Fully covered	Check whether the models always minimise flight sector and airport capacity violations	The overall number of capacity violations show an improvement from the reference scenario to the solution scenario.

B.1.4 Summary of validation exercise #02 validation scenarios

B.1.4.1. Initial GRC Solution

The Initial GRC Solution is tested on a set of instances of real European air traffic data from 2019 consisting of 56 days of traffic have been chosen: 28 days of congested traffic and 28 days of low traffic volume (details in B.1.5.1). Such a choice allows to validate the effectiveness of the route calculated route charging schemes under different level of traffic, enabling the comparison with the actual historical situation. In other words, thanks to the historical data we can evaluate the real performance of the network according to the selected KPIs and, via the simulation of the traffic when reacting to the new route charging scheme, we can create a what-if scenario and measure the effects on the same KPIs.

For the validation of the exercise the reference scenario is simply represented by the traffic of the selected days. We once again remark that the flight patterns, as revealed by the data, provide the foundation for establishing initial benchmarks for both the Initial and Full Solutions. These benchmarks encompass several critical aspects: environmental impact, congestion levels, delays, and operational costs.

It is important to note the distinction in how these benchmarks are derived. Congestion levels and delays are directly extracted from the available flight data, providing immediate and accurate

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measures. In contrast, environmental effects and operational costs require estimation through post-processing techniques, as direct data for these factors are not available in the dataset.

This approach combines directly observed metrics with calculated estimates to create a comprehensive baseline, which is crucial for assessing the potential improvements and impacts of both the Initial and Full Solutions across these key performance areas. By using real-world flight data as a starting point, the analysis ensures that the benchmarks reflect actual operational conditions, providing a realistic foundation for evaluating the proposed changes in the Green Regional Charging system.

To compare the performance of the network with the actual traffic, the Solution scenario is represented by the simulated traffic resulting from the implementation of the computed new route charges on the same days with respect to the ones of the reference scenarios.

Table 23 Initial Solution exercise #02 scenarios.

Scenario	Description
Reference scenario	Planned traffic (FTFM) for the AIRAC cycles considered.
Solution scenario	Same traffic as reference scenario to which the modulation mechanisms are applied.

B.1.4.2. Full GRC Solution

For this exercise, the Full Solution is using wider example for the validation scenario. Here, we are using the 10 busiest airports in Europe, covering a wide geographical area, but not the full ECAC area and traffic. The three scenarios are applied, as in exercise #01, and described in Table 24.

Table 24 Full Solution exercise #02 scenarios.

Scenario	Description
Benchmark scenario – 'free'	Idealised scenario where airspace capacities are infinite and airlines do not have constraints on their routes, apart from their utilities
Reference scenario – 'cap'	This is an optimised scenario where capacity constraints are enforced through strategic delays, applied on the sectors. This is the closest scenario to the present situation.
Solution scenario – 'full'	This is an optimised scenario where a central planner tries to minimise the environmental impact while capacity constraints are enforced. This represents the closest situation to what the system with the full solution would look like. In this situation, the central planner can play with the EI rate, a multiplicator factor to decrease the revenue of the CRCO charges (to keep revenue neutrality), and delays applied to sectors.

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B.1.5 Summary of validation exercise #02 validation data description

Data considered: historical traffic, historical state of the airspace environment, and cost estimations of delay. The traffic and airspace were from the EUROCONTROL Demand Data Repository (DDR2) [21]. Delay cost estimations have been made according to the methodology of report of Cook and Tanner (2015) [22].

B.1.5.1. Initial GRC Solution

Description and filtering

Raw data from DDR2 for the considered AIRAC cycle were loaded in NEST from which the required data were exported.

Historical traffic was exported in EXP2/T5/SO6 format, representing:

- EXP2: flights, with detailed information.
- T5: intersection of flights with airspace elements (sectors, ACC, FIR, etc.).
- SO6: segments representing flights trajectories.

Airspace environment data used:

- GSL: describe how airspace elements are built from airblocks.
- NCAP: contains the declared capacities of airspace elements and airports.
- NTFV: details traffic volumes and their flows.
- NARP: describe airports’ location and characteristics.
- MWC: contains the MTOW of the aircraft.
- CRCO: details intersections of flights with ANSPs.
- UR: provides Unit Rates of CRCO (and adjacent) states.

Fields considered were origin and destination airports, aircraft type, departure day and time, declared fuel consumption and flight ID. For the trajectories and the timings, we considered only the filed tactical flight model (FTFM).

Several fields were calculated for each flight, merging data from the other traffic and airspace environment files: MTOW of aircraft, flight length and duration, and, for each intersection of the flight trajectory with elementary sectors, their name, distance flown, and time spent in them. In addition, intersections with ANSPs were taken into account, to compute route charges.

From the list of flights we removed:

- entries with aircraft type representing helicopters, since their management was out of the scope of this work;

- flights not departing or arriving in ECAC (and adjacent) states;
- flights with duplicated flight ID, because in most cases they represented exceptional behaviours and their contribution was negligible (they were less of 0.05% of the total).

The AIRAC cycles taken into account was 1902 (from 31/01/2019 to 27/02/2019) and 1910 (from 12/09/2019 to 09/10/2019).

This resulted, for the AIRAC cycles considered, in 1,655,071 flights between 59,590 origin-destination pairs. Every day considered had between 16,279 and 36,101 flights departing on that day. For each airport and each sector, the declared hourly capacity for each day in the AIRAC cycle was considered. Since we observed that, for some sectors/airports in a specific hour, the entry count was much greater than the declared capacity, we choose to consider the capacity as follows.

For each sector and airport flow (global, departures, arrivals) in each hour of the AIRAC cycle considered:

1. we computed the entry count from FTFM;
2. if the entry count did not exceed the declared capacity for more than 10%, we used the declared capacity as reference, otherwise we considered the entry count.

Parameter settings and computational set up

All models take into account the traffic which depart (and/or) arrives at an airport included into a CRCO area. However, for flights departing or arriving outside the CRCO area, the CRCO route charging cost represents only a fraction of the total en route operational costs, so their weight in the route planning is potentially only marginal. For this reason, when solving M3 we do not consider re-routing options for these flights assigning them directly to their planned route. For all other flights with a great circle distance between origin and destination airports greater than 300 kilometres, route options have been computed with a clustering methodology similar to the one proposed by [19], and, in order to remove outliers (anomalous trajectories or test flights), trajectories which were longer than the shortest trajectory of the same origin-destination pair for more than the 20% have been discarded. To estimate constants ρ and $\bar{c}_s$ for M1 and M2, in the first case we used the total number of flights with the same origin destination of the whole dataset divided by the number of days considered, multiplied by the number of hours in a day. For the value of the sector capacity we used for each sector its declared capacity reached within the considered period.

B.1.5.2. Full GRC Solution

The data description can be found in section Appendix AA.3.2.2.4.

The only difference is that this exercise is performed on flights between 10 busiest European airports: LFPG, LEMD, EDDF, EGKK, LIRF, LEBL, EHAM, LTFM, EGLL.

B.1.6 Summary of validation exercise #02 validation assumptions

In addition to those described in section 3.2.3, the assumptions regarding the data presented in B.1.5.1 are used.

B.2 Deviation from the planned activities

There are no deviations from the planned activities.

B.3 Validation exercise #02 results

B.3.1 Summary of validation exercise #02 results

Table 25 Summary of validation exercise #02 results.

Exercise #02 validation objective ID	Exercise #02 validation objective title	Exercise #02 success criterion ID	Exercise #02 success criterion	Sub-operat-ing environ-ment	Exercise #02 validation results	Exercise #02 validation objective status
OBJ1	Feasibility	Exercise #02 success criterion #1.1	Each model assumption (Section A.1.1) has to be fully satisfied.			Ok
OBJ2	Environmental impact	Exercise #02 success criterion #1.2	The success criteria are different for Initial and Full Solutions. For the Initial one the success would be achieved with the reduction of ENV1, while for the Full Solution, the success is the reduction of the climate impact of CO_2 and non-CO_2.			Ok
OBJ3	Congestion reduction	Exercise #02 success criterion #1.3	The overall number of capacity violations show an improvement from the reference scenario to the solution scenario.			Ok

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B.3.2 Analysis of validation exercise #02 results

In the following sections the results of each part of the validation exercise #02 are presented.

B.3.2.1. Initial Solution – Modulation of route charges

Running the modulation of route charges mechanism even on a single day of full ECAC area traffic requires a significant amount of computation time. The annual volume of flights is such that a single model capable of handling the whole year traffic at once would result intractable. To overcome these limitations, we develop a refined version of MRC model, that tackles the issue by dividing the problem into three sub-tasks: starting from statistics on the average hourly demand of each OD and considering system capacity, a first continuous linear programming model establishes how to redistribute the traffic flow to simultaneously reduce emissions and limit congestion levels. A second linear programming model establishes the modulation factor of each trajectory in such a way to incentivise airlines to fly the trajectories chosen by the first model while preserving ANSPs' appropriate income with respect the assigned workload (measured in service units). Once trajectories modulation factors are determined, a third integer linear programming model takes care of daily traffic management, treating each flight as a separate variable for which it is necessary to decide the route and/or a shift in departure time.

By using this multi-stage procedure, we were able to compute the results of eight weeks of traffic, i.e. AIRAC 1902 and 1910, in a very reasonable amount of time (less than 5 hours of computation). Modulation factors were computed once using the aggregated statistics from both periods.

In the following sections, the results of each validation objective are presented. For each AIRAC cycle, the aggregated KPIs for reference and solution scenario are compared.

OBJ1 – Feasibility

The modelling and the implementation of MRC are compliant with the stakeholders' requirements, implemented as models' constraints, and the modelling assumptions described in section A.1.1 related to the Initial Solution (A1 to A4) have been properly captured in the model.

This is a consequence of validating the model on a reduced scale, as done for the Exercise #01.

OBJ2 – Environmental impact

The success criterion of OBJ2 is the reduction of KPI ENV1 (the amount of fuel burnt x 3.15 (CO_2 emission index) divided by the number of flights [kg CO_2/flight]). To assess the environmental impact of MRC, we compare also, for both AIRAC cycles considered, the distance flown and the fuel consumption. Table 26 evaluates all flight departing **or** arriving in ECAC (and adjacent) states, while Table 27 evaluates flights departing **and** arriving in ECAC (and adjacent) states.

From Table 26 we can see that applying MRC always lowers all the KPIs, with respect to the reference scenario. For AIRAC 1910 the reduction of the distance flown is 0.661%, corresponding to a reduction of fuel consumption of 0.412% and a reduction of ENV1 by 0.412%. For AIRAC 1902, representing a low traffic period, the reduction is lower but significant.

Considering only flights departing and arriving in ECAC (and adjacent) states, Table 27, the reduction for a high traffic period (AIRAC 1910) is bigger – distance flown 1.384%, fuel consumption 1.364%, ENV1 1.364%. This behaviour was expected, since the trajectory of flights departing or arriving outside

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ECAC states has deliberately not been affected by MRC. Also in this case, the reduction for a low traffic period is lower.

Table 26 Environmental performance indicators of MRC model applied to two AIRAC cycles, one of high traffic and one of low traffic, considering flights departing or arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Distance flown	Diff	Fuel consumption	Diff	ENV1	Diff
1902	Reference	725,431	1,325,262	/	7,297,870	/	31689	/
1902	MRC	725,431	1,319,492	-0.435%	7,279,678	-0.249%	31610	-0.249%
1910	Reference	929,640	1,726,552	/	8,946,937	/	30316	/
1910	MRC	929,640	1,715,138	-0.661%	8,910,106	-0.412%	30191	-0.412%

Table 27 Environmental performance indicators of MRC model applied to two AIRAC cycles, one of high traffic and one of low traffic, considering flights departing and arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Distance flown	Diff	Fuel consumption	Diff	ENV1	Diff
1902	Reference	571,746	571,876	/	1,870,955	/	10308	/
1902	MRC	571,746	566,106	-1.009%	1,852,762	-0.972	10208	-0.970%
1910	Reference	739,305	824,530	/	2,701,070	/	11509	/
1910	MRC	739,305	813,116	-1.384%	2,664,238	-1.364%	11352	-1.364%

OBJ3 – Congestion reduction

To assess the congestion, we evaluate the overall number of capacity violations and check if they show an improvement from the reference to the solution scenario.

From the Table 28 below, we can see that the number of capacity violations decreases in both the high and low traffic periods considered. In particular, the capacity violation reduction is massive, ranging from 91.2% for high traffic period to 94.1% for low traffic period.

CAP2 were not considered in this validation exercise, since the capacity violations is a more accurate indicator for the congestion.

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Table 28 Congestion performance indicators of MRC model applied to two AIRAC cycles, one of high traffic and one of low traffic, considering flights departing or arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Capacity violations	Diff
1902	Reference	725,431	3,160	/
1902	MRC	725,431	188	-94.1%
1910	Reference	929,640	7,493	/
1910	MRC	929,640	658	-91.2%

Additional results

Here we present further results, taking into consideration only high traffic period, i.e., AIRAC 1910.

AUs cost analysis (AUC3)

The modulation of route charges, and the introduction of a time shift clearly influence flight costs. The table below presents summary statistics on how MRC model impacts costs for AUs. The columns labelled "Diff" show the differences between the total original costs of all flights (including total, RC, and fuel costs) and the costs after applying MRC. There is an average reduction in total costs. Notably, while RC costs are reduced, they still account for approximately 25% of the total costs. This indicates that the main driver of overall cost savings is the reduction in fuel costs across all scenarios.

Table 29 shows the proportion of flights whose costs increased, decreased, or remained nearly the same compared to the baseline. Flights categorized as having the "Same cost" experienced changes of less than 1%. Importantly, the majority of flights are not significantly affected in terms of cost, a small share sees cost increases, and a substantial portion benefits from cost reductions.

Table 29 Cost analysis for AUs, comparing total cost, divided in RC and Fuel cost.

Total cost		RC cost		Fuel cost	
Diff	%	Diff	%	Diff	%
-8,350,052	-0.1%	-5,859,330	-0.8%	-22,142,436	-0.4%

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Table 30 Cost change distribution of flights whose costs increased, decreased or remained nearly the same compared to the baseline.

Distribution		
Increased	Decreased	Same cost
8.8%	25.4%	65.8%

ANSPs income analysis

Changes in AUs' expenses are reflected in ANSPs' revenues, and varying traffic configurations also influence their workload. Table 31 presents statistics on the overall variations in revenue and workload (measured in service units) compared to the baseline scenario.

As expected, the model shows a revenue decrease that is proportionally similar to the reduction in AUs' RC costs (see RC cost % in Table 31). While total Service Units also decrease, the decrease is not directly proportional to the reduction in distance flown (Diff columns in Table 31). This is because Service Units, even though correlated to the total distance flown of a flight, depend on the great circle distance, which might not vary linearly with the change of trajectory length.

Focusing on the ANSP-specific analysis, Table 31 reports the maximum, minimum, mean, and standard deviation of the percentage change in service costs. There is an average increase of 0.3%, and the minimum and maximum variations stay within the ±2% range. This is illustrated in Figure 9, where ANSPs are ordered by revenue change for each model. The top plot displays differences in Service Units, and the bottom plot shows revenue differences. In all cases, the two plots closely align, indicating that the ratio between revenue and workload remains approximately stable.

Table 31 ANSPs revenue-workload and cost of service statistics.

Total % difference		Cost of service % diff. per ANSP			
Revenue	Service Units	Max	Min	Mean	Std
-0.72	-0.20	1.80	-0.06	0.3	0.37

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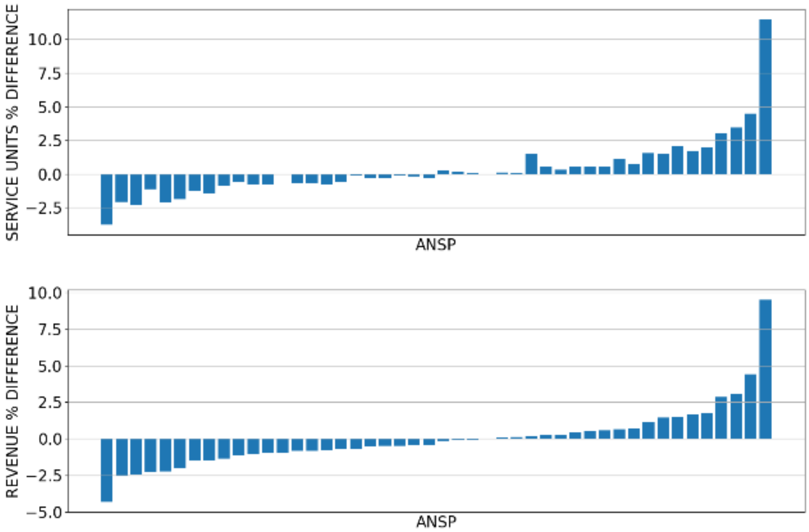

Figure 9 Top, service units difference, for each ANSP. Bottom, revenue difference, for each ANSP.

Explanatory example

To facilitate the MRC rationale, we show here two representative examples of ODAs (Figure 10 and Figure 11) where we compare two possible routes, reporting the respective original costs (pre-MRC) and modulated cost (post-MRC).

In the first (Figure 10), we have two routes for the A320 aircraft departing from Istanbul (SAW) and arriving Barcelona (BCN). Route A (yellow in the Figure 10) is 171 km longer than the Route B (the blue one). However, also considering the fuel costs, due to the route charges A was initially cheaper than B. Thanks to the MRC modulation the order of the costs is inverted, and the shortest route becomes the most convenient.

The second example is slightly different. We here consider two routes still for the A320 but connecting Istanbul (IST) and Paris (CDG). After the modulation both routes result having the same price. Here, the model chose to leave some flexibility to better handle the congestion considering the traffic configuration of the whole airspace: in fact, if the model predicts some demand/capacity unbalance on one of the areas involving one of the routes, the equivalence of the prices allows to use both routes to distribute the traffic without penalising some flights at the expense of some others, and avoiding the overload of the critical sectors.

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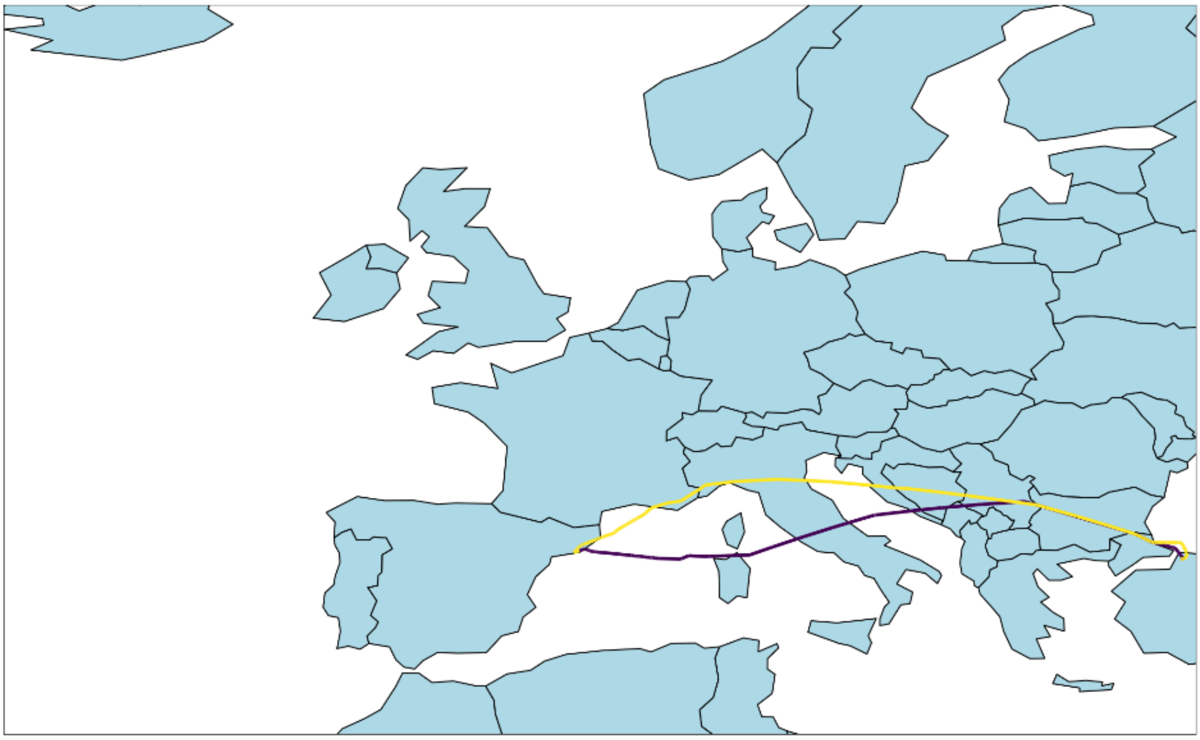

Figure 10 Trajectory example of a A320 flight from Istanbul (SAW) to Barcelona (BCN).

Table 32 Comparison of routes of Figure 10.

	Route A		**Route B**	
Length (km)	2615		2444	
Fuel cost (€)	3722		3691	
	Initial	**Modulated**	**Initial**	**Modulated**
RC (€)	1388	1666	1558	1166
TOT (RC + Fuel, €)	**5110**	5388	5249	**4857**

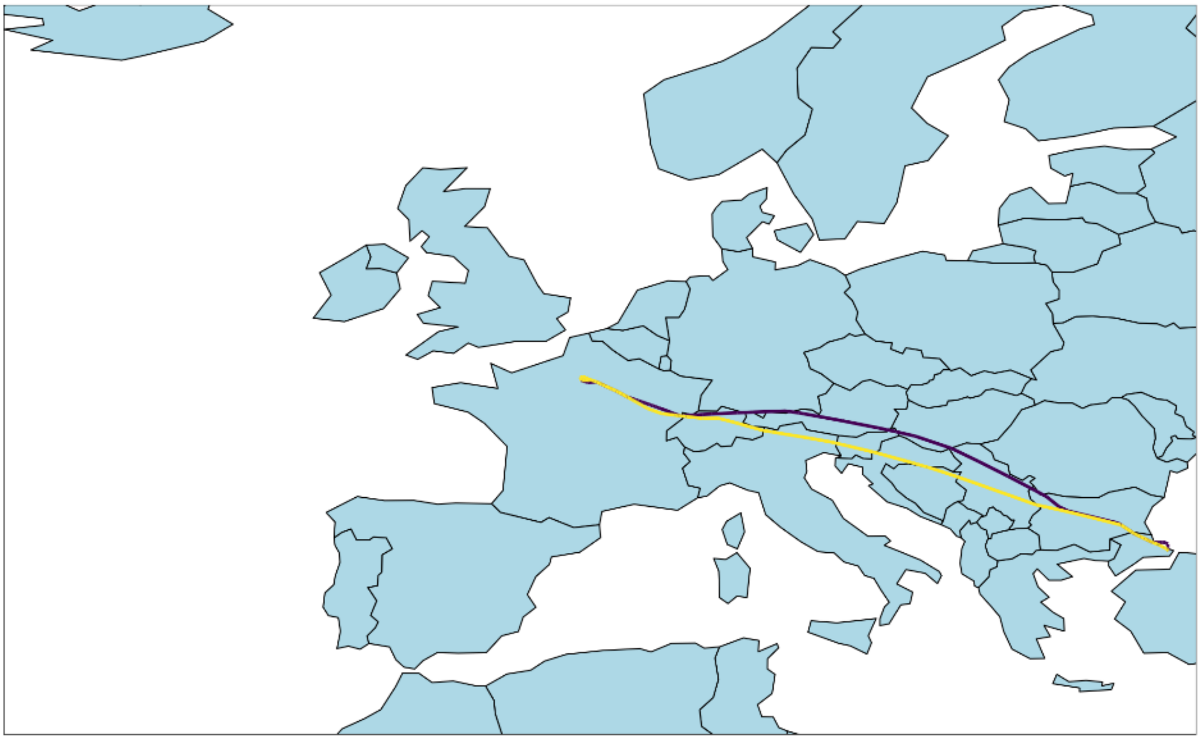

Figure 11 Trajectory example of a A320 flight from Istanbul (IST) to Paris (CDG).

Table 33 Comparison of routes of Figure 11.

	Route A		Route B	
Length (km)	2312		2282	
Fuel cost (€)	5086		5072	
	Initial	**Modulated**	**Initial**	**Modulated**
RC (€)	1346	1616	1407	1630
TOT (RC + Fuel, €)	**6432**	6702	6479	**6702**

B.3.2.2. Initial Solution – Origin-destination charging with modulation of route charges

For ODC+MRC the same methodology explained in B3.2.1 is used, with the exception of the route charging mechanism from which the modulation starts.

In the following sections, the results of each validation objective are presented. For the period considered, the aggregated KPIs for reference and solution scenario are compared.

OBJ1 – Feasibility

The modelling and the implementation of ODC+MRC are compliant with the stakeholders' requirements, implemented as models' constraints, and the modelling assumptions described in section A.1.1 related to the Initial Solution (A1 to A4) have been properly captured in the model.

This is a consequence of validating MRC during exercise #01, since the model of ODC+MRC is the same of MRC, except from the different charging method from which the model starts.

OBJ2 – Environmental impact

The success criterion of OBJ2 is the reduction of KPI ENV1 (the amount of fuel burnt x 3.15 (CO_2 emission index) divided by the number of flights [kg CO_2/flight]). To assess the environmental impact of ODC+MRC, we compare also the distance flown and the fuel consumption. Table 34 evaluates all flight departing **or** arriving in ECAC (and adjacent) states, while Table 35 evaluates flights departing **and** arriving in ECAC (and adjacent) states.

From Table 34 we can see that applying ODC+MRC always lowers all the KPIs, with respect to the reference scenario. For AIRAC 1910 the reduction of the distance flown is 0.696%, corresponding to a reduction of fuel consumption of 0.435% and a reduction of ENV1 by 0.435%.

Considering only flights departing and arriving in ECAC (and adjacent) states, Table 35, the reduction is bigger – distance flown 1.457%, fuel consumption 1.440%, ENV1 1.442%. This behaviour was expected, since the trajectory of flights departing or arriving outside ECAC states has deliberately not been affected by ODC+MRC.

Table 34 Environmental performance indicators of ODC+MRC model applied to one AIRAC cycle, considering flights departing or arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Distance flown	Diff	Fuel consumption	Diff	ENV1	Diff
1910	Reference	929,640	1,726,552	/	8,946,937	/	30316	/
1910	ODC+MRC	929,640	1,714,535	-0.696%	8,908,046	-0.435%	30184	-0.435%

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Table 35 Environmental performance indicators of ODC+MRC model applied to one AIRAC cycle, considering flights departing and arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Distance flown	Diff	Fuel consumption	Diff	ENV1	Diff
1910	Reference	739,305	824,530	/	2,701,070	/	11509	/
1910	ODC+MRC	739,305	812,512	-1.457%	2,662,179	-1.440%	11343	-1.442%

OBJ3 – Congestion reduction

To assess the congestion, we evaluate the overall number of capacity violations and check if they show an improvement from the reference to the solution scenario.

From Table 36, we can see that the number of capacity violations decreases in the period considered of 90.9%.

Table 36 Congestion performance indicators of MRC model applied to one AIRAC cycle, considering flights departing or arriving in ECAC (and adjacent) states; comparison with reference scenario.

AIRAC cycle	Scenario	No. of flights	Capacity violations	Diff
1910	Reference	929,640	7,493	/
1910	ODC+MRC	929,640	685	-90.9%

B.3.2.3. Full solution

In this section, we present the results obtained with the model for the full solution on the big scenario. As seen in Figure 12, this scenario encompasses most of the core of the Europe, with medium- and long-haul flights. As with the small scenario, only two routes per OD were considered, and only the sectors crossed by these routes are used.

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Figure 12 Map for the big scenario.

Figure 13 shows the results of the 'full' optimisation, as a function of different capacity modulations. Capacity modulations are used as a sensitivity analysis, in order to test the impact of the level of stress/congestion on the system. When a modulation of X% is applied, all sector capacities are multiplied by this factor. As can be seen on Figure 13, the optimal EI rate is set by the optimiser depending on the state of the system. In this case, it seems that the optimal EI rate is around 10€/nK most of the time, with a corresponding decrease in route charges of 18% or so (to keep ANSP revenue neutrality). When less capacity is available, it seems that the optimal point for the system switches to around 2€/nK and around 2% or decrease for the route charges.

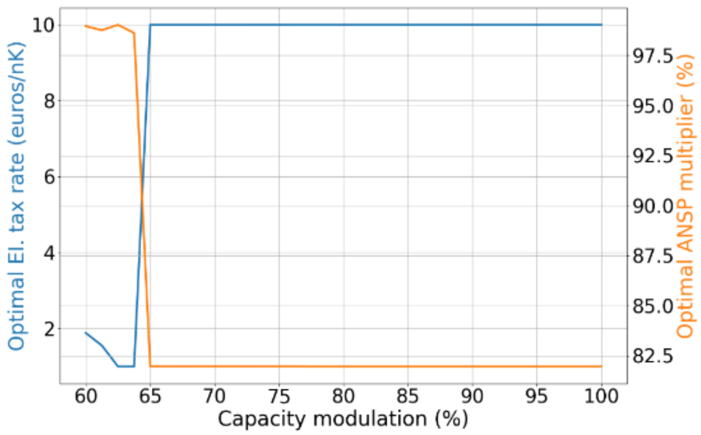


Figure 13 Optimal EI rate and ANSP revenue multiplier.

The capacity modulation has other impact on the system. As shown in Figure 14 on the left, the savings in terms of emissions depend a lot on the congestion level. In these plots, we show the difference between the 'free', 'cap', and 'full' computation modes/scenarios[9]. As expected, the EI in the full optimisation is always smaller than in the 'cap' mode, since the latter only solves for capacity congestion. Note that the EI almost always increases when capacity decreases, as also shown in the exercise #01. The EI increases much faster when the capacity decreases in the 'cap' case compared to the 'full', but it can be seen on the far left of the plot that EI starts to increase even in the 'full' mode when capacity is very scarce.

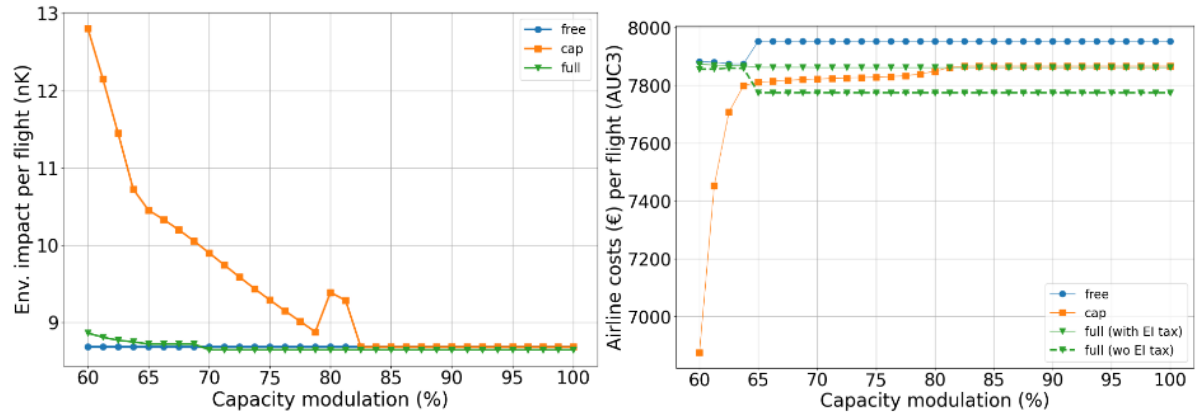
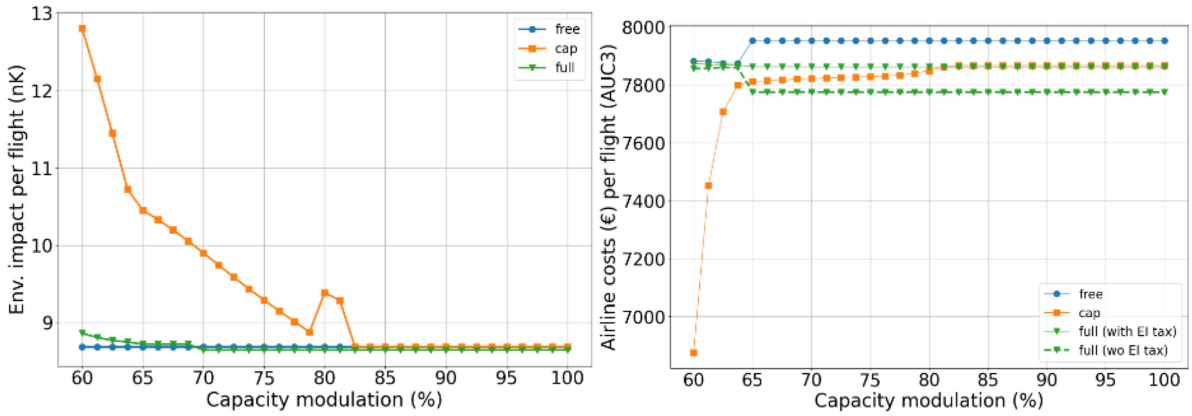


Figure 14 EI and airline costs per flight.

The level of congestion also has an impact on the airline costs, albeit a non-trivial one. We show in



on the right the airlines' costs, and for the full mode we show the difference between the costs (only fuel and route charges) without the EI rate[10], and with the charges. In general, at high capacity, the

[9] As a reminder, the 'free' mode is just a computation of the KPIs assuming no optimisation other than the utility maximisation of the airlines, and no capacity constraints. The 'cap' mode features an optimisation loop with solves capacity overloads by setting delays to flights. The 'full' mode, on the capacity, solves the system for minimum EI.

[10] Note that we use EI rate and EI tax interchangeably.

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costs are very similar in the 'cap' and 'full' modes, if one takes the EI tax into account. It looks like most of the increase in costs due to the EI rate is offset by the decrease in route charges. When capacity drops, the costs per flight starts decreasing slowly and then more sharply in the 'cap' phase. The costs in the 'full' case are always higher, as expected, since the 'full' optimisation does not solve for minimum cost, but for minimum EI.

Note that, because we apply very harsh types of constraints (applying same delay over all time windows for a given sector), the system starts 'losing' flights quite early when the capacity drops (they are pushed out of the last time window), see Figure 15. This has an effect on the statistics if the more or less expensive flights are lost first. In this case, it looks like the expensive flights are lost first, by chance, leading to a decrease in airline cost per flight. Note that the number of dropped flights does not drop as quickly in the 'full' scenario, leading to a more stable cost per airline.

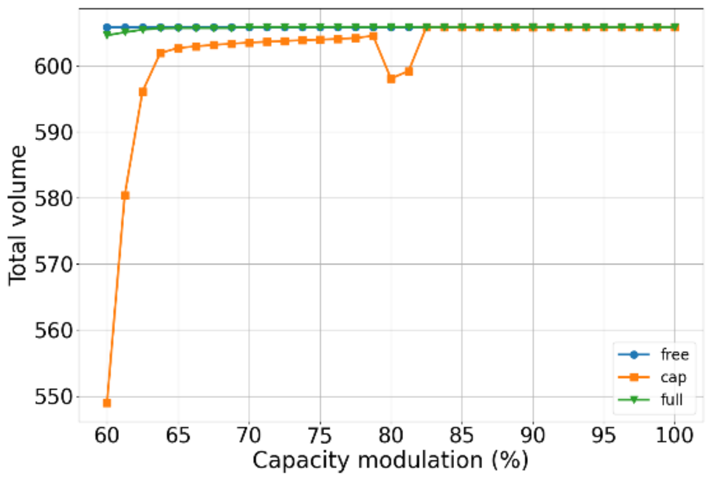

Figure 15 Number of flights.

Finally, we are interested in seeing the difference between the actual environmental impact and the one computed internally by the model using the hotspot. Indeed, as a reminder, the model takes into account only flights that are going through a hotspot to measure the environmental impact. This is an approximation made for simplicity of the operational solution and tractability of the model. However, one can also take into account the fact that flights not crossing hotspots can also have a significant impact. In Figure 15, we show the difference in the two evaluations of the impact, **only using the approximate EI in the optimisation process**, but measuring the two metrics post-simulation. From this plot, it can be seen that using approximate metrics in general is almost as good as the full one, with an error of 0.4% or so. Moreover, it looks like the error is systematic, which in principle could be corrected ex ante in the model. This is a strong argument in favour of a full solution designed around hotspot instead of full emissions taxes/incentive schemes.

Finally, we show in Figure 16 an estimation of the SESAR KPIs that are computable with this model, plus the ATR20 one, used in the simulation to estimate the environmental impact (note: here shown for at 70% of capacity). The KPIs are defined in section Appendix AA.3.2.2.2, Table 11. Overall, the impact of the full solution on the KPIs is nearly neutral (slightly negative), except for ATR20. This is to be expected, since the point of the full solution is indeed to reduce non-CO2 emissions, which were not captured by other KPIs.

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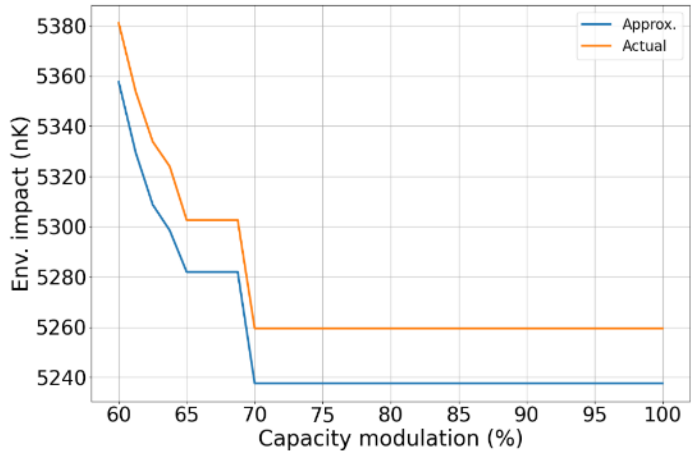

Figure 16 Environmental impact computed using the hotspot approximation and the full distribution of impact.

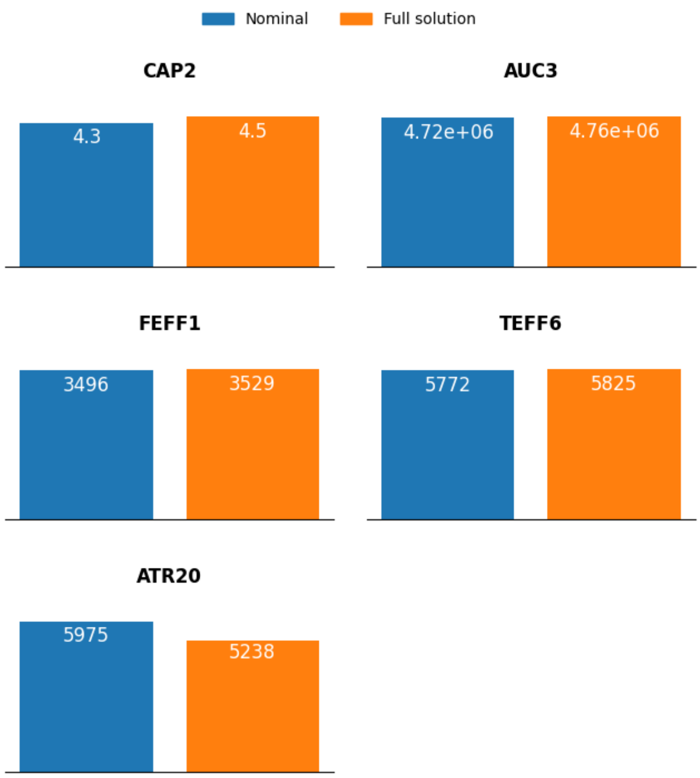

Figure 17: Estimation of SESAR KPIs and ATR20 in the reference/nominal ('cap') and full solution ('full'). CAP2 is in number of movements, AUC3 in euros, FEFF1 in kg of fuel, TEFF6 in minutes, ATR20 in nK.

B.3.3 Unexpected behaviours/results

Not present.

B.3.4 Confidence in results of validation exercise #02

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

Initial GRC Solution. The sample used in this analysis, although it covers two complete AIRAC periods, which have been selected to be representative enough—one with high traffic and one with moderate traffic—represents only a portion of the entire year. Therefore, the behaviour modelling is subject to limitations, as it is based on just 8 weeks out of the 52 in a calendar year. In addition, the estimates of fuel and delay costs play a crucial role, and even small variations in these values can significantly affect the results.

Full GRC Solution. The results significance is limited by the size of the Solution scenario applied – traffic between 10 busiest airports in Europe. The route charging mechanism is applied to the entire CRCO network, for all flights, not only for this selection, however significant it is. Furthermore, these are the assumptions used in the exercise that are somewhat limiting the representativeness of results:

- the information on the airspace capacity used is limited in scope, and should be extended for a fuller analysis,
- having only two routes per OD pair to choose from is also a limitation, which should be addressed in the future,
- the choice of the EI threshold needs to be discussed with a wider community and decided on the value/percentage that makes environmental and operational sense,
- the reduction of the route charges experimented is done through the optimisation, but it should also be tested with the ANSPs, CRCO and AUs, in terms of operational implementation.

B.3.4.2. Quality of validation exercises results

Initial GRC Solution. Exercise #02 improved representativeness by incorporating two complete AIRAC cycles (covering both peak and off-peak periods), yet its eight-week scope still omits potential seasonal variations and exceptional operational scenarios. Consequently, while demonstrating consistent performance across examined conditions, projecting these results across an entire calendar year introduces uncertainties. A notable sensitivity exists regarding fuel cost and delay assumptions, which substantially influence cost-benefit analyses and could meaningfully alter conclusions about economic and environmental impacts. This dependence highlights the importance of ongoing refinement of foundational assumptions to enhance result dependability.

Nevertheless, the systematic validation approach - employing diverse traffic scenarios and comparative benchmarking against reference cases - bolsters confidence in the models' consistency and precision. The documented improvements in emissions reduction, congestion mitigation, and cost efficiency align with theoretical projections, substantiating the solution's core principles. It should be noted, however, that the quantitative improvements observed should be viewed as directional indicators rather than definitive values, given the inherent limitations of the validation framework's scope and coverage.

Full GRC Solution. The results obtained in the exercise are valuable as they point to the potential benefits. The quality however, is limited by the same factors described above.

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B.3.4.3. Significance of validation exercises results

Initial GRC Solution. Exercise #02 substantially enhanced the validation framework by incorporating two complete AIRAC cycles (1902 and 1910) representing both low and high traffic periods. This expanded dataset, covering eight weeks of operations, provided significantly greater statistical reliability than Exercise #1, particularly in demonstrating consistent performance across different demand scenarios. The larger sample size and inclusion of seasonal variability strengthened confidence in observed improvements for key metrics like fuel efficiency (0.249-1.364% reductions) and congestion mitigation (91.2-94.1% violation decreases). However, the continued reliance on 2019 data and exclusion of atypical operational scenarios (e.g., major disruptions) means the exercise could not fully capture the complete range of real-world conditions. Operationally, Exercise #02 more comprehensive validation confirmed the solution's scalability and its ability to maintain performance benefits across different traffic volumes. The persistent sensitivity to fuel cost assumptions and the ECAC-specific focus remain important considerations, but the exercise successfully demonstrated that core benefits observed in Exercise #01 controlled environment translate effectively to broader operational contexts.

Full GRC Solution. The highest significance can be given to analysing additional climate considerations. Due to the dynamical nature of the non-CO2 emissions, the project needed to clarify whether a concept based on the concept of a climate hotspot could be applied, and then what would be the impact on aviation emissions. The results demonstrate that the hotspot concept could be used in route charging scheme, as the environmental impact diminishes. However, these results should be further analysed to account for limitations mentioned above.

B.4 Conclusions

B.4.1 Conclusions on concept clarification

Initial GRC Solution. The expanded validation in Exercise #2 reinforced and enhanced these findings through comprehensive testing across two full AIRAC cycles (8 weeks covering high/low traffic periods). This exercise:

- Confirmed scalability: demonstrated consistent performance improvements across different traffic volumes (0.249-1.364% fuel savings, 91.2-94.1% congestion reduction)
- Validated robustness: maintained system stability while handling significantly larger traffic samples (725,431-929,640 flights)

While providing more statistically significant results, Exercise #02 still shared limitations with #01 regarding data vintage and lacked extreme scenario testing. However, its expanded scope substantially increased confidence in the solution's operational viability across normal traffic conditions.

The **Full GRC Solution** concept builds incorporates additional climate considerations.

This exercise further clarified the following:

- Most KPIs are slightly or neutrally impacted by the full solution, except for PI on full emissions,

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- The inclusion of CO_2 emissions in the total impact leads to less drastic changes of fuel consumption in general, and thus impacts airlines much less in terms of fuel costs.

The solution has demonstrated strong alignment with Digital European Sky performance objectives while maintaining operational practicality. The validation results provide sufficient confidence in the fundamental concept to proceed with further research, while highlighting specific areas needing additional clarification before full implementation.

B.4.2 Conclusions on technical feasibility

The GRC Solution proposes new route charging mechanisms. As such, these are not ATM Solutions per se, as no particular ATM system would be impacted. However, throughout the duration of the project, several aspects of the concept were clarified and the following new functions needed identified:

- Central planner that would determine the environmental modulation (in both Initial and Full Solution), and hotspots in the case of Full Solution, and then communicate the information to the airlines,
- MET provision of forecast for hotspot determination. The forecasts are already being provided in aviation. However, this particular forecast might need some specific additional requirements that should be further investigated.
- Flight planning software being to take new information (e.g. EI rate) in order to optimise to properly optimise trajectories.

B.4.3 Conclusions on performance assessments

Initial GRC Solution. The MRC (Modulated Route Charges) model has been successfully validated against stakeholder requirements and operational constraints, with all key assumptions (A1–A4) from the Initial Solution properly integrated. This feasibility was confirmed through preliminary small-scale testing (Exercise #01), ensuring the model's structural soundness before broader application.

In assessing environmental impact (OBJ2), the MRC model demonstrated consistent reductions in CO_2 emissions, fuel consumption, and distance flown across both high and low traffic periods (AIRAC 1910 and 1902). For flights departing or arriving in ECAC (and adjacent) states, the high-traffic period saw a 0.66% reduction in distance flown, 0.44% lower fuel burn, and 0.41% decrease in CO_2 emissions per flight (ENV1). When focusing solely on flights departing and arriving within ECAC, improvements were more pronounced, with 1.38% less distance flown, 1.36% lower fuel use, and a 1.36% drop in ENV1—confirming that MRC's optimization is most effective for fully ECAC-contained routes.

For congestion reduction (OBJ3), the model delivered exceptional results, cutting capacity violations by 91.2% in high-traffic conditions and 94.1% in low-traffic scenarios. This sharp decline in airspace bottlenecks highlights MRC's ability to balance traffic flows efficiently while maintaining operational feasibility.

Overall, the validation confirms that MRC effectively enhances environmental performance and reduces congestion, with particularly strong results for flights operating entirely within ECAC airspace.

Full GRC Solution. . Regarding **the capacity**, the Full Solution shows that traffic moves around, but the capacity with the Full Solution could become slightly more saturated. Furthermore, an important

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finding is that when there is a lack of capacity, it is much less possible to reduce environmental impact of flights, as there is no space for manoeuvre left. For **the efficiency**, the FEFF1 and TEFF1 are slightly higher (less than 1%) in the solution scenario than in the reference one (see Figure 17 for details), which is a normal consequence of minimising the emissions instead of fuel. The **environmental impac**t for all emissions, as measured by ATR20, is 14% lower in the solution scenario. The incentivisation to minimise the environmental impacts, slightly increases the costs **(cost-efficiency KPA)** to airlines (AUC3), less than 1%. This is due to higher fuel consumption, and EI modulation rate. The ANSP revenues are held constant, which is aligned with only slight increase in capacity saturation. Other KPAs are not impacted by this solution.

B.5 Recommendations

The validation results show promising trends in environmental efficiency, congestion reduction, and cost savings, with consistent performance across various traffic scenarios. However, statistical certainty is limited by the small sample size and reliance on historical data, while operational realism is constrained by the lack of edge cases and potential shifts in aviation dynamics since 2019. To enhance significance, future validation should expand sample diversity, incorporate recent operational data, update aircraft fuel consumption metrics, and conduct sensitivity testing on critical assumptions. While current results indicate potential, further validation under broader and updated conditions will improve statistical confidence and operational applicability.

We also remark how the Exercise #2 results highlighted that the MRC and the ODC+MRC provide very similar performance with respect to all KPIs. Although this fact suggests the effectiveness of both mechanisms, the ODC+MRC requires a significant change from the regulatory perspective. Since, on the other hand, the MRC has much lower impact on the existing rules, further development efforts should probably focus more on this simpler but equally performing framework.

The validation results demonstrate promising trends in environmental efficiency, congestion reduction, and cost savings, supported by consistent performance across different traffic scenarios. However, the limited sample size and reliance on historical data temper the statistical certainty, while operational realism is constrained by the absence of edge cases and potential shifts in aviation dynamics since 2019.

To strengthen the concept and the significance of results, future validations should:

- Increase sample diversity (e.g., more AIRAC cycles, extreme traffic conditions).
- Incorporate recent operational data to reflect current aviation trends.
- Incorporate up-to-date/new aircraft fuel consumption performance data.
- Conduct sensitivity testing on critical assumptions to assess their influence on model outcomes.
- Improve the capacity input data and test its impact on the traffic re-distribution and environmental impact values.
- Include the assessment of equity for different AUs and ANSPs.

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- Assess the impact of forecast uncertainties on the proposed mechanisms (see next section for detailed discussion).
- Perform targeted Monte-Carlo simulations with the full solution and/or develop new analytical methods to deal with the dimensionality of problem (lots of routes, lots of airlines).
- Requirements analysis (from technical and operational points of view) for the three identified new functions: central planner, MET provision of non-CO_2 forecast and inclusion in flight planning software.

The forecasting for climate impact determination still needs research in terms of uncertainties and setting of the appropriate threshold for minimisation of aviation climate impact. This would need discussions between atmospheric scientists and operational stakeholders (AUs and ANSPs) to understand the climate impact and what can be done operationally to diminish it. Furthermore, given the necessity for transparency in charges, it is crucial that all stakeholders utilise the same information, which would require the establishment of new functions to source, compute, and disseminate this information among all stakeholders (see bullet points above).

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