European ATM Network Capacity Optimisation Measures: The Role of the EUROCONTROL Network Manager in Collaborative Decision-Making

AE5322: Thesis Control & Operations

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EUROCONTROL

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Thesis report

by

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Preface

In front of you lies the Thesis: *European ATM Network Capacity Optimisation Measures: The Role of the EUROCONTROL Network Manager in Collaborative Decision-Making*, work I have completed during the past year and which concludes my Sustainable Air Transport Master's program at the Faculty of Aerospace Engineering of the Delft University of Technology.

The course of work inside the EUROCONTROL Network Management Directorate, more precisely within the Operations Planning Unit of the Airspace and Capacity Division, the direct impact it has on the European Air Traffic Management Network, as well as the direct negotiation and interaction with various Stakeholders, were the source of inspiration for me to start this Thesis. Their ideas led me to consider the evaluation of a potential increase in decision power of the EUROCONTROL Network Manager in its relationship with stakeholders, which in turn would lead to a higher overall network performance — this being the research objective of this work.

I was privileged to have the opportunity to work again with Adelin Cîrstică and Goran Pavlović, as supervisors from EUROCONTROL — I much appreciate your continuous support, openness, step-by-step guidance and feedback throughout the entire process, helping me shape and keep the model within certain limits of realism.

I would like to thank Dr. Junzi Sun for being my supervisor on behalf of the TU Delft, for always being by my side with fresh ideas and suggestions, and for proposing the examination and use of game theory as a means of modelling and simulating the outcome sought after in the Thesis. I would also like to thank Dr. Ramon Dalmau, whom I have had several meetings with, after Dr. Sun introduced us.

A special thank you to professors Nikola Ivanov and Radosav Jovanović from the Faculty of Transport and Traffic Engineering at the University of Belgrade, the coordinators of the COCTA project — the main academic source of inspiration for this Thesis. I very much enjoyed the discussions we had, and surely hope our paths will cross again in the future. The latest developments on the Thesis, as well as the meeting with the academic, ANSP and airline stakeholders would have not been possible without you.

I would like to express my gratitude towards my family for constantly backing me throughout this difficult, but rewarding Master's programme — my father Bogdan, my brother Călin, my grandmother Adriana and my mother Anca — it was her who inspired me to pursue a path in aviation. Without your support, I could have not reached this far. I would also like to thank Alex, a fellow TU Delft colleague, for being a good friend, for getting along and learning much from each other from Day 1.

I cannot end the preface without being thankful to my girlfriend, Maria, for going on this academic path and pursuing this profile together — without you always being by my side every day, throughout the entire degree and not only, without your inspiration, endless support and understanding, none of this would have been possible.

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Nomenclature

Abbreviations

Abbreviation	Definition
ACC	Area Control Centre
ANS	Air Navigation Services
ANSP	Air Navigation Service Provider
AO	Aircraft Operator(s)
AoR	Area of Responsibility
AU	Airspace User(s)
ATC	Air Traffic Control
ATCO	Air Traffic Controller/Air Traffic Control Officer
ATM	Air Traffic Management
ATF(C)M	Air Traffic Flow (and Capacity) Management
CAA	Civil Aviation Authority
CDM	Cooperative/Collaborative Decision-Making
CTA	Control Area
CTM	Cooperative Traffic Management
COCTA	Coordinated capacity ordering and trajectory pricing for better-performing ATM
DDR	Demand Data Repository
ECAC	European Civil Aviation Conference
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
EC	European Commission
FAB	Functional Airspace Block
FMP	Flow Management Position
ICAO	International Civil Aviation Organisation
JU	Joint Undertaking
KPI	Key Performance Indicator
MTOW	Maximum Take-Off Weight
NEST	Network Strategic Tool
NM	Network Manager
NMD	Network Management Directorate
NMB	Network Management Board
NOP	Network Operations Plan
NSP	Network Strategic Plan
OPL	Operations Planning Unit
PRR	Performance Review Report
RAD	Route Availability Document
RPLC	Route Pricing Least-Cost Choice Assumption

Abbreviation	Definition
SAAM	System for Traffic Assignment and Analysis at a macroscopic level
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
SESAR	Single European Sky ATM Research
SOSc	Sector-opening Scheme
TMA	Terminal Manoeuvring Area
UAC	Upper Area Control Centre
UAS	Unmanned aircraft systems

Symbols

Symbol	Definition	Unit
f_b	Fuel burn	kg
f_c	Fuel cost	EUR
f_p	Fuel price	EUR/kg
$\dot{f}_b$	Fuel burn rate	kg/min
d_f	Distance factor	km
$p_i(s_i; S)$	Player payoff under the current mixed strategy	Dimensionless
$p_i(\pi_{ij}; S)$	Payoff if the pure strategy j were played	Dimensionless
R_c	Revenue drawn from route charges [ANSP]	EUR
$R_i(s_i)$	Regret vector for player i	Dimensionless
r_i	Adjustment rate	Dimensionless
$SU_{\text{en-route}}$	En-route service units	Dimensionless
s'_i	Current mixed strategy	Dimensionless
t	Crossing duration	min
u_r	Monthly-adjusted service unit rate	EUR
w_f	Weight factor	t
$w_{\Delta_{f_c}}$	Weight/coefficient of average fuel cost difference [AU]	Dimensionless
$w_{\Delta_{r_c}}$	Weight/coefficient of average route charges difference [AU]	Dimensionless
w_{Δ_t}	Weight/coefficient of average time difference [AU]	Dimensionless
w_{R_c}	Weight/coefficient of route charges [ANSP/AU]	Dimensionless
δ	Total delay [ANSP]	min
Δ_{f_c}	Average fuel burn cost difference [AU]	EUR
Δ_{r_c}	Average route charges difference [AU]	EUR
Δ_t	Average delay difference [AU]	min
$\phi_{ij}(s_i)$	Regret for a pure strategy j	Dimensionless

1
Introduction

This chapter lays down the premises which have led to the development of the problem to be researched. It begins with a description of EUROCONTROL - The European Organisation for the Safety of Air Navigation, then goes from top-to-bottom, describing the specific division, unit, and team under whose supervision and with whose assistance this thesis is written.

In the end, an opening to the problem is presented, which creates the link to further explanations.

1.1. EUROCONTROL

Founded in 1963, EUROCONTROL is a pan-European, civil-military organization dedicated to supporting European aviation.

The activity of EUROCONTROL focuses on operations, service delivery, concept creation, research, project implementation at a European level, performance enhancements, coordination with important aviation stakeholders at different levels, and support for the strategic orientations and future evolution of aviation [1].

1.2. EUROCONTROL Operations Planning Unit

The Operations Planning Unit (OPL) is part of the Airspace & Capacity Division inside the Network Management Directorate (NMD), which operates and supports the development of the ATM network in Europe. The smooth flow of traffic is ensured, and performance challenges are addressed strategically, operationally and technically.

1.2.1. Network Manager (NM) Strategic Team

The NM Strategic Team within the OPL contributes to an efficient planning of the Network at least 6 months before to 7 days before the day of operation. In this process,

- Stakeholders participate by providing insights into local operational challenges and potential solutions.
- Comprehensive simulations at local and network level are then performed to identify potential issues and their scale, as well as possible solutions to improve network performance.
- Remedial measures are then taken to mitigate these issues.
- The goal is to optimize the utilization of available capacity on the day of operations.

A result of this specific activity is the NOP (Network Operations Plan), which provides the users with an overview of the ATM Network's short- to medium-term operations, including anticipated network and local performance.

The NOP:

- Includes anticipated network and local performance, steps for improving capacity and flight efficiency, strategies for airport performance enhancement, and performance assessment.
- Provides both qualitative and quantitative insights into how changes will affect the functionality of the European ATM Network.

1.3. Relevant main past findings leading to the problem

Research conducted by a Consortium formed of the Faculty of Transport and Traffic Engineering of the University of Belgrade (UB-FTTE), the University of Warwick, the Worms University of Applied Sciences [2] under the auspices of the SESAR Joint Undertaking 2020 program, has tackled the issue of different planning horizons of capacity suppliers and aircraft operators [3]. As such, the aims of the *Coordinated capacity ordering and trajectory pricing for better-performing ATM — COCTA* research project are to:

- Strengthen the role of the Network Manager (NM) to address existing problems.
- Propose reforms in the regulatory framework based on thorough analysis.
- Propose the shift from current supply-driven approach to a demand-driven one, reducing excessive provision of airspace capacity and saving costs
- Empower the Network Manager (NM) to conduct trajectory pricing, providing route options to aircraft operators.

It has been acknowledged that the **inefficient airspace utilization** together with an **increasing demand** lead to a continuously growing congestion of the European airspace. Its effects are, among others, the generation of significant delays with their associated costs [4].

Hence, the possibility to **change the role of the Network Manager** from a "passive mediator […] to an active actor" in its relationship with the Aircraft Operators (AOs) and Air Navigation Service Providers (ANSPs) has been explored [4].

The Network Manager would "purchase airspace capacity" aligned with anticipated demand and "sell trajectories". This would yield a **more direct decision capability of the NM** in the European ATM value-chain by **mandating it to take capacity and demand management decisions and actions** [4]. These actions are currently mostly performed by the ANSPs and AOs, the NM bearing a more supervisory or advisory function.

In this new role, the NM should have contractual relationships with the ANSPs and AOs, with the goal of optimising network performance as defined by the policymakers [5]. Such policy might include, but not limit itself to:

- Acceptable ranges of network performance indicators
- Areas of safety, cost-efficiency, capacity, environment, or equity, also known as KPAs (Key Performance Areas) - defined in the Commission Implementing Regulation (EU) 2019/317 laying down a performance and charging scheme in the single European sky [6]

The Consortium produced an **optimization model** jointly deciding on sector charges and capacities, using a *non-linear programming mathematical model under least-cost choice assumption (RPLC)* [4], as well as a *non-linear mathematical model based on simplified assumptions regarding capacity provision* [5].

Through the previously named mathematical model [5], basic trade-offs between providing more capacity or re-routing flights are underlined.

The problem is further developed in the next chapter, which presents the *Literature review*. Under its scope, the current academic point of view is highlighted.

1.4. Structure of the report

The report standing in front of you has been constructed as such: following the introduction given above, literature relevant to the subject of the thesis has been examined. Emphasis has been put on the study which gave the impulse to start the work, namely the *Coordinated capacity ordering and trajectory pricing for better-performing ATM — COCTA* research project.

One of the main discoveries of the said research work was that, in order to allow for a more efficient utilization of the capacity provided across the European ATM Network, a mathematical model addressing the demand-capacity imbalance problem had to be devised. To enact the changes brought by the model, a "collaborative setting" needed to be respected between the EUROCONTROL Network Manager and the main concerned stakeholders in the Collaborative Decision-Making (CDM) process. Within this already existing setup, it was stated that the decision capability of the Network Manager could benefit from further evaluation and enhancement.

The report continues by presenting economics literature considerations which are coupled with social welfare, explaining the implications of the establishment of monopolistic structures (such as the air navigation service providers — ANSPs) on the general public. This serves as a preamble to the analysis of different transportation research works involving multiple players, akin to the stakeholders party to the Collaborative Decision-Making process, which we aim to simulate within a model, to test their acceptance in the case of a higher Network Manager decision power. The game theoretic approach to such settings is also reviewed — this part serves as a motivation for the choice of game theory to be used for the simulation within this thesis.

The research objective and questions are then laid down, taking the reader through an introduction of the current practices in processes regarding capacity provision and demand management. The involvement of the air navigation service providers, airports, airlines (seen as aircraft operators or airspace users), and the position of the EUROCONTROL Network Manager are discussed.

Then, potential strategies for improving the Network Manager's decision-making abilities and the proactive manner in which the Network Manager fulfils its role are examined.

In the end, the model setup is presented, as well as the different testing scenarios. The last research question aims to verify how the stakeholders can be treated fairly in the process, as well as possible methods of incentivization with the aim of optimizing overall network performance.

The results are showcased, accompanied by relevant commentary. The opinion of specific stakeholders, both on the mentioned COCTA model and on the idea of the thesis, containing potential ideas for improvement, is then presented.

A conclusion comes next, and the report is completed with a *Way forward*, giving possible lines for future follow-up research on the subject.

2
Literature review

2.1. Preliminary academic point of view on the topic to be researched

In this section, our topic is viewed from an academic perspective (mainly the COCTA study). It is elaborated on the issues the authors of the study have found, as well as on the solutions they proposed. Three large problems have been identified, as such:

2.1.1. Main identified problems

Problem 1
Inefficient airspace utilization is the first and foremost. Coupled with an increased demand, this leads to a rapid congestion of the European ATM Network, which in turn leads to significant delays and associated costs [4].

Problem 2
In the current system, NM acts as a "mediator" or "moderator" between the Airspace Users (AU) and ANSPs, and does not have an economic instrument to take capacity and demand decisions [7].

Problem 3
The supply (in our case, the capacity) is provided by the ANSP following a "piecemeal" (unsystematic and partial) practice which is often tailored to their needs [7] rather than trying to have a general and more long-term overview.

Which come with their subsequent solutions, as proposed within the COCTA study:

Solution 1
The solution to the first problem is the mathematical model which addresses the demand-capacity imbalance by "jointly deciding on sector charges and capacities" [4]. For its application, a collaborative setting would need to be enacted between the ANSPs and the NM [5], in which the purchasing of capacity by the NM and selling it under the form of trajectory products, as permitted by its higher decision capability (Section 1.3), would be enabled. The NM would become, as called by the authors, "an active actor" [4].

Solution 2
Expanding on the previous, the NM should be in the position to order en-route capacities from the ANSPs and offer specific routes, with varying prices considering the costs borne by NM for specific cases. As such, a shift from the *airspace-use* charging to *trajectory-use* charging would take place [4].

Solution 3
NM is envisioned to adjust opening schemes at pre-tactical level (up to 1 day before the operations - see ATFCM timeline), which addresses **capacity management** [7]. A change in paradigm to a demand-driven, network-centred, rather than a supply-driven approach which focuses only on local or ANSP-level traffic peaks, is necessary. Nonetheless, the trajectory assignment products proposed by the COCTA study

would account for the airspace users' business or operational needs (addressing **demand management**), while also ensuring the achievement of the network performance goals [7]. Which in turn should lead to an overall performance-based usage of the Network (considering key indicators such as cost efficiency or CO_2 emissions) [4].

2.1.2. Other problems

The COCTA researchers have also come across other problems, which sustain the larger ones presented above. In brief, they include, but not limit themselves to:

- Mandatory re-routings used by ANSPs to reduce ATFM delays so they would comply with their local targets [7]
- The proneness of NM to decide "by consensus" within the CDM process, which leads to "weak compromises" [5].
- The demand-capacity situations which are tackled on D (day of operations), in spite of the fact that the planning is initiated several months before the day of operations, in the strategic phase (see ATFCM timeline), which leads to delays [5]. The demand management actions are defined at the end of this list.
- Seasonal traffic variability (especially during the summer or important events) is a root cause of capacity/demand mismatch [5].
- High valuation by AUs of their **planning flexibility**, leading to the tendency of making available their route decisions shortly before the time of departure, sometimes even on D, to take advantage of the most recent situational awareness. In turn, this translates into **unpredictability** for the ANSPs and the NM [5], leading to a possible dichotomy. Within this practice of theirs, there is an inclination to submit late flight plans, which further contributes to inefficient resource allocation by the capacity providers [4].

Demand management: Denotes a collection of administrative or economic measures and regulations designed to limit demand for access to congested infrastructure (e.g., airspace or airport) and/or to alter the spatial and temporal attributes of that demand, aligning it more closely with available capacity [8].

In response to the above presented issues, there have been strategies devised to tackle them or mitigate their impacts. As such, mathematical models simulating the route pricing under the least-cost choice assumption (RPLC) have been proposed, with the aim of minimizing the **overall cost faced by the airlines**. The composition of the latter is the following [4]:

$$\text{overall cost of airlines} = \text{route prices} + \text{displacement costs}$$

To allow for such optimization, a new pricing scheme has been devised with the aim of obtaining an equilibrium which should be fair on both individual and social level for the AUs [4] - this is further elaborated in the Economics literature review section. This scheme is to contribute to the general reduction in delays and bottlenecks as well.

Several characteristics of the pricing scheme are [4]:

- Phased approach (long-, medium-, and short-term), involving coordination between NM and ANSPs to establish and deliver necessary capacity for each period, leading to implementation on the day of operations [5].
- Capacity decisions are guided by long-term traffic forecasts, forming the basis for ANSP planning [5].
- Charging principle is based on airport pairs, which promotes more predictable routing
- Airport-pair charges are calculated solely on MTOW, removing the incentive for AOs to fly longer to reduce ANS costs
- Last, but not least, demand is managed by NM through offering AUs a variety of trajectory choices.

For the comprehension of the ATFCM planning time spectrum, a timeline is introduced below [7] [5]:

Long-term	5 years, due to long lead times related to the capacity planning process
Strategic	(D - 1 year; D - 7)
Pre-tactical	(D - 6; D)
Tactical	D (only considered to a certain extent)

where D represents the day of operations.

The previous overall cost borne by the AUs can also be seen as:

$$\text{total charges} = \text{airport-pair base charges} + \text{trajectory charges}$$

The proposed trajectory charging products belonging to this new pricing scheme are [5]:

Type of trajectory pricing	Characteristics/benefits	Pricing	Appropriate for
Standard trajectory (ST)	Shortest route between two airports, including relatively narrow and pre-agreed spatio-temporal trajectory margins, potentially needed for trajectory fine-tuning at a later stage (e.g. shortly before take-off)	Base charge	Flights/flows which are not likely, based on strategic assessment, to be subject to demand management actions
Discounted trajectory (DT)	AO delegates the decision to the NM to delay or re-route its flight within pre-agreed margins (wider than those for ST), if needed	Lower charge than ST	Flights/flows which might be subjected to demand management actions to a certain extent (within pre-agreed margins)
Premium trajectory (PT)	AOs have an option for last minute trajectory changes, either in space or time, within agreed margins	Higher than ST	Flights/flows which can keep their option to submit late flight plans (even on D), within agreed margins

Table 2.1: NM trajectory pricing options, building on Ivanov et al. [5]

Based on this choice menu, the main objective of the NM is to offer incentives to a set of flights/traffic flows to select the discounted trajectory product, to enable a higher margin of assignment of the final trajectories, enhancing flexibility [7].

2.1.3. Conclusions and redesigned ATM value chain

In the envisioned new ATM value chain, the NM is responsible for making strategic decisions regarding capacity, such as determining the sector-opening scheme (SOSc). This involves collaborating with ANSPs to decide which SOSc will be ordered and which flights or flows need to be delayed or rerouted, aiming to minimize overall costs. The NM evaluates capacity needs based on expected traffic, tests different scenarios, and selects the optimal SOSc. After placing its initial capacity order, the NM defines trajectory options and pricing to guide AOs towards system optimization, while also refining its initial capacity order as necessary [5].

The new ATM value chain, as envisioned by the authors of COCTA and laid down in [5], presents itself as follows:

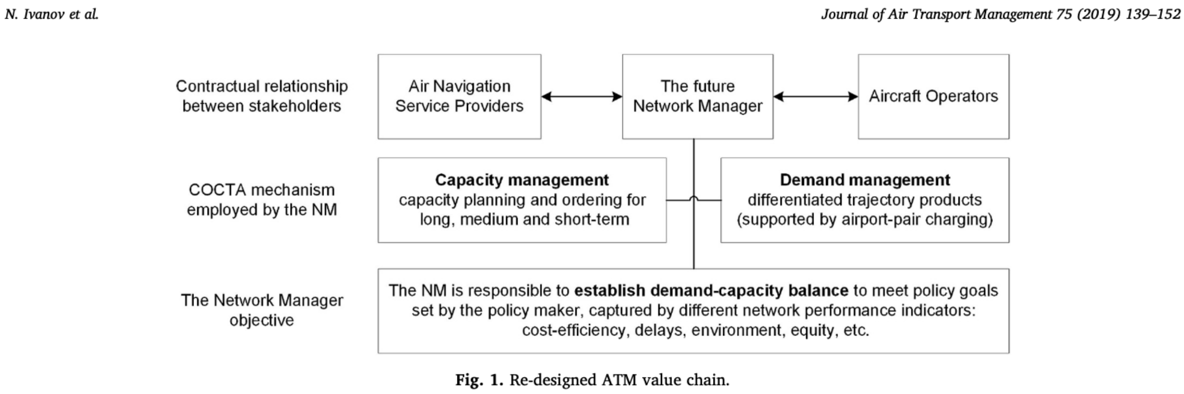


Figure 2.1: New ATM value chain (Ivanov et al., 2019)

2.2. Economics considerations and literature review

This chapter highlights the position of the most relevant entities involved in the negotiation process and part of the ”ATM value chain” from an economic standpoint. At first, a theoretic economic base is built to facilitate the understanding of the subject, then specific ATM examples and considerations are discussed.

2.2.1. Laying the foundation

In order to delve into some economic determinants lying at the base of air navigation service provision and the relationship the ANSPs have with national governments as well as the EUROCONTROL NM, several definitions need to be given.

Natural monopoly: ”A natural monopoly exists when, due to the nature of the industry, a single firm can produce the total output at a lower cost than multiple firms, typically due to economies of scale” [9].

Natural monopolies frequently form in businesses with large infrastructure costs and strong ”barriers to entry”, such as utilities or transportation networks. In these industries, the high fixed costs of developing and maintaining infrastructure make it more effective for a single firm to supply the entire market than for multiple firms to compete, because the average cost per unit lowers with increased output. These high expenses (which can also appear in the form of large permanent investments sometimes needed to compete on a market with high quality standards) pose significant impediments for new enterprises attempting to enter the market, virtually preventing effective competition and leading to a monopolistic structure. [10] [11].

A simple mathematical representative of natural monopolies is the subadditivity of functions. This property states that the value of the function at the sum of two points is less than or equal to the sum of the function’s values at each individual point [12]. Formally, a function f is subadditive if:

$$\forall\, x,\, y\, \in A, \quad f(x+y) \leq f(x) + f(y)$$

Translated into economic terms, a cost function is subadditive if the total cost of a single firm producing the entire output is less than the combined cost of multiple firms producing the same output, indicating that it is **more efficient for a single firm to serve the market**. This property often arises in industries with high fixed costs and significant economies of scale, justifying the existence of natural monopolies [13].

To continue on the route of economic considerations, we may summarize some of the important terms addressed before and state:

If the *subadditivity* OR the *barriers to entry* conditions are met, we may speak of a natural monopoly.

If BOTH the *subadditivity* AND the *barriers to entry* conditions are met, we may speak of an *abuse* of the monopoly position.

To prevent such abuse of the monopoly position, put in practice by an *unregulated firm* through means such as charging of an unreasonable price or providing insufficient quality, governmental intervention is seen as justified to increase social welfare [14].

For that purpose, specific frameworks for the regulation of natural monopoly companies or providers have been implemented. Largely, one can split such companies into two categories, namely firms under national government ownership (either wholly or partially), or private ownership.

In their project deliverables (which are distinct from and more technical than their published academic papers), the authors of the COCTA study analyse the two above-named categories [14].

Entities under government ownership

Usually, monopolistic services are provided by publicly traded or government-owned businesses, and profit maximization is not the primary goal. For instance, in many European nations, the government owns a large number of municipal utilities, which run more for the benefit of the general public than for financial gain.

Entities under private ownership

- **User cooperative or club:** In this model, the firm is owned by the users of the service. If users prioritize efficiency, the monopoly is less likely to exploit its position. However, this system only works well when the number of users is small. As the number of users grows, the risk of free-riding increases, leading to inefficiencies.
- **Dominant user influence:** If one or a few members dominate the user cooperative, competition can be hindered. This could result in those dominant users shaping the service to their advantage. In extreme cases, a **vertically integrated firm** may control both the infrastructure and services, further limiting competition.

Vertical integration: A strategy allowing a company to streamline its operations by taking direct ownership of various stages of its production process, rather than relying on external contractors or suppliers [15].

Companies can achieve vertical integration by acquiring or establishing their own suppliers, manufacturers, distributors, or retail locations rather than outsourcing them [15] - in other words, the entire supply and production operation takes place "in-house".

2.2.2. Types of regulations regarding price setting

The regulation side of the economic considerations is taken further by the COCTA deliverable discussing the state-of-the-art at the beginning of their research [14]:

Institutional arrangement

Independent regulators are generally preferred, especially within the EU, where directives such as Directive 2009/12/EC on airport charges mandate this approach. Additionally, the role of users, particularly airlines, has been enhanced. For instance, large European airport operators are now required to inform airlines of investment plans and consult with them on any changes to the pricing structure.

Formal process

- **Traditional regulation:** This approach limits the profits of monopoly firms by tying their prices to actual costs. The idea is to allow the monopoly to recover the cost of service provision. However, this method can be inefficient, as firms lack incentives to operate efficiently.
- **Incentive regulation:** Proposed by the former UK Treasury economist and professor Stephen Littlechild ([16], cited in [14]), this approach aims to motivate efficiency by loosening the direct link between costs and regulated prices. The **most common form** of this regulation is the **price-cap regulation**, which encourages firms to improve efficiency while maintaining competitive prices.

Price cap: A form of economic regulation that sets a limit on the prices that a utility provider can charge [17].

The cap is determined by taking into account a number of economic variables, including inflation, predicted efficiency savings, and a price cap index [17].

In practice, as explained in Blondiau et al. (2014) [18], the strategy is to impose a price cap that is roughly equivalent to the industry average of the enterprises' predicted cost levels. Businesses might retain the advantages of operating more profitably than the price cap, but they would also be responsible for any cost overruns that exceed it. If viewed from a regulatory perspective, this is called the "yardstick regulation", as per the theory proposed by Shleifer ([19], cited in [18]).

As the authors of COCTA further argue, regulation influences not only the pricing or charging structure but also the overall price and charging level. Further, economic efficiency requires that prices be established in accordance with **marginal costs** [14].

Marginal cost: the change in total production cost that comes from making or producing one additional unit. For its calculation, the change in production costs is to be divided by the change in quantity [20].

Considering the newly-introduced notions, we may further say that if, for a monopoly, the marginal cost is smaller than the average costs, then the firm registers losses. As such, an equilibrium is reached in practice, in which the regulated prices are equal to the average costs [14]. This ensures that the price cap is put forward, and economic efficiency is maintained, while the corporation has a higher degree of protection against potential losses.

Pricing alternatives

On a general level, two ways of setting the price for a monopoly firm (providing a utility) would be [14]:

1. Set two-part tariffs, namely:
   - A fixed fee
   - A variable unit price
2. Differentiate prices according to the elasticity of demand:
   - For low elasticity of demand - charge a higher unit price
   - For high elasticity of demand - charge a lower unit price

On the second point, there is further elaboration both in the COCTA study and other literature. As such, it is explained that demand elasticity cannot be directly observed or quantified, and for this reason it can be appraised through other variables (called proxies) such as the Maximum Take-Off Weight (MTOW) in case of the determination of airport charges [14] [21].

To move further with the literature findings, another definition must be given, which sums up point 2 and its subsequent enlargement:

Ramsey pricing: a form of pricing regulation used primarily for natural monopolies, where a firm sets prices above marginal cost to cover fixed costs while minimizing the welfare loss. Prices are typically adjusted based on the price elasticity of demand—products with inelastic demand are priced higher, while those with elastic demand are priced closer to marginal cost. [22].

The goal is to allocate the burden of cost recovery in a way that reduces the negative effects on consumer welfare. At the same time, it is aimed to balance efficiency with the firm's need to cover costs.

Hakimov and Mueller [21] particularize the concept of Ramsey pricing in the case of a monopoly regulating the prices according to demand elasticity, presenting the example of uncongested German airports. According to them, Ramsey pricing is a ”quasi-optimum pricing scheme” if we consider a ”multi-product natural monopolist”.

The Ramsey pricing has certain shortcomings which are highlighted by Hakimov and Mueller [21] - in the following paragraph, we provide a short summary of their findings.

At uncongested airports, Ramsey pricing is considered optimal because it allows the service to be provided efficiently. However, at congested airports, **peak-load pricing** is more effective, as it ensures that customers with a higher willingness to pay use the service. Ramsey pricing involves setting charges inversely to the elasticity of demand, which is a form of price discrimination ”where charges are set on the basis of the ability to pay” [21]. This approach often conflicts with regulators, who oppose such discriminatory practices. While Ramsey pricing is easier to implement in deregulated environments, it can still attract scrutiny if it gives unfair advantages to specific players.

On the other hand, if the peak pricing method is employed, customers will pay a higher (or additional) fee during the periods of high demand. The purpose of peak pricing is to regulate demand so that it stays within a manageable level of what can be supplied [23].

The concepts of **congestion** and **peak-load pricing** have been investigated in works such as [24], or [25]. In the latter, a bidirectional bottleneck network with a spatial pattern of parking is treated, in which the commuters travel both from the place of residence to the workplace and vice versa. Both named locations constitute the ends of the environment used for analysis, called the ”linear city”. In such a model, which is often used in transportation analysis, the passengers' origins and destinations are placed into a two-dimensional rectangle [25]. Another literature example using the linear city methodology is the modelling of the demand side in [26], which studies the impact of the presence of the two types of rail system in the Republic of China (Taiwan) - the high-speed and conventional rails across the “north-south corridor along the west coastal plain”.

2.2.3. Air navigation service provider applications

The authors of COCTA proceed to state that, given the current technology available and the nature of the service provision, ANSPs can be seen as natural monopolies [14]. We can break down some ANSPs by type of ownership, although many of them are part of the public sector. Nevertheless, at a lower level, they can be:

- part of the state administration (government), such as the ANA - Administration de la Navigation Aérienne (Luxembourg) [27]
- separate entities with the state as a dominant, or simple shareholder, such as Austro Control (Austria) [28], or BULATSA (Bulgaria) [29].
- a public-private partnership, NATS (UK) in which UK-based airlines hold shares, being the single example in the European airspace so far [14].

ANSP regulation

It is further explained that the air navigation charges were based purely on costs in the past - however, elements of price cap regulation were recently introduced by the time the COCTA study was performed [14]. The ICAO framework (2012) [30], followed by the EU Commission Implementing Regulation 391/2013 (since repealed by the Commission Implementing Regulation 2019/317 [6]) led to the establishment of a common charging scheme for air navigation services in the EU. Key principles of this regulation include transparency in performance indicators, mandatory consultations with users, and the analysis of key performance indicators (KPIs) submitted by the air navigation service providers, in the annual Performance Review Reports ([31], cited in [14]).

The authors recall the Ramsey pricing methodology in stating that the setting of route charges can be seen as such. A parallel is drawn to the economy theory presented before. It is affirmed that the incentive regulations applied to European ANSPs due to their nature as monopoly service providers, likely have the purpose to offset the costs associated with providing services [14].

The ANSPs' budget constraints should be taken into consideration while creating a model for estimating the prices that the NM pays to the ANSPs as, under the COCTA model, the NM and not the airspace users, would be the one paying for the services offered by the ANSPs [14].

The importance of giving incentives within the pricing scheme is stressed. Next to a method akin to peak-load pricing (Premium trajectory - Table 2.1), pricing models rewarding a higher degree of predictability (such as the Discounted trajectory - Table 2.1) could influence the decisions of the airspace users and enhance the preparedness of the NM in terms of organising the operations, especially when there is a risk of a bottleneck. Moreover, there can be financial incentives offered at ANSP level to enable a reduction or increasing in capacity, should it be needed.

The regulatory discussion is concluded by explaining that, at the time the research was published, the implementation of COCTA did not require any modification at EU framework level regarding ANSP regulation. The authors have highlighted, however, that it is essential for the NM **to be independent from the ANSPs or airlines**, so that there is a very limited possibility for the traffic decisions taken by the NM to be disproportionally influenced in favour of a party [14].

2.2.4. Relationship between the NM and the concerned stakeholders in the process

We cannot end this chapter without reminding the reader of the problem which has led us to this point - namely, the need to increase performance at Network level by augmenting the efficiency of airspace utilization, which the authors of the COCTA study have proposed to solve using a mathematical model "jointly deciding on sector charges and capacities" (subsection 2.1.1). To empower such a system, the decision power of the NM needs to be increased and the new framework of action to allow it to take capacity management decisions.

It is noteworthy that, while the mathematical optimization model which raises the overall ATM Network performance has already been handled by the COCTA authors, **there still is progress which can be made** on the determination of the extent to which the concerned stakeholders (most directly the ANSPs and AUs) would be willing to accept an increase in decisional capability of the EUROCONTROL NM in the CDM process. An example of a current stakeholder concern, which needs further attention, is that airlines argue that it should be their option to choose between traffic decongestion measures such as re-routing and accepting a delay, as they view re-routings simply as a tool to reduce ATFM delay statistics to help the ANSPs meet their delay targets [7].

Considering all that has been previously discussed, we have envisaged the possibility of such NM-stakeholder relationships to be put in the form of a model, to see where an equilibrium could be reached, which would assist in enhancing the overall network performance, but also keep the stakeholders content. In the next section, we examine specific literature leading us along this path.

2.3. Existing research models

This chapter presents specific ATM- and transportation analysis-related literature which has been examined to understand an academic point of view on the modelling of a multi-player setting, each different setting with its implications, with the purpose of reaching an equilibrium between the parties. It opens the path to the next chapter, which ultimately leads to the research purpose and proposal of this Thesis.

2.3.1. Welfare and external costs in transportation networks

The concept of welfare, particularly in the context of transportation systems, is closely linked to both internal market effects and externalities. Schipper et al. (2003) present a welfare analysis of airline deregulation, stressing the importance of accounting for environmental externalities such as noise, emissions, and accidents, seen as external costs. They argue that, while market deregulation (**N.B.** different from monopoly [de-] regulation, which can allow the monopolies to abuse their position) improves consumer welfare by fostering competition and reducing fares, it also exacerbates the external costs. To achieve a more socially optimal outcome and prevent welfare loss, they recommend policies that internalize these costs, such as environmental charges [32].

In a regulated market, a specific provider can have monopoly on the provision of services (e.g., energy, gas). In a deregulated market, more providers can exist and be in competition with each other.

In the urban context, Li and Wu (2009) extend this analysis to traffic congestion, viewing it as a game between planners and travelers, as well as among travelers themselves. Their game-theoretic models demonstrate how unregulated road usage leads to excessive consumption of road resources due to individual rationality, weakening the optimization of other travellers' traffic modes [33]. Zhang et al. (2008) similarly propose dynamic tolling to manage urban traffic, using a Nash equilibrium framework where commuters adjust departure times to minimize personal costs, aligning individual and social utility [25].

In aviation, Delgado (2015) introduces another layer to this discussion by analyzing the impact of airspace charges on airline route choices. The research highlights how different pricing zones in European airspace can influence operators' route selection, especially in areas where price disparities are significant. By adding a monetary cost to the use of congested airspace, the study suggests that airlines could be more involved in the capacity-demand balancing process, potentially achieving an economic optimum by allocating resources more efficiently [34]. This idea is also supported in the study performed by Altus (2009) [35].

2.3.2. Equilibrium in transport systems

Nash equilibrium plays a central role in several of these studies. Schipper et al. (2003) apply a Nash equilibrium model to airline competition, focusing on a two-stage game where airlines first set flight frequencies and then adjust ticket prices. The equilibrium ensures that no airline can improve its position by unilaterally changing its strategy once frequencies are set [32]. Similarly, Zhang et al. (2008) model commuter behavior using Nash equilibrium to describe how commuters adjust departure times to minimize travel costs, resulting in stable congestion patterns [25].

Li and Wu (2009) also use Nash equilibrium to model traveler decisions in urban traffic systems. They show that when travelers act based on individual rationality, it leads to suboptimal resource use. However, through appropriate policy interventions, such as tolls or traffic regulations, social utility can be maximized, aligning individual behaviors with broader network goals [33].

Hsu et al. (2010) provide a comprehensive game-theoretic analysis of competition between high-speed and conventional rail systems in Taiwan, using Nash equilibrium to model pricing strategies between rail operators, regulators, and competing transportation modes. Their study underscores how government interventions, such as price floors and ceilings, influence the Nash equilibrium (following the same rule of action as for other monopolies) and promote competitive balance between different transportation modes [26].

2.3.3. Regulation and congestion management

Several papers highlight the role of regulation in managing congestion and optimizing system efficiency. Von Massow and Canbolat (2010) examine a method of connecting the capacity provider (in this case, the taxis) with the demand (the fares – passengers needing a ride). They discuss how automated dispatch systems can reduce congestion in taxi services, while Schipper et al. (2003) suggest integrating environmental policies, such as emissions charges, to balance market deregulation in the airline industry [24] [32].

Delgado (2015) adds that air traffic flow management (ATFM) regulations, which delay aircraft at departure to meet en route capacity constraints, are the current norm for countering air traffic saturation. The study further shows that pricing mechanisms are a factor which influences airline route choices, especially when neighboring airspaces have significant differences in unit costs. As such, airlines may alter their routes to minimize costs, thus redistributing traffic and reducing congestion in higher-cost zones [34].

2.3.4. Peak-load pricing and dynamic solutions for congestion

Dynamic pricing emerges as an important tool for alleviating peak-load congestion. Schipper et al. (2003) propose environmental charges to help airlines internalize the external costs of high traffic activity. Zhang et al. (2008) also propose dynamic road tolls that vary with traffic demand to incentivize commuters to adjust their travel times and reduce peak-hour congestion [32] [25].

Delgado (2015) suggests that similar pricing mechanisms can be applied to airspace, where congestion in high-demand areas could be managed by assigning higher fees. Airlines, faced with varying costs across different airspace zones, might select routes that optimize cost efficiency, thereby alleviating congestion in the most saturated sectors [34]. It is to be noted, however, that the fuel price is also a variable in this case, which, when high enough, could allow for the airlines to select shorter routes even through airspaces with a higher unit rate charge. On the other hand, if the fuel price is low, airlines might decide to bypass the more expensive airspaces, even if their flown route is longer.

Hsu et al. (2010) discuss two-part tariff pricing structures in rail systems, which allow operators to adjust prices based on demand levels. This dynamic pricing mechanism is key to balancing demand between high-speed and conventional rail services, reducing strain on any single system during peak periods [26].

2.3.5. Cooperative game models and negotiation outcomes

Cooperation between stakeholders in transport systems is another recurring theme. Li and Wu (2009) propose that urban traffic congestion can be modeled as a cooperative game between travelers and policy makers, where mutual collaboration leads to more efficient resource allocation. However, if goals conflict, individuals tend to prioritize personal benefit over collective welfare, resulting in suboptimal outcomes [33]. This is similar to dynamics in air traffic management, where stakeholders (air navigation service providers and airspace users) may prioritize their own performance metrics unless cooperative frameworks are established.

Hsu et al. (2010) explore the potential for cooperation between high-speed and conventional rail operators, highlighting how government regulation can foster collaboration and ensure that both systems operate efficiently. This cooperative approach can lead to better resource management and improved service for passengers [26].

2.3.6. Parallels to ATM drawn from non-ATM transportation analysis papers

Several parallels can be drawn between the findings of these transportation studies and challenges faced in Air Traffic Management (ATM). Li and Wu (2009), for instance, highlight the connection between urban transportation planners and travelers, akin to the relationship between the EUROCONTROL Network Manager and the various air navigation service providers (ANSPs) and airspace users. In both contexts, individual players—whether road users or airlines—tend to act based on "individual rationality," seeking to maximize their own benefits [33]. This mirrors the tendency of ANSPs and airlines to prioritize their own performance metrics and costs, which can create inefficiencies in the overall system. Just as cooperative game models could lead to optimized urban traffic flows, similar frameworks could help align the interests of ATM stakeholders to improve overall network performance and reduce delays.

Moreover, Zhang et al. (2008)'s proposal for dynamic road tolls and Hsu et al. (2010)'s two-part tariff pricing in rail systems both reflect strategies that could be adapted to ATM. As dynamic tolls aim to reduce peak-hour road congestion, leading to changes in the departure times of the drivers, airlines might also be incentivized to adjust their departure or arrival times (with the possibility of extending this even to airport slot definition). These pricing strategies, modeled through Nash equilibrium and not only, could balance the competing interests of airlines, ANSPs, and regulators [25][26].

Finally, the emphasis on cooperation found in Li and Wu (2009) and Hsu et al. (2010) has clear implications for ATM applications. Just as combining efforts between different transportation stakeholders leads to more efficient resource usage in urban traffic and rail systems, fostering collaboration among ANSPs, the Network Manager, and airspace users can help mitigate bottlenecks and improve the overall performance of the European airspace network. Which is the reason why the **negotiation process can benefit from further applied research**.

2.4. Game theory literature review

This chapter follows upon the discoveries and discussions from the previous chapters, especially section 2.3. In what follows, the reader is presented with an overview of game theory, including related player settings and models. Several definitions (presented, as before, in italic text) are placed where it has been deemed relevant. In the end, the reader is led to the research objective and questions which are posed within this Thesis.

The sections to follow have been elaborated by making use of the review of game theory in transportation analysis, performed by Zhang et al. (2010) [36], as well as the game-theoretic airline competition modelling in air transport markets research work by Gelhausen (2010) [37].

Game: Any set of circumstances in which the outcome depends on the choices made by two or more players [38].

Since the Nash equilibrium, one of the most common forms of game theory outcomes, is extensively used throughout the thesis, we see fit to give a definition:

Nash equilibrium: An outcome that, once achieved, does not provide benefit to any player who would choose to unilaterally change its strategy [38].

2.4.1. Structural elements of a game

1. Players

   Participants to the game who can decide on their strategies
   An important trait of the player is its **rationality**, which means they:

   - "Don't leave things to chance" [36]
   - "Don't take advantage of others' mistakes" [36]

2. Strategy set

   Action: A single choice of a player at a specific time point.

   Strategy: A composition of actions spanning multiple time points, constituting the behaviour of a player in a game [37].

   Largely, the strategy can either be *pure*, or *mixed*.

   - *Pure strategy: The player makes a choice with certainty (a probability of 100%)*
   - *Mixed strategy: This case refers to a probability distribution over the set of strategies of the player - in other words, at a time point, the player makes a choice with a given probability, say 33.3%* [38].
   - According to the "duration" (time span) of the strategy, the games can be split into *finite*, or *infinite* [36]. During infinite games, players can obtain new knowledge throughout the game, which might prove essential to their decisions, and consequently change their strategy [37].

3. Payoff functions

   A function showing the gain or loss of each player (as a collection of information providing a pertinent outcome based on each player's selection of strategy) [36].

   A good payoff function lies at the basis for a player's judgment and behaviour [36].

4. Orders

   Refers to the order in which decisions are taken. As such, the game can be *simultaneous* - in which the players decide at the same time, which increases fairness, or *sequential*, in which they decide one after the other [36].

2.4.2. Six common models of game theory

1. Ordinary non-cooperative game

   Non-cooperative game theory is based on the absence of coalitions in that it is assumed that each participant acts independently, without collaboration or communication with any of the others [39].

   Reaching a solution for this setting follows the basic idea of analysing the problem and materializing extracted elements into constraints and variables, then crafting a model and deciding on the properties the equilibrium solution should present, and finally, simulating and solving.

   Inside the air transport markets, the competitive game is a common form of non-cooperation between the parties [37]. It can be further split into:

   (a) Monopolistic competition

      Monopoly [gr. mono = one]: a type of market structure when a single manufacturer or seller controls the entire market for a specific good or service [40].

      Such a setting can be applied in air transportation to the:

      - Optimization of flight schedules between airports, particularly within complex hub-and-spoke (H&S) systems
      - Problems involving high coordination costs

   (b) Oligopolistic competition

      Oligopoly [gr. oligo = few]: a type of market structure in which a small number of powerful enterprises control the majority of the market. When combined, their market share is so great that they might control the whole market [40].

      This setting focuses more on:

      - Point-to-point traffic and simpler hub-and-spoke systems
      - The analysis of market equilibrium and social welfare under both deregulated and regulated environments (also discussed in [32]).

2. Generalized Nash equilibrium game – In this scenario, each player's choices influence both the payoffs and the set of feasible strategies available to other players.
3. Cournot game – One of the earliest applications of Nash equilibrium, with the classic example being the prisoner's dilemma model.
4. Stackelberg game – The simplest model of a leader-follower dynamic, where one player leads and the others follow.
5. Bounded rationality game – This approach considers the potential limitations in players' ability to make fully rational decisions, addressing constraints often overlooked in traditional game theory.
6. Repeated game – A game consisting of several repetitions of a basic game, where each stage is treated as a complete game on its own. [36].

2.4.3. Game theory applications in transportation analysis

1. Macro-policy analysis
    (a) Games between travellers and authorities - in this setting, the goals of the two parties are not necessarily contradictory.
    (b) Games between authorities - authorities play against each other without involving the travellers.
    (c) Games between travellers - all players are travellers.
2. Micro-behaviour simulation
    (a) Games between travellers and authorities (strategies for traffic control at junctions)
    (b) Games between travellers

We present below Zhang et al. (2010)'s practical breakdown of game theory applications per types of policy analysis, players, game models, and specific transportation problems [36]:

TABLE I. GAME THEORY APPLICATIONS IN TRANSPORTATION ANALYSIS

Type	Players	Common Models	Transportation Analysis Examples
Macro-policy Analysis	Travelers and Authorities	Ordinary Non-cooperative Game Generalized Nash Equilibrium Game Stackelberg Game	Road/Parking Tolls Policy Vehicle Routing Problems Transportation Network Reliability Urban Traffic Demand Drivers' Response to Guidance Transport Modes Competition Risk Allocation Local Competition's Effects to Overall Situation
	Authorities	Ordinary Non-cooperative Game Cournot Game	
	Travelers	Ordinary Non-cooperative Game Generalized Nash Equilibrium Game Stackelberg game	
Micro-behavior Simulation	Travelers and Authorities	Ordinary Non-cooperative Game Generalized Nash Equilibrium Game Stackelberg Game	Adjacent Traffic Signals Strategy Emergency Rescue Conflicts between Two Airplanes Collision Avoidance between Vehicles Conflict between Pedestrians and Vehicles
	Travelers	Ordinary Non-cooperative Game Bounded Rationality Game Repeated Game	

Figure 2.2: Game theory applications in transportation analysis (Zhang et al., 2010)

From the above, the reader may recognize the **travellers-authorities**, as well as **travellers-travellers** game settings falling under the *Macro-policy analysis* category, as presented in the work of Zhang et al. (2008) regarding dynamic solutions for road traffic congestion and parking [25]. There is also literature presenting game models used in tackling airplane routing and conflict resolution in a cooperative [41], as well as non-cooperative setting [42]. These fall under the *Micro-behaviour simulation* category depicted above.

Drawing upon a comprehensive synthesis of the literature review and under direct inspiration of the research process proposal by Zhang et al. (2010) [36] of a game theory-related study, our own chart below has been developed, showing our current research flow and progress. This supports our choice of **game theory** as one of the main instruments to attempt an improvement at the current negotiation process between the NM and the stakeholders (research question 3). We are now ready to move forward to detailing the research objective and its undertaken questions in the next chapter.

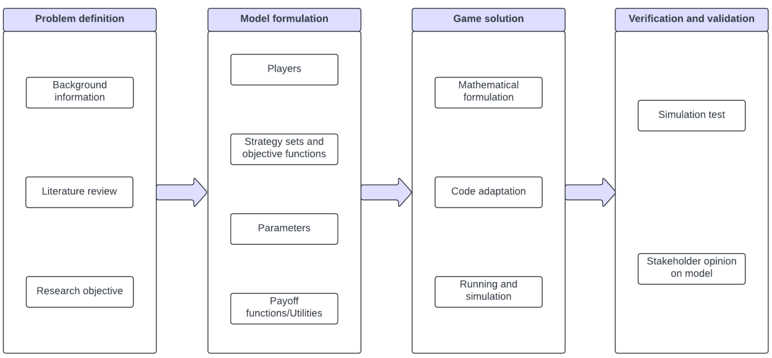


Figure 2.3: Research process overview (inspired by Zhang et al., 2010)

2.5. Research formulation

This section presents the research objective and the main research question, which is then split into the sustaining research questions together with their sub-questions.

Research objective

This research tackles optimization measures applied to the European ATM Network. It focuses on the Network Manager's (NM) ability to become an active decision-making entity, strengthening its current mediation position in the relationship with relevant stakeholders (ANSPs, AUs) inside the Collaborative Decision-Making (CDM) process. The work investigates and analyses a game theoretic model with the aim to measure the acceptance of stakeholders to partially cede decision autonomy to the NM within the aforementioned process. The goal is to improve overall ATM Network performance.

Main research question

How can the decision capability of the EUROCONTROL Network Manager (NM) in its relationship with the concerned stakeholders be evaluated and increased within the Collaborative Decision-Making process, in order to allow for an appropriate implementation of capacity optimisation measures?

Research question 1

What degree of involvement in the decision-making process regarding capacity provision and demand management does the EUROCONTROL Network Manager currently have, with respect to its relation with the concerned stakeholders (ANSPs and AUs)?

Research question 2

What are possible ways of enhancing the decision power of NM, and in what aspects can the NM play a more proactive role?

Research question 3

What would be a proper way of introducing related changes to the stakeholders, to ensure acceptance of the new setup?

a) How can it be ensured that the stakeholders are treated fairly in the process?
b) How could the stakeholders be incentivized to take measures leading to an improvement of network performance?

3

Current role of the Network Manager in the decision-making process

This research question aims to lie in front of the reader the status quo of the relationship between the EUROCONTROL Network Manager and the (main, as they are not singled out) stakeholders involved in the Collaborative Decision-Making (CDM) process — namely the air navigation service providers (ANSPs) and airspace users (AUs).

This chapter has been put up mostly by consulting the state-of-the-art reports drawn up by the COCTA consortium, as well as maintaining constant discussion with EUROCONTROL, to ensure the background and other information presented in this thesis are correct.

It proceeds to giving a top-down overview of the European ATM Network structures, focusing on the capacity providers (mostly airports and ANSPs) and demand (air traffic, generated by airspace users). The demand-capacity imbalance problem has prompted much research, including the full COCTA study and this thesis, and is briefly presented in this chapter, followed by the current capacity planning process and the NM collaborative framework in regard to the stakeholders.

3.1. Methodology

In determining an answer to this question, literature including, but not limited to COCTA and EUROCONTROL sources describing the processes has been studied. Discussions took place between the student and relevant experts from the field at EUROCONTROL (inside and outside OPL) to supplement and complete the information. The answer to this question is a description of the actual conditions under which business is conducted between the NM and the concerned stakeholders and serves as reference conditions (baseline) for the next questions.

3.2. Development

3.2.1. Air Transport System

We begin with a high-level description of the problem, starting from the Air Transport System, as it is described in the COCTA State-of-the-art report [14].

The authors explain that **airports and air traffic management (ATM)**, which represent the *supply/-capacity side*, and **airspace users (AUs)**, who create *demand* for air traffic, are the two main subsystems that make up the dynamic and complex air transport system ([43], cited in [14]).

The air transport system also involves other pertinent stakeholders, including the industrial sector (aircraft, equipment, etc.), national and European organizations and bodies, member states, ministries, trade and employee unions.

The relationship between the entities are presented diagrammatically below:

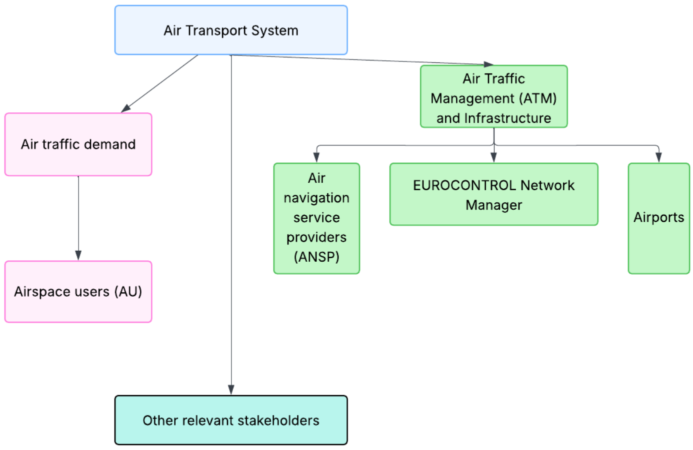


Figure 3.1: Air Transport System diagram, inspired by COCTA

Air traffic demand
In the figure above, the air traffic demand is represented mostly by passenger and cargo flights.

Airspace users (AUs)
As defined by ICAO ([44]), airspace users can be categorized in the following way:

1. ICAO-compliant manned flight operations
2. ICAO non-compliant manned flight operations
3. Flight operations of unmanned aircraft systems (UAS)

The first bullet point can be expanded to:

1. All civil aircraft operators — commercial and private air transport
2. States' users operating State aircraft using civil air traffic rules

Supply and demand
The European ATM Network is one of the most complex systems in the world ([14]) — the largest forum covering most of the European continental landmass is the ECAC — European Civil Aviation Conference, having 44 Member States. Those include all 27 EU, as well as the 42 EUROCONTROL Member States [45].

The countries closely work together with the goal of achieving a "safe, efficient and sustainable European air transport system" [46]. It is sought to achieve a harmonization of policies and practices, leading to an optimization and, where applicable, unification of fragmented, more time and resource-consuming, processes.

As the authors of COCTA have summarized [14], the ANSPs have the primary role in providing Air Traffic Control (ATC) services; during the en-route portion of a flight, Area Control Centres (ACCs) are in control within a designated amount of airspace. More than 65 ACCs [47] build up this highly fragmented airspace, whose central figure is the EUROCONTROL Network Manager (NM). Its role is to optimize the aviation network's performance.

ACC breakdown
An ACC is broken down into multiple sectors (elementary and collapsed). The elementary sector is the smallest unit of airspace, while the collapsed sectors are formed out of multiple elementary sectors. The sectors can also be arranged in specific configurations, suitable for different moments in time. In the figures below, both the ACC disposition at European level can be seen (highlighting the airspace complexity), and sector combinations (elementary into collapsed, and sector configurations).

The sectors are capacity constrained (number of aircraft per hour) considering safety and required level of service.

Note: In the figure below, Area Control Centres (ACC), as well as smaller airspace entities such as Control Areas (CTA) and Terminal Manoeuvring Areas (TMA) can be seen.

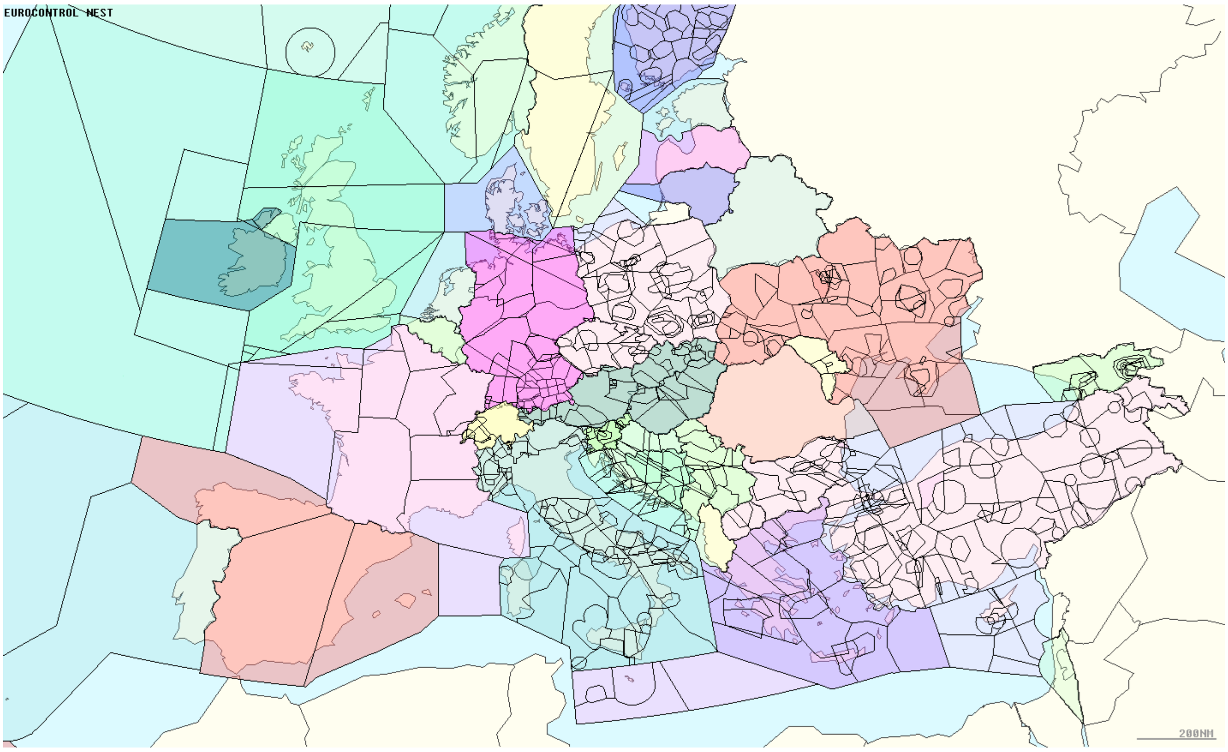
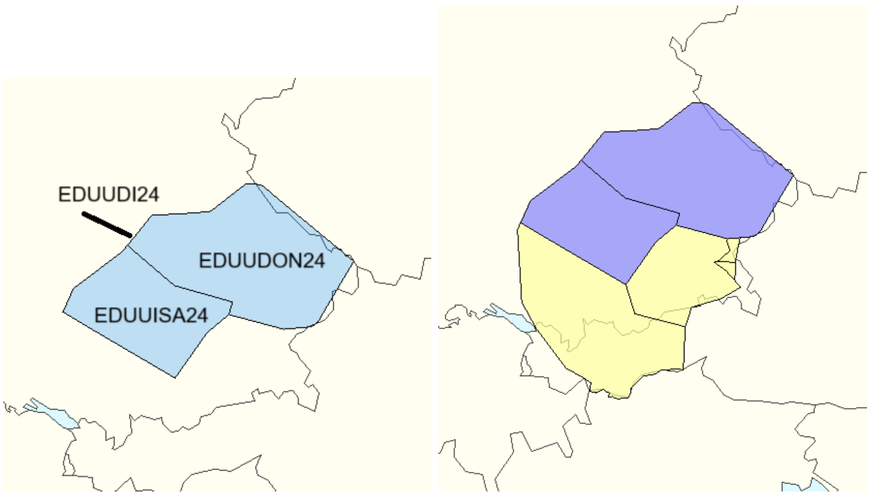


Figure 3.2: Complexity of the European airspace (EUROCONTROL NEST)



(a) Collapsed sector **(b)** Sector configuration

Figure 3.3: Sector arrangement (EUROCONTROL NEST)

Not only is European airspace highly fragmented, but it is also highly complex due to its dynamic nature (Figure 3.2); specifically, in order to maintain or even increase their operating capacity levels, ANSPs must dynamically change the configuration of the sectors in use, to align them with anticipated traffic flows. Similarly, several European airports have limited airport capacity that is strategically allocated through airport slots based on priority rules (also known as "grandfathering rules").

Grandfathering rule: a policy or provision (usually contained in statute) under which an old rule continues to apply to some existing situations while a new rule will apply to future cases [48].

To combat the shortcomings in capacity, ANSPs and airports must function flexibly to deal with various aspects of traffic fluctuation (and predictability), and to give a specific (necessary and/or acceptable) level of service in handling the traffic demand [14].

Matching capacity to demand without inefficiencies in terms of delay (insufficient capacity) or cost (underutilization of resources) becomes more challenging the less predictable the situation is. Although there may occasionally be capacity issues, area control centers (ACCs) should not routinely cause significant delays ([31], cited in [14]).

3.2.2. Demand-capacity imbalance problem

One of the main problems leading to the need of ATFM regulations (more usually applied in the pre-tactical and tactical level) and definition of scenarios, RAD restrictions (devised in the strategic level), thus prompting negotiations for different measures between multiple stakeholders, is the demand-capacity imbalance problem. This issue arises from traffic demand exceeding available airspace or airport capacity. The imbalance problem can be addressed from both sides of the inequality, as follows:

Capacity
As explained in [14], capacity expansion (or increase) is typically viewed as a long-term strategy to deal with rising demand; there are very few choices to increase capacity on short notice [31]. Additionally, increasing the capacity of airspace (and airports) comes with significant expenditures, many of which are transferred to airspace users, thereby depressing demand.

Demand
On the other side, ATFM delays are imposed on the affected traffic. The delays are differentiated based on the position of the aircraft where the capacity shortfall is encountered — either en-route, or ground (airport).

As highlighted in the EUROCONTROL Performance Review Report (PRR) 2023 [47], the en-route ATFM delays in 2023 were the second-highest value in the last 20 years. 11% of flights were subjected to en-route ATFM delay, with an average value of 1.8 minutes per flight and 18.1 million minutes in total. The main driver for such delay were the adverse weather conditions (29.7%), followed by ATC (27.8%).

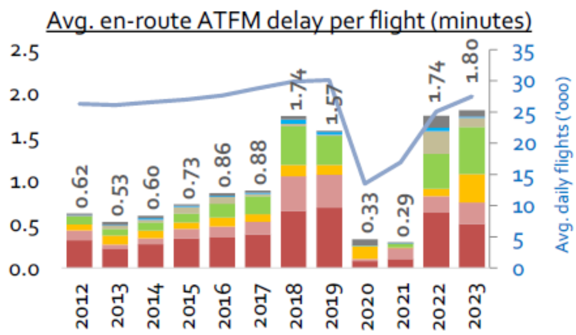


Figure 3.4: Average en-route ATFM delay per flight (EUROCONTROL PRR, 2023)

Regarding ATC, the PRR notes that states had different courses of action (mainly two) with respect to personnel numbers, namely *cost recovery* and *performance regime*. Those operating in the first category increased the number of ATCOs proportionally to the traffic growth, while the latter have kept the number constant, or even decreased it.

It is crucial to lessen the growing strain on the few ATCOs when much-needed capacity development projects, such as technical advancements made possible by SESAR, are implemented into ATC operations. It is necessary to make sure that the training requirements do not interfere with the availability of air traffic controllers for real-time operations while allocating long- or mid-term resources [47].

The Performance Review Commission promotes a comprehensive approach to capacity planning, pointing out the recurring inability to fulfil performance targets using the solutions decided upon by the Network Manager and ANSPs, pointing at a need to ”change the system” [47].

3.3. Current practice

EUROCONTROL has been appointed as the Network Manager (NM) of the Single European Sky by the European Commission firstly for 2009-2019, then re-appointed for 2020-2029 (European Commission implementing regulation 2019/123 - [49]).

As stated in the abovementioned regulation, which lays down detailed rules for the implementation of air traffic management (ATM) network functions, the air traffic flow management (ATFM) function as an ”integral part of the network functions [...] to optimize available capacity in the use of airspace” [49]. The partnership between the Network Manager and the stakeholders to ”improve air traffic flow management” and ”take remedial measures” is also evoked. The Network Manager is mandated to introduce ATFM measures to make best use of the available capacity and promote the best provision of capacity by ATC sectors [49].

The Network Manager is responsible for the coordination of the air traffic flow and capacity management (ATFCM), which is pivotal for the balance between the demand exerted by air traffic and capacity at network level [31]. For reader convenience, we repeat the ATFCM planning timeline, mentioned in the literature review, as well as in the ATFCM Operations Manual [50]:

Strategic	[< 1 year; D - 6) - *long-term*
Pre-tactical	[D - 6; D) - *medium-term*
Tactical	[D] - *short-term*
Post-operational analysis	[D; D+1] - *analysing D*

where D represents the day of operations.

Within ATFCM, it is ensured that airport and airspace capacity can accommodate traffic demand. Should the final capacity allocation possibilities have been consumed, the process moves on to managing the demand to allow for the maximum available capacity to be met [50]. All pertinent parties—including ANSPs, airports, AUs, etc.—participate in the ongoing process of collaborative decision-making.

3.3.1. Collaborative Decision-Making (CDM) process

As defined in the ATFCM Operations Manual [50], CDM is a process ensuring that all relevant stakeholders have the chance to influence the choice and decisions to be made by the appropriate authority, which does so based on the most thorough, current, and accurate information. This allows decisions to be made jointly in order to meet performance goals and allows specific flights to be dynamically optimized to reflect events that are happening soon or in real time.

A CDM procedure should come before a decision to develop and carry out ATFCM measures within the Area of Responsibility (AoR) of a Flow Management Position (FMP) [designated at Member State/ACC level]. This procedure gives the different organizations the chance to promptly and accurately inform one another of happenings at every stage, from the strategic level to real-time. The topics are discussed during regular sessions, during which plans are put forward [50].

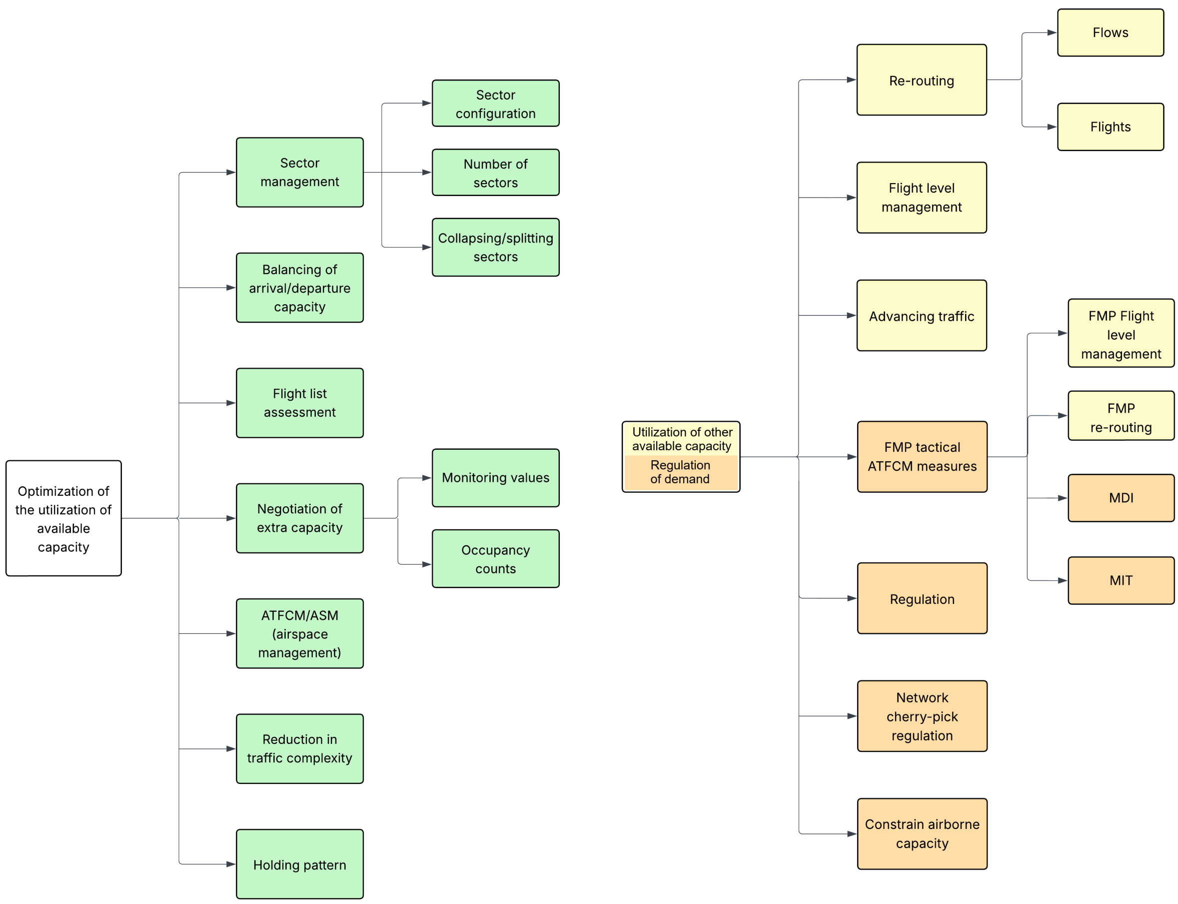
The strategic phase (which is also the central point of this Thesis) focuses on the analysis of significant events, during which either a sharp increase in demand or a reduction in capacity at ACC or airport level is envisioned [50]. The outcome of the discussions is a set of agreed ATFCM measures to be implemented in the pre-tactical and tactical phases. Measures of this kind are incorporated for example during peak periods, such as the summer - the application thereof is discussed in the Thesis.

3.3.2. Schematic process

The authors of the COCTA study acknowledge that the role of NM in the CDM process is relatively limited, as it ”moderates” between capacity providers (ANSPs and airports) and airspace users (mostly Aircraft Operators) [14].

At a general level, NM’s possibilities of influencing capacity or demand decisions are the following [14]:

- Negotiation of extra capacity from the ANSPs (Figure 3.5a)
- Identification of a solution that uses other accessible adjacent airspace capacity (close in both space and time) - e.g., re-routing flights (Figure 3.5b - upper, light yellow rectangles)
- Regulation of demand (at the request of ANSPs) by imposing ground delays on regulated flights/-mandatory re-routings (Figure 3.5b - lower, light red rectangles)



(a) Optimization of the utilization of available capacity

(b) Utilization of other available capacity or regulation of demand

Figure 3.5: ATFCM solutions to capacity shortfalls (reproduced after Sfyroeras, 2024)

The authors of COCTA [14] further argue that, although significant resources are invested in the strategic and pre-tactical phases, the tactical phase of the ATFCM process, on the day of operations, is where the majority of demand-capacity imbalances are handled by airspace slot management and/or flight or flow re-routings. This, in turn, leads to:

- Delays
- Longer routes flown, with:
  - Additional fuel consumption
  - Additional CO_2 emissions
- Flight cancellations

Moreover, the European Commission acknowledges that the NM ”tends to decide by consensus, which often results in weak compromises” due to the absence of defined executive powers in practice [14]. Thus, they emphasize that an expanded operating scope of operations by the NM is necessary to optimize the network’s performance. This is, for the moment, out of the scope of this Thesis, but is to be taken into consideration for an actual implementation of a model in which the NM would have increased decision power.

One of the main facilitators for achieving the goals outlined in the European legislation ([14] [49]) is the European capacity assessment and planning process, together with the required operational cooperation.

3.3.3. On a general level

A comprehensive lay-down of the capacity planning process and its applications across the entire Network, can be found in the Network Strategic Plan (NSP) and the Network Operations Plan (NOP), published annually by EUROCONTROL and approved by the Network Management Board (NMB).

The strategic instrument for overseeing the European ATM network is the Network Strategy Plan (NSP). It outlines the strategic operational goals required to meet the necessary ATM performance standards. [51].

The ATM Network’s short- to medium-term perspective, including anticipated network and local performance, is provided by the Network Operations Plan (NOP).

It offers an overview of the ATM Network’s short- to medium-term operations, including anticipated network and local performance. It provides information about the planned steps for improving capacity and flight efficiency at the network level and by each ACC. It also describes the planned strategies for improving airport performance and performance assessment. It offers a qualitative and quantitative outlook on how these changes stand to affect the functionality of the European ATM Network [52].

While the main NOP is published for a range of 5 years (the actual being for 2023-2027), it also presents a weekly version, called the Rolling Seasonal Plan (NOP), which covers a rolling eight-week period and consolidates data from 350 airlines, 68 ACCs, 55 airports and 43 States [53].

The board overseeing this process, the NMB, was established by the European Commission Regulation (EU) No. 677/2011 of 7.7.2011 (subsequently amended and repealed by the European Commission Implementing Regulation (EU) No.2019/123). Its attribute is to monitor and steer the execution of the network functions, including the performance of the tasks of the Network Manager. The European capacity planning mentioned in an earlier paragraph represents a major contribution to the content of the NOP.

In broad terms, the time spectrum of the capacity planning process is defined by EUROCONTROL, in the Capacity Assessment and Planning Guidance Document [54] as follows:

Medium- to long-term view of the capacities and capabilities of the ACCs [D – 3 months; D + 5 years]

- The early identification of capacity shortfalls or potential bottlenecks produces a dialogue between stakeholders, with ATFCM measures as a result

Annual assessment of the capacity delivered; capacity required in the medium term (D + 5 years) at:

- Network level

- Individual ACC level within the ECAC area (what is defined and published in the Rolling NOP

The traffic projection, anticipated traffic distribution over the route network, the agreed-upon European delay objective, and the cost-benefit ratio of providing air navigation services are all taken into consideration in this planning [14].

3.4. Synthesis

This research question presents the reader with the baseline operational context, including air traffic demand, airspace user definitions, supply-demand dynamics, and ACC (Area Control Centre) structures. It highlights the persistent issue of demand-capacity imbalances and details the current Air Traffic Flow and Capacity Management (ATFCM) process, emphasizing the role of the Network Manager (NM) as defined by EUROCONTROL and the European Commission. Additionally, it presents an overview of capacity planning procedures, noting the approval processes for the Network Strategy Plan (NSP) and the Network Operations Plan (NOP) by the Network Management Board (NMB).

4

Enhancing the decision power of the Network Manager

This chapter discusses the second research question we aim to answer within this report. It is thought to offer an idea on the point where NM stands in a possible configuration where it would have an augmented decision power. To facilitate understanding, before proceeding with the explanations, we repeat the question below:

What are possible ways of enhancing the decision power of NM, and in what aspects can the NM play a more proactive role?

4.1. Methodology

For this research question, data and statements given by EUROCONTROL (through publications and from experts), as well as the point of view of COCTA related to a redesigned ATM value chain [55] (especially for stakeholder — AU and ANSP positioning) are reviewed and presented to the reader. The capacity-demand relationship, which is pivotal to the discussed problem is briefly restated, mentioning assumptions on both sides, then presenting the standpoints of both ATM providers and AO related to trade-offs on their decisions. In the end, methods to increase the decision power of the Network Manager are mentioned, then expanded upon.

4.2. Development

To begin with this research question and re-state the need and possibilities for the EUROCONTROL Network Manager (NM) to enhance its decision power within the Collaborative Decision-Making (CDM) process, we may touch upon several assumptions regarding capacity provision, demand, as well as the standpoint of the aircraft operators (AO) and ANSPs on the matter. These are derived from the *ATM value-chain redesign* deliverable proposed by the COCTA consortium [55].

4.2.1. Assumptions on capacity provision

There are several key points related to the ACC capacity:

- **Sector limits:** Each ACC has a maximum number of sectors that can be opened per hour, determining the upper capacity limit based on traffic patterns. Additional constraints like staffing may further limit this over longer periods (e.g., a week or month).
- **Capacity increases:** Increasing maximum capacity requires long-term investments such as new equipment, ATCO training, and airspace sectorization changes, which can take several months to years. The focus here is on short-term capacity variations within existing maximum limits, with long-term strategies discussed later.
- **Short-term adjustments:** Within the set maximum, capacity can be adjusted by changing sector configurations, affecting ATCO hours and costs. The cost function is influenced by ATCO labour

contracts and staffing constraints, and though exact costs are proprietary to each ANSP, general cost features align with typical ATC service provision economics.

- **Incremental capacity increases:** Capacity increases incrementally, typically in larger batches by opening additional sectors, each allowing more aircraft entries. Marginal costs of an additional flight are nearly zero until maximum throughput is reached.
- **Cost asymmetry:** Adding capacity increases average costs due to overtime premiums and diminishing returns with each new sector, while reducing capacity results in smaller cost savings. This short-term perspective does not conflict with studies showing long-term, increasing returns to scale in ATC.
- **Timing and costs:** Costs for increasing capacity rise with shorter notice before service provision (e.g., due to roster changes), whereas savings from decreasing capacity are reduced the later decisions are made.

4.2.2. Assumptions on demand

The COCTA authors consider the fact that the Aircraft Operators (AOs) pursue profit maximization primarily through the minimization of the overall flight costs. Key factors to influence these costs are:

- Fuel prices
- Route charges imposed by the ANSPs
- Composition and volume of airline customers, encompassing both passenger and cargo segments

Additionally, operational constraints such as airport operating hours and flight crew scheduling play a critical role. Furthermore, for airlines operating within a hub-and-spoke network, cost considerations are interdependent across the broader network, requiring integrated planning to optimize efficiency and profitability.

The authors further note that it is an “undisputed aspect related to the AO decision-making” that airlines operating *scheduled services* typically engage in flight planning well in advance. In contrast, other sectors, such as *business aviation* (which offers on-demand services), charter operations, and military flights, tend to operate on a shorter planning horizon. Once key cost components—such as user charges and fuel prices—are determined, scheduled airlines can establish their preferred flight trajectories as part of their scheduling decisions [55].

4.2.3. Trade-offs pertaining to ATM providers’ decisions linked to capacity and trajectories

From an ATM provider point of view

In an ideal case, the early submission of four-dimensional (4D) trajectories by Aircraft Operators would enhance the predictability of the Air Traffic Management (ATM) system, particularly regarding the spatio-temporal distribution of traffic across the network. This increased predictability supports more effective capacity management and air traffic controller (ATCO) roster planning, ultimately contributing to a reduction in capacity provision costs.

From an aircraft operator (AO) point of view

The determination of an optimal trajectory is often possible only within days or hours of the flight, as it is subject to dynamic factors such as prevailing weather conditions and payload considerations. While trajectories submitted well in advance may align with expected or typical conditions, they may not necessarily represent the most cost-efficient option under actual, real-time circumstances.

4.3. Possible methods to increase the decision power of the Network Manager

4.3.1. Flexibility of airspace users (AUs) related to flight planning

The decision power of the capacity provider parties devising or agreeing to specific traffic measures may be seen in conjunction with the flexibility of airspace users (AUs)/aircraft operators (AOs) in terms of flight planning. As already described in the *Literature study*, subsection 2.1.2, there is a balance between the planning flexibility, which is of high value to AUs for various reasons, among which we could name the response towards unforeseen circumstances (e.g. meteo). This, in turn, translates into (un-)predictibility on the Network Manager's side.

A short breakdown obtained as a result of discussions with the supervisors and several EUROCONTROL experts is constituted as follows:

- **Complete operational flexibility** is granted to Airspace Users (AUs) to plan their flights without restrictions, such as Route Availability Document (RAD) measures.
- **Full authority** is given to the Network Manager (NM) to assign trajectories to individual flights, effectively diminishing the role traditionally performed by Computer Flight Plan Service Providers (CFSPs).

These two different approaches could be seen, as pinpointed by the supervisors, as "extremes" — there are multiple approaches in which the decision power of NM could be enhanced. reaching to the flexibility of planning of the airspace users, out of which we could name:

1. The Network Manager (NM) proposes specific trajectories for individual flights — an important point of discussion of the COCTA study, and a current point, carried out at present through re-routings.
2. NM collects inputs regarding available capacity and expected demand, and subsequently proposes the package of NM Route Availability Document (RAD) measures for a particular situation (ad-hoc event or whole summer season).
3. NM is assigned a stronger role in the current CDM process with the operational stakeholders, producing a "mixed" situation in which both NM and ANSPs would propose re-routing measures — which is specifically what this thesis aims to contribute to.

4.3.2. Proposal of specific trajectories for individual flights

This is one of the pillars of the COCTA study, as revealed by multiple journal papers and deliverables, out of which the most notable would be the *ATM value-chain redesign* [55].

The authors describe a process in which the Network Manager (NM) begins by establishing an initial capacity requirement based on a traffic estimate. Further, binding offers are requested from the air navigation service providers (ANSPs) for the provisions of this capacity, expressed in sector hours.

Based on a traffic estimate, the network manager establishes an initial capacity requirement and requests binding offers from the Air Navigation Service Providers (ANSPs) for the provision of this capacity (expressed in sector hours) as well as for a greater or lower level of capacity. The Network Manager can order capacity from the ANSPs and calculate the network configuration that minimizes costs based on their offers [55].

The Aircraft Operators can select their preferred alternative from a set of paths provided by the Network Manager (NM) within the specified capacity supply (also known as a **purchased specific trajectory**. As the authors of COCTA continue to explain, charges are frequently established at the airport (city) pair level, avoiding negative incentives brought on by disparate unit charges. However, there are incentives for early trajectory booking, which helps NM estimate traffic. In situations when capacity is limited, a charge distinction may also be applied. Additionally, the NM may provide a discounted product called **flexibly assigned trajectory**, which permits aircraft operators having acquired the flexible product to be allocated trajectories in the short term [55].

In other words, we might speak of a trade-off between the amounts the aircraft operators would be charged and willing to pay, and the notice of the trajectories they wish to use — which normally should happen at flight plan filing.

This balance between the planning flexibility of the AUs and predictability for the ANSPs coupled with possible (financial) incentives, or quantifiers, has been touched upon in the *Literature study*, subsection 2.1.2.

As stated in the deliverable 5.4. *Effects of increased flexibility for airspace users on network performance*, the above-mentioned trajectory products have the increase of airspace user/aircraft operator acceptance as a goal [56].

At present, demand is managed by re-routing the flights to offload congested areas - such a measure to alleviate pressure above a specific sector is central to the examination of our thesis.

4.3.3. Proposal of given RAD measures for a particular situation

The NM Strategic Team within the Operations Planning Unit of the Airspace & Capacity Division of EUROCONTROL contributes to an efficient planning of the Network at least 6 months to 7 days before the day of operation.

A key focus area for the NM Strategic Team is the preparation of Special Events with anticipated high impact on the Network. This includes for example the preparation of transition plans or busy seasons such as summer season. Strategic ATFCM measures are developed, i.e. ATFCM Scenarios or specific network measures (published in the Route Availability Document — RAD) that are to be applied by and within specific ACCs to alleviate the pressure and ensure a smooth flow in a given section of the Network. The RAD is a standard reference document presenting the route and traffic orientation policies, procedures, and descriptions. It also covers the availability and rules for using free route airspace and the route network.

The RAD was created in response to the need to strengthen the connections between the Airspace Design and Airspace Utilization processes in cooperation with the Operational Stakeholders. It is a component of the NM Air Traffic Flow and Capacity Management (ATFCM) role. Its legal basis is the Commission Regulation (EU) No 255/2010 of the 25th of March 2010, laying down common rules on air traffic flow management, in accordance with its Article 4, stipulating that “a common reference document containing the policies, procedures, and description for route and traffic orientation shall be created” ([57], pp. 1)

To implement this work, a NM RAD Team was formed, which assists the Operational Stakeholders in handling every characteristic of the RAD, from policy to implementation. The content of the RAD is agreed upon between the Network Manager and the Operational Stakeholders through a Cooperative Decision Making (CDM) process.

4.3.4. A stronger role in the current CDM process with the operational stakeholders

This very position is the one our thesis seeks to explore - which is done by the means of the game-theoretic model in which the parties to the Collaborative Decision-Making (CDM) meeting are portrayed as players. The Network Manager (NM) issues a re-routing measure above the airspace of the Karlsruhe UAC South (EDUUUTAS) to reduce the congestion generated by traffic flow overflying it. This is done by gradually removing flights from a selected pool.
Then, the acceptance of the stakeholders (in our case, air navigation service providers [ANSPs] and airspace users [AUs]), thus the reaction to this measure, is evaluated. All of what is mentioned in this paragraph is to be expanded and discussed in chapter 5.

4.4. Synthesis

The research question began with the discussion of the capacity-demand relationship and the positioning of both the ATM providers and AUs towards it. The trade-off in flight planning flexibility of the AUs, who prefer to perform it on shorter notice because of their dynamic needs (e.g. meteorological conditions or payload determination), which translates into lower predictibility for the capacity providers and viceversa, has also been mentioned. In the end, three different ways to enhance the decision power of the Network Manager in its relationship with the stakeholders have been highlighted.

5

New system for ensuring stakeholder acceptance

This chapter discusses the third research question we have undertaken to clarify in this Thesis. The game theoretic model is proposed, along with the extraction and calculation of variables necessary to generate the payoff of the players (in our case, the ANSP and AU stakeholders). In the end, a short explanation on the game theoretic algorithm and its choice are presented.

To facilitate understanding, before proceeding with the explanations, we repeat the question below:

> What would be a proper way of introducing related changes to the stakeholders, to ensure acceptance of the new setup?
>
> a) How can it be ensured that the stakeholders are treated fairly in the process?
>
> b) How could the stakeholders be incentivized to take measures leading to an improvement of network performance?

5.1. Methodology

We begin with addressing the fairness towards the stakeholders involved in the concrete case of introducing a new ATFCM measure. For this study, a section of the European ATM Network, which contains one or more congested areas (at sector or entire ACC level), is analysed. The said measure mostly consists in diverting a given number of flights which would cross the congested sector, making them avoid ('offload') it, to alleviate ATC workload/pressure. Air traffic is then analysed in a cross-border area, where neighbouring sectors would receive ('onload') (a part of) the diverted flights from the congested sector.

The purpose of this model is to evaluate the position at which a Nash equilibrium is reached, taking into consideration the interests and payoffs of the stakeholders - represented as players in the game theoretic model elaborated on below. The players range from airspace users (AU) to ANSPs (represented through sectors or ACCs); **the found equilibrium** should offer the EUROCONTROL Network Manager (NM) **an image of the fairness** towards the stakeholders **and their acceptance** of a devised network measure. This would also present NM with the **theoretical reaction** of the stakeholders to a decision taken at central level, in the context of increasing the power of EUROCONTROL related to issuing capacity measures.

The completion of the answer to the first letter of this research question, related to the **fairness** towards the stakeholders, consists in the simulation. The final outcome is based on the payoffs, or utility variables, of each stakeholder (the players of the model). As such, the game measures their response based on their benefits from a certain choice of strategy.

The point referring to the **incentivization of stakeholders** to take action leading to an improvement of the network performance is examined through setting of different weights on specific payoffs, as the reader can see in figures Figure 6.7 or Figure 6.12.

5.1.1. Game theoretic model

Our game theoretic model is based on a relatively straightforward template, where we can introduce the players and define their payoffs for each combination of strategies possible in the game. The Nash equilibrium is calculated through a geometrical regret matching algorithm as per the work of Lan [58] — further explained in subsection 5.5.4. As such, we move forward to introducing the strategies and the payoff calculation method for each type of players.

5.1.2. Strategies

We consider a "binary" strategy type for this game, as related to the network restriction (measure). As such,

- Strategy 0 — the measure is rejected
- Strategy 1 — the measure is accepted

The strategies can be further split into sub-strategies, considering a different number of flights, arbitrarily given by the user, to test different degrees of acceptance of all parties involved.

The **measure** refers to diverting ('offloading') the above-said number of flights from the congested sector. It results in a change in trajectory of the selected flights, which may overfly ('onload') other sectors.

To obtain the airspace and flight data and gather the base values which have been used to calculate the player payoff functions (which are later explained), we have made use of the EUROCONTROL NEST - Network Strategic Tool.

NEST
Developed by EUROCONTROL, NEST is a scenario-based modeling tool used by air navigation service providers (ANSPs) and the EUROCONTROL Network Manager. It helps optimize resources, enhance network performance, design airspace structures, and plan capacity. NEST also supports traffic flow organization, scenario preparation for simulations, and post-operation analyses. Additionally, it aids in ad-hoc studies at both local and network levels and can be utilized by area control centers (ACCs), airports, and other stakeholders involved in strategic network planning [59].

Out of the main functions NEST can perform, we name [59]:

- **4D traffic distribution:** Computes flight trajectories considering aircraft performance, route restrictions, flight levels, SID/STAR, and military airspace availability, optimizing routes by shortest, cheapest, or most efficient paths.
- **Regulation builder:** Automates capacity adjustments to manage overloads, customizable to reflect real-world operations.
- **Delay simulation:** Estimates ATFM delays for an entire day while accounting for network-wide impacts.

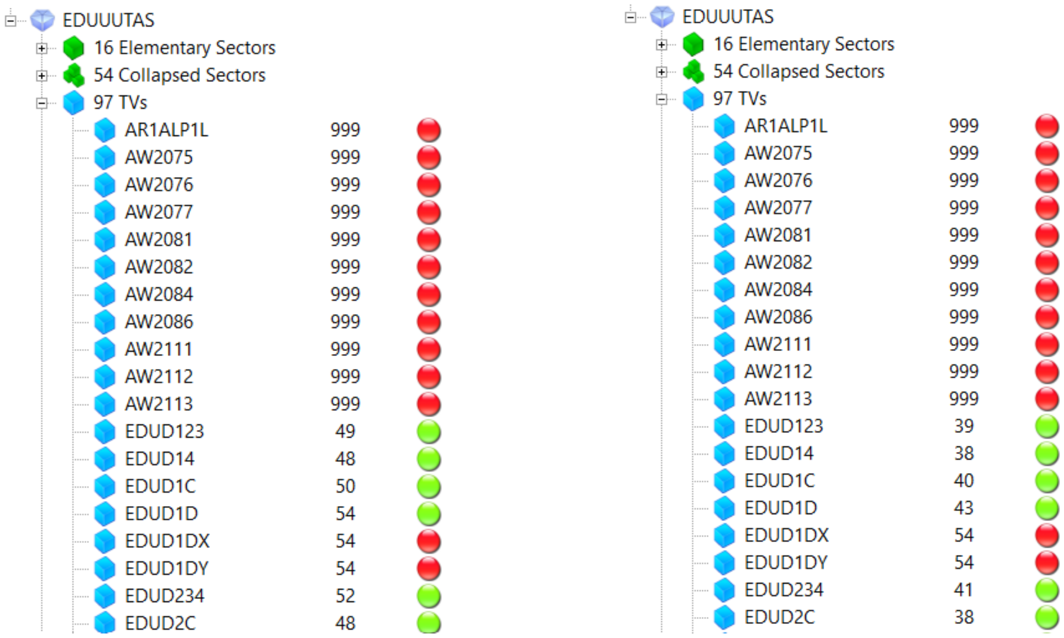
These capabilities have especially been put to the test in creating the use cases for the game theoretic model. In what follows, an in-depth explanation is provided.

5.1.3. Defining the environment

The Karlsruhe UAC is one of the most congested airspaces in the European Network, making it the ACC with the most delays in absolute value, and putting it on the second place after Marseille ACC in terms of average delay per flight [60]. It is also noted in the Performance Review Report (PRR) 2023 [47], that Karlsruhe UAC generated the largest share of delay in that year (16%).

Considering the above, we saw fit to explore the effects of issuing an ATFCM measure aiming at decongesting a key area in the Karlsruhe UAC South ACC (EDUUUTAS), during a regular peak period, such as the summer.

To enable a tangible difference between the baseline case and the simulated case, in which the ATFCM measure is applied on a certain traffic flow, to properly measure its effect, we analyzed the current capacity (expressed in hourly monitoring values) of the sectors composing EDUUUTAS. A screenshot of the relevant display of the capacities is shown below:



(a) Original **(b)** Reduced by 20%

Figure 5.1: EDUUUTAS sector capacities

In this menu, the user can see whether the sectors are activated (i.e., the light is green, and a number usually between 0 and 100 defines its capacity) (Figure 5.1a). The remaining inactive sectors are not considered for the analysis. For precision, it needs to be mentioned that the above entities are *traffic volumes* — similar to sectors from a 3D representation, but different in terms of traffic flows (which can be included or excluded in the counts, for specific cases).

It was suggested to decrease the capacity of the active sectors by 20% and simulate the issuing of new ATFM regulations (which are one of the main drivers of delay incurred en-route). Further, the delays were also simulated, to take into account the newly-issued measures as a result of the simulation. In Figure 5.1b, the new capacities can be observed.

These modifications were undertaken to create an artificial baseline case, enabling us to measure a significant effect between the initial scenario, in which no flight is re-routed because of the measure, and the simulated scenario, accounting for the re-routings.

The selection of sectors was performed by checking the repetitivity of a regulation associated to a certain sector and the subsequent delay taken in descending order, on a flight list. The latter was the result of the two different traffic flows which we analyzed. These are a UK - Türkiye flow (EG-LT) and an outbound flow from major German airports - Frankfurt am Main (EDDF), München (EDDM), Düsseldorf (EDDL) and Stuttgart (EDDS).

The result of the traffic flow - sector combination, described in terms of number of flights and delay, prompting us to further analyze the stakeholder acceptance on this use case in the game theoretic model, is the following:

- Scenario 1a. EG-LT, avoid EDUUCHI1K sector
- Scenario 1b. EG-LT, avoid EDUUDI3C sector

- Scenario 2a. ED airports, avoid EDUUCHI1K sector
- Scenario 2b. ED airports, avoid EDUUISA1I sector

In the above scenarios, the result of the simulation (a full re-route) was the following:

- Scenario 1a. 44 flights, 43 re-routed, 62509/60292 minutes of delay (3.54% less in EDUUCHI1K, by extracting 42 out of 926 total flights from said sector)
- Scenario 1b. 77 flights, 64 re-routed, 65703/60318 minutes of delay (8.19% less in EDUUDI3C, by extracting 64 out of 1076 total flights from said sector)
- Scenario 2a. 112 flights, 111 re-routed, 48250/43730 minutes of delay (9.36% less in EDUUCHI1K, by extracting 112 out of 983 total flights from said sector)
- Scenario 2b. 133 flights, 124 re-routed, 40728/35777 minutes of delay (13.83% less in EDUUISA1I, by extracting 42 out of 926 total flights from said sector)

The players (aside from the German sectors and the airspace users, later defined) affected in each scenario are the following:

- Scenario 1a. Slovenia (LJLACTA) - 14 flights offloaded (less); Croatia (LDZOCTA) - 13 flights offloaded (less); Hungary (LHCCCTA) - 23 flights onloaded (more); Bulgaria (LBSRCTA) - 13 flights onloaded (more)
- Scenario 1b. Slovenia (LJLACTA) - 24 flights onloaded (more); Croatia (LDZOCTA) - 18 flights onloaded (more); Hungary (LHCCCTA) - 18 flights offloaded (less)
- Scenario 2a. Italy (LIPPCTA) - 16 flights onloaded (more); Austria (LOVVCTA) - 5 flights offloaded (less), Slovenia (LJLACTA) - 24 flights offloaded (less), Hungary (LHCCCTA) - 20 flights onloaded (more)
- Scenario 2b. Italy (LIPPCTA) - 21 flights onloaded (more); Austria (LOVVCTA) - 5 flights offloaded (less), Slovenia (LJLACTA) - 5 flights offloaded (less); Croatia (LDZOCTA) - 4 flights offloaded (less)

Note: The reader may sum the onloaded and offloaded flights in absolute value and observe that they do not add up to the total number of flights re-routed; this happens both because of the airspace-level breakdown, and the fact that some re-routed flights only suffered a change in trajectory above a certain airspace; hence they do not count as onloaded or offloaded.

In what follows, an explanation is given regarding the payoff parameters for each type of player (ANSP and AU), then the different scenarios are briefly presented.

5.1.4. Payoff/utility function parameters

ANSP

For the ANSPs, the following parameters have been calculated, by exporting values from NEST and processing them in a Python script. We make use of the:

- Revenue drawn from route charges — Rc* **[EUR]**
- Delay — δ **[min]**

*The revenue drawn from charges is given by the formula $Rc = SU_{\text{en-route}} * u_r$

u_r [EUR] is the monthly-adjusted unit rate as published by the Central Route Charges Office (CRCO) within EUROCONTROL; July 2024 [61] for our studied scenarios, and $SU_{\text{en-route}}$ are the en-route service units, calculated as per Annex VIII article 1 of the Commission Implementing Regulation (EU) 2019/317, pp. 55 [6].

The en-route service units are thus calculated by the formula:

$$SU_{\text{en-route}} = d_f \cdot w_f \tag{5.1}$$

where d_f [km] and w_f [t] are the distance and weight factors, respectively. They follow the equations $d_f = \frac{d}{100}$ and $w_f = \sqrt{\frac{MTOW}{50}}$, with d [km] the en-route distance flown by an aircraft through the analysed airspace and $MTOW$ [t] the maximum take-off weight of said aircraft. As per the Commission regulation, $MTOW$ is taken to the precision of one decimal place, and w_f to two decimal places.

AU
For the airspace users (three different players, collectively representing three types of airlines: low-cost, traditional, and 'other' [not falling in the first two categories]), the parameters are aggregated across all flights, as follows:

- Average route charges difference* — Δr_c **[EUR]**
- Average fuel burn cost difference** — Δf_c **[EUR]**
- Average delay difference - Δt **[min]**

*The route charges have been calculated using NEST, by performing an intersection of the flight trajectories with all the overflown airspaces.

This way, it is ensured that all overflown airspaces are considered when calculating the payoff for the AUs, not only the ACCs specifically analyzed for the game.

**The fuel burn has been calculated per flight, using aircraft performance data issued by the EUROCONTROL Innovation Hub (then, EUROCONTROL Experimental Centre) [62].

It is noteworthy that the latter two payoffs have been chosen as a result of the discussion with airline representatives, as well as the consultation of the COCTA study, namely deliverable 3.1 *ATM value-chain redesign* for Research Question 2, in subsection 4.2.2.

The performance table distinguishes between cruise, climb, and descent phases. For each of them, a value of the fuel burn rate [kg/min] is given according to the flight level [FL] and TAS [kts], while for climb and descent, the rate of climb/descent is also a parameter. For calculation simplicity, the fuel burn rate was taken at nominal value for each aircraft type as corresponding to the closest flight level flown - the flight levels were taken from an export of each flight route.

The attitude ('cruise', 'climb', and 'descent') was determined by checking whether the next flight level measured was higher than the previous (yielding 'climb'), lower (yielding 'descent'), or constant (yielding 'cruise'). Each fuel burn rate value, closest to the flight level at the measured data point, was multiplied with the duration of the flight at a certain level.

Giving:

$$f_b = \dot{f}_b \cdot t \tag{5.2}$$

where:

f_b	fuel burn [kg]
$\dot{f}_b$	fuel burn rate [kg/min]
t	crossing duration [min]

Finally, the fuel cost was obtained by multiplying the fuel burn rate f_b with the fuel price f_p in EUR/kg, transformed from USD/gallon through the formula:

$$f_p\left[\frac{EUR}{kg}\right] = \frac{f_c\left[\frac{USD}{gal}\right]}{3.785\frac{l}{gal}\cdot 0.8\frac{kg}{l}}\cdot 0.92\frac{EUR}{USD}$$

where 0.8 $\frac{kg}{l}$ is the density of kerosene and f_p = 2.57 $\frac{USD}{gallon}$ the kerosene price as per July 2024 (7.06.2024, IATA/Platts, cited in the European Aviation Overview 01-07 Jul 2024 [63]).

Note: The average values have been computed on a weight basis: as the AU payoffs were both negative and positive values, we counted the negative, as well as the positive values, and made them into weights for the sums of the negative and positive values. As such, we obtained:

$$\text{weighted average} = \frac{\text{\#positive values}\cdot\sum\text{positive values} + \text{\#negative values}\cdot\sum\text{negative values}}{\text{\#positive values} + \text{\#negative values}} \tag{5.3}$$

5.1.5. Strategy meaning and model layout

In what follows, the model layout is presented — using this structure, the code which passes the data from the NEST variable calculation scripts and then calculates the Nash equilibrium for all players and their subsequent strategies, has been constructed.

- **Strategy 0** – the measure is not accepted $\Rightarrow$ we use the *initial* case.
- **Strategy 1** – the measure is accepted $\Rightarrow$ we use the *simulated* case

We consider that the measure "passes" if it is accepted by a minimum number of players (AU and ANSPs alike - explained for each scenario); leading to consideration of the simulated case. Else, it "fails", resulting in the payoffs staying the same as in the initial case.

Initial strategy setting

As the model of Lan allowed for an initial strategy set to be given to all players, we used it to initialize the game with different degrees of acceptance. A table of initial strategies looks as follows:

	Strategy - accept	**Strategy - reject**
Player 1	x	1-x
Player 2	x	1-x
...	x	1-x

Table 5.1: Initial strategy acceptance

where x is a number between 0 and 1 (representing the degree of acceptance) This table is shown next to each scenario.

5.1.6. Players

ANSPs

For all ANSPs, the payoffs are calculated as follows:

$$\text{Payoff}_i = w_{Rc_i} * Rc_{ij} + w_{\delta_i} * \delta_{ij} \tag{5.4}$$

where the parameters are the following:

Parameter	**Code equivalent**	**Meaning**
Rc_{ij}	`total_route_charges`_player_strategy	Route charges [EUR]
δ_{ij}	`total_delay`_player_strategy	Delay [min]

Table 5.2: Parameters for the ANSP players

w being the weights for each parameter, i the player, and j the strategy (0 — initial, 1 — simulated).

- w_{Rc_i} - positive (to be maximized)
- w_{δ_i} - negative (to be minimized), both of them larger in absolute value for Player 1, as it is the one primarily benefiting from the offload.

AUs

For the airspace users, the payoffs are calculated as follows:

$$\text{Payoff}_i = w_{\Delta r_{cAU}} * \Delta r_{cAU} + w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU} \tag{5.5}$$

w being the weights of the parameters, negative (as the parameters need to be minimized).

Note: Since these payoffs measure difference, in the initial case (strategy 0), the payoff is 0, as nothing changes. The parameters can be found in the table below:

Variable	Code equivalent	Meaning
Δr_{cAU}	`avg_route_charges_difference_simulated_flights`	Avg. route charges difference [EUR]
Δf_{cAU}	`avg_fuel_cost_difference_simulated_flights`	Avg. fuel cost difference [EUR]
Δt_{AU}	`avg_time_difference_simulated_flights`	Avg. time difference [min]

Table 5.3: Parameters for the AU players

5.1.7. Choice of flights

In order to simulate a more realistic stakeholder acceptance, re-routed flights were not taken by chance. We started from a full re-routing (of all flights), then gradually removed:

1. Multiple flights, by city pair, in descendent order of delay sum per city pair
2. Per flight, in descendent order of delay

Each iteration is seen as a negotiation round, and the game theoretic model based on the iterations measures after how many re-routed flights we can observe the highest degree of acceptance for each of the players.

5.1.8. Choice of coefficients/weights

For the baseline (”raw”) case shown in the results, a fixed value of the weights was used - hence the name ”coefficients”. Distinct values have been used for the ANSPs and the AUs, as follows:

- 100 EUR/minute of delay* [ANSP - w_{δ_i}]
- 50 EUR/minute of delay, coming from an average of 3000 EUR/hour** [AU - $w_{\Delta t_{AU}}$]
- 1, for all the other weights, to ensure a uniform subtraction/addition within the payoff formulas and maintain EUR as the unit of expression

*as expressed in the *En-route total strategic costs* from the 2015 Westminster study related to the European airline delay cost reference values [64].

**as expressed in the cost-effectiveness analysis section of the EUROCONTROL ACE Benchmarking report, 2024 edition [65].

5.2. Scenario 1a. EG-LT flow, avoid EDUUCHI1K sector

5.2.1. Environment

We chose the day of 4.07.2024 (AIRAC cycle 2406) and analysed an **en-route** traffic flow departing from the United Kingdom airports, with all airports of the Republic of Türkiye as destination.

5.2.2. Traffic flow

As mentioned before, we start from the congested sector EDUUCHI1K – belonging to Germany (DFS); bottom FL 315. We offload this sector by turning it into a restricted area. As such, the airspace becomes unavailable for any flight on a 24H basis for the date of 4.07 (figure below):

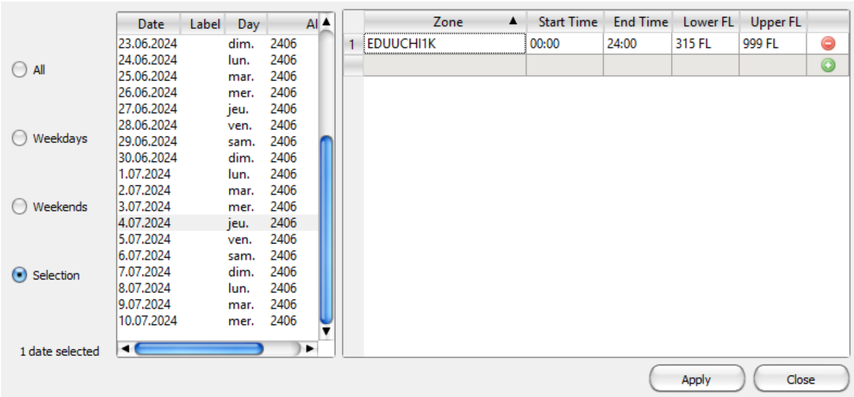


Figure 5.2: EDUUCHI1K exclusion area (EUROCONTROL NEST)

The trajectory simulation for the flight re-routing manages to remove **43 out of the 44 flights** from the UK - Türkiye airports flow crossing the EDUUCHI1K airspace.

The layout of the airspaces selected for examination together with the flights crossing them can be seen in the figure below:

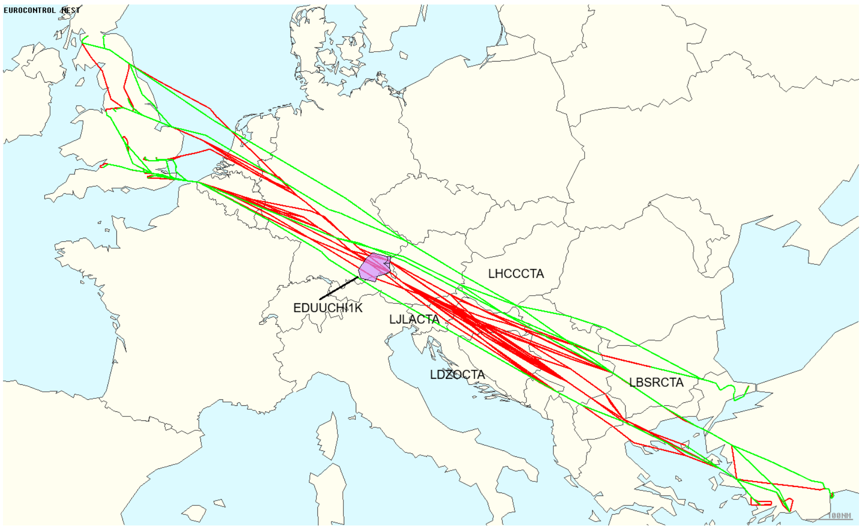


Figure 5.3: Airspaces and flights selected for examination (EUROCONTROL NEST)

The flights in red represent the *Initial* flights, while the ones in green are the *Simulated*.

As one can see on the figure, the simulation brings changes in the LJLACTA (Slovenian), LDZOCTA (Croatian), LHCCCTA (Hungarian) and LBSRCTA (Bulgarian) airspaces (which have also been briefly addressed in subsection 5.1.3. The effects of the simulation are summarized in the next table:

Airspace	Number of flights	Effect
EDUUCHI1K	42	Offloaded (removed)
LJLACTA	14	Offloaded (removed)
LDZOCTA	13	Offloaded (removed))
LHCCCTA	23	Onloaded (added)
LBSRCTA	13	Onloaded (added)

Table 5.4: Effects of the simulation on the five considered airspaces

The note related to the summing-up of the flights remains valid here as well.

5.2.3. Strategy choice

For this scenario, we composed the general acceptability of a strategy (engage or not engage measure) as follows: in order for the measure to be accepted (enter *Simulated* case), it was mandatory for 5 players to agree to it, under which there needed to be EDUUCHI1K, low-cost and traditional AUs (having ”veto power”). Since for this game, we had two strategy choice possibilities and eight players, the number of combination of strategies is $2^8 = 256$ different strategies - due to brevity reasons, we only displayed the first 11 combinations, for Player 1 (EDUUCHI1K) and Player 6 (low cost AUs) in the Appendix.

Initial strategy division

For this scenario, the initial strategies were composed in two different manners: *All are neutral*, and *Acceptance by inclination*. For the first, a ’0.5’ will be written both for acception and rejection of the strategy, simbolizing the neutrality in acceptance, while the third is based on our assumption of the acception of the strategy of each player based on the flight onload/offload, as well as the payoff - and is presented in the table below:

	Strategy - accept	**Strategy - reject**
EDUUCHI1K	0.85	0.15
LJLACTA	0.7	0.3
LDZOCTA	0.6	0.4
LHCCCTA	0.2	0.8
LBSRCTA	0.3	0.7
AU - low-cost	0.5	0.5
AU - trad.	0.5	0.5
AU - other	0.5	0.5

Table 5.5: Initial strategy acceptance for Scenario 1a.

5.3. Scenario 1b. EG-LT flow, avoid EDUUDI3C sector

5.3.1. Environment

We chose the day of 4.07.2024 (AIRAC cycle 2406) and analysed an **en-route** traffic flow departing from the United Kingdom airports, with all airports of the Republic of Türkiye as destination.

5.3.2. Traffic flow

We start from the congested sector EDUUDI3C – belonging to Germany (DFS); bottom FL 365. We offload this sector by turning it into a restricted area. As such, the airspace becomes unavailable for any flight on a 24H basis for the date of 4.07 (figure on the next page):

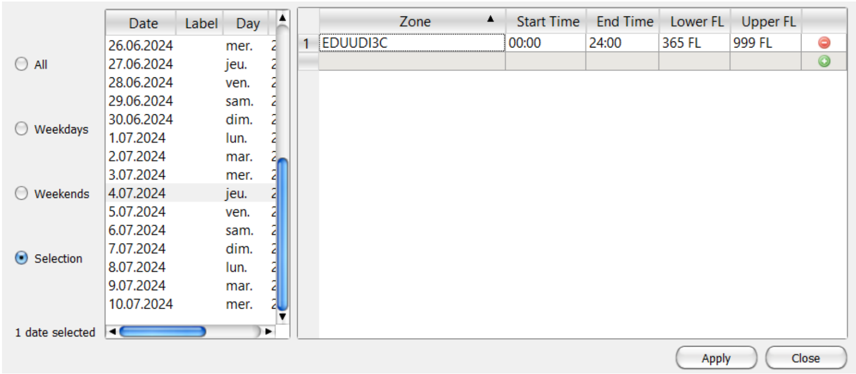


Figure 5.4: EDUUDI3C exclusion area (EUROCONTROL NEST)

The trajectory simulation for the flight re-routing manages to remove **64 out of the 77 flights** from the UK - Türkiye airports flow crossing the EDUUDI3C airspace.

The layout of the airspaces selected for examination together with the flights crossing them can be seen in the figure below:

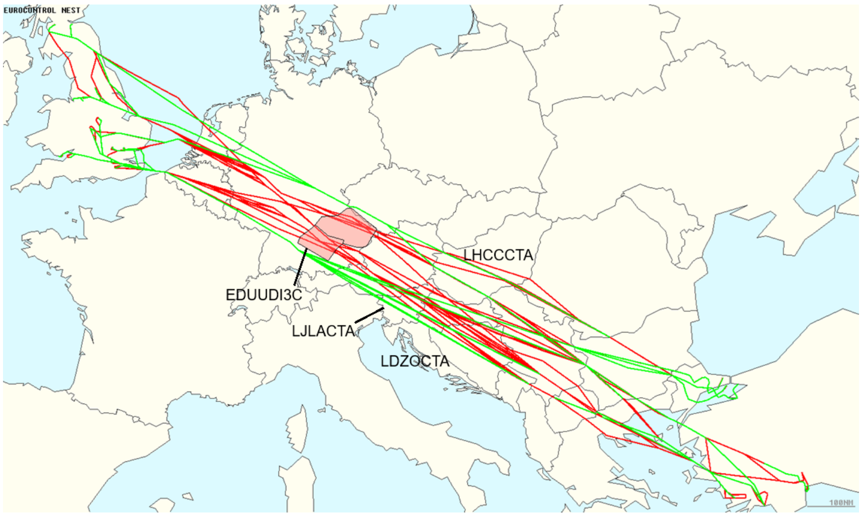


Figure 5.5: Airspaces and flights selected for examination (EUROCONTROL NEST)

The flights in red represent the *Initial* flights, while the ones in green are the *Simulated*.

As one can see on the figure, the simulation brings changes in the LJLACTA (Slovenian), LDZOCTA (Croatian) and LHCCCTA (Hungarian) airspaces (which have also been briefly addressed in subsection 5.1.3. The effects of the simulation are summarized in the next table:

Airspace	Number of flights	Effect
EDUUDI3C	64	Offloaded (removed)
LJLACTA	24	Onloaded (added)
LDZOCTA	18	Onloaded (added))
LHCCCTA	18	Offloaded (removed)

Table 5.6: Effects of the simulation on the five considered airspaces

The note related to the summing-up of the flights remains valid here as well.

5.3.3. Strategy choice

For this scenario, we composed the general acceptability of a strategy (engage or not engage measure) as follows: in order for the measure to be accepted (enter *Simulated* case), it was mandatory for 4 players to agree to it, under which there needed to be EDUUDI3C, low-cost and traditional AUs (having ”veto power”). Since for this game, we had two strategy choice possibilities and seven players, the number of combination of strategies is $2^7 = 128$ different strategies - due to brevity reasons, we only displayed the first 11 combinations, for Player 1 (EDUUDI3C) and Player 5 (low cost AUs) in the Appendix.

Initial strategy division

For this scenario, the initial strategies were composed in two different manners: *All are neutral*, and *Acceptance by inclination*. For the first, a ’0.5’ will be written both for acception and rejection of the strategy, simbolizing the neutrality in acceptance, while the third is based on our assumption of the acception of the strategy of each player based on the flight onload/offload, as well as the payoff - and is presented in the table below:

	Strategy - accept	**Strategy - reject**
EDUUCHI1K	0.85	0.15
LJLACTA	0.2	0.8
LDZOCTA	0.3	0.7
LHCCCTA	0.8	0.2
AU - low-cost	0.5	0.5
AU - trad.	0.5	0.5
AU - other	0.5	0.5

Table 5.7: Initial strategy acceptance for Scenario 1b.

5.4. Scenario 2a. ED airports, avoid EDUUCHI1K sector

5.4.1. Environment

We chose the day of 4.07.2024 (AIRAC cycle 2406) and analysed an **en-route** traffic flow departing from several large German airports, namely Frankfurt Airport (EDDF), München (EDDM), Düsseldorf (EDDL) and Stuttgart (EDDS) and flying to any destination.

5.4.2. Traffic flow

We start from the congested sector EDUUCHI1K – belonging to Germany (DFS); bottom FL 315. We offload this sector by turning it into a restricted area. As such, the airspace becomes unavailable for any flight on a 24H basis for the date of 4.07 (figure below):

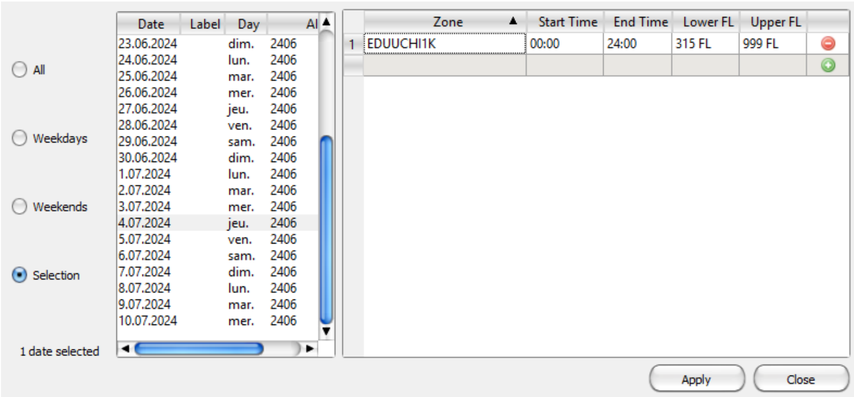


Figure 5.6: EDUUCHI1K exclusion area (EUROCONTROL NEST)

The trajectory simulation for the flight re-routing manages to remove **111 out of the 112 flights** from the German airports outbound flow crossing the EDUUDI3C airspace.

The layout of the airspaces selected for examination together with the flights crossing them can be seen in the figure below:

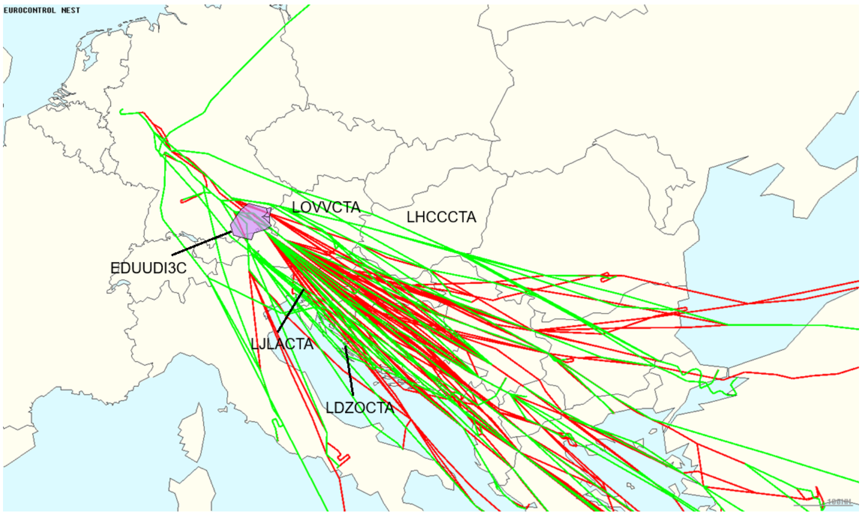


Figure 5.7: Airspaces and flights selected for examination (EUROCONTROL NEST)

The flights in red represent the *Initial* flights, while the ones in green are the *Simulated*.

As one can see on the figure, the simulation brings changes in the LIPPCTA (Italian), LOVVCTA (Austrian), LJLACTA (Slovenian), LDZOCTA (Croatian) and LHCCCTA (Hungarian) airspaces (which have also been briefly addressed in subsection 5.1.3. The effects of the simulation are summarized in the next table:

Airspace	Number of flights	Effect
EDUUCHI1K	111	Offloaded (removed)
LIPPCTA	16	Onloaded (added)
LOVVCTA	5	Offloaded (removed))
LJLACTA	24	Offloaded (removed)
LDZOCTA	11	Offloaded (removed)
LHCCCTA	20	Onloaded (added)

Table 5.8: Effects of the simulation on the five considered airspaces

The note related to the summing-up of the flights remains valid here as well.

5.4.3. Strategy choice

For this scenario, we composed the general acceptability of a strategy (engage or not engage measure) as follows: in order for the measure to be accepted (enter *Simulated* case), it was mandatory for 6 players to agree to it, under which there needed to be EDUUCHI1K, low-cost and traditional AUs (having "veto power"). Since for this game, we had two strategy choice possibilities and seven players, the number of combination of strategies is $2^9 = 512$ different strategies - due to brevity reasons, we only displayed the first 11 combinations, for Player 4 (LOVVCTA) and Player 8 (traditional AUs) in the Appendix.

Initial strategy division

For this scenario, the initial strategies were composed in two different manners: *All are neutral*, and *Acceptance by inclination*. For the first, a '0.5' will be written both for acception and rejection of the strategy, simbolizing the neutrality in acceptance, while the third is based on our assumption of the acception of the strategy of each player based on the flight onload/offload, as well as the payoff - and is presented in the table below:

	Strategy - accept	Strategy - reject
EDUUCHI1K	0.85	0.15
LIPPCTA	0.3	0.7
LOVVCTA	0.5	0.5
LJLACTA	0.8	0.2
LDZOCTA	0.7	0.3
LHCCCTA	0.15	0.85
AU - low-cost	0.5	0.5
AU - trad.	0.5	0.5
AU - other	0.5	0.5

Table 5.9: Initial strategy acceptance for Scenario 2a.

5.5. Scenario 2b. ED airports, avoid EDUUISA1I sector

5.5.1. Environment

We chose the day of 4.07.2024 (AIRAC cycle 2406) and analysed an **en-route** traffic flow departing from several large German airports, namely Frankfurt Airport (EDDF), München (EDDM), Düsseldorf (EDDL) and Stuttgart (EDDS) and flying to any destination.

5.5.2. Traffic flow

We start from the congested sector EDUUISA1I – belonging to Germany (DFS); bottom FL 315. We offload this sector by turning it into a restricted area. As such, the airspace becomes unavailable for any flight on a 24H basis for the date of 4.07 (figure below):

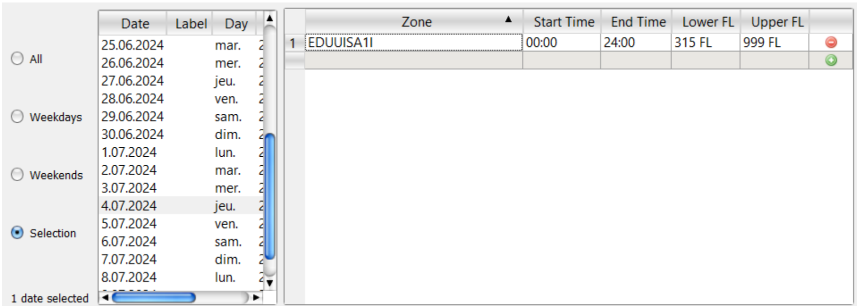


Figure 5.8: EDUUISA1I exclusion area (EUROCONTROL NEST)

The trajectory simulation for the flight re-routing manages to remove **124 out of the 133 flights** from the German airports outbound flow crossing the EDUUISA1I airspace.

The layout of the airspaces selected for examination together with the flights crossing them can be seen in the figure below:

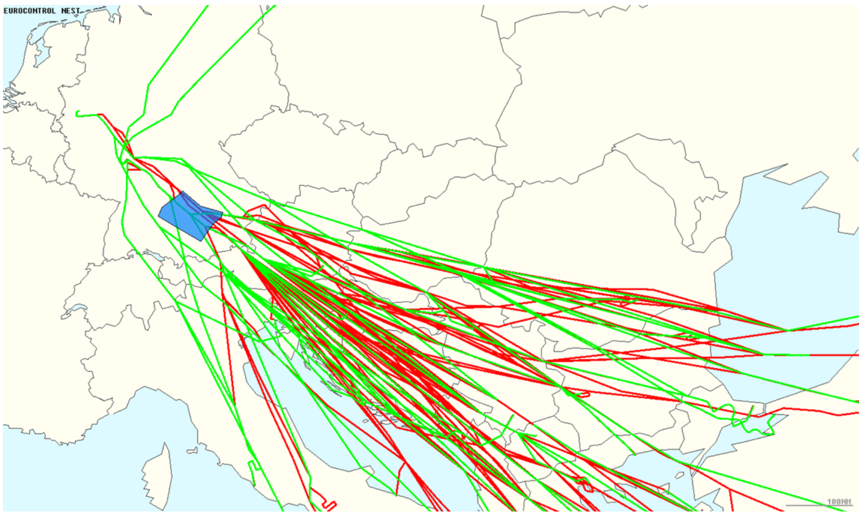


Figure 5.9: Airspaces and flights selected for examination (EUROCONTROL NEST)

The flights in red represent the *Initial* flights, while the ones in green are the *Simulated*.

As one can see on the figure, the simulation brings changes in the LIPPCTA (Italian), LOVVCTA (Austrian), LJLACTA (Slovenian) and LDZOCTA (Croatian) airspaces (which have also been briefly addressed in subsection 5.1.3. The effects of the simulation are summarized in the next table:

Airspace	Number of flights	Effect
EDUUISA1I	124	Offloaded (removed)
LIPPCTA	21	Onloaded (added)
LOVVCTA	5	Offloaded (removed))
LJLACTA	5	Offloaded (removed)
LDZOCTA	4	Offloaded (removed)

Table 5.10: Effects of the simulation on the five considered airspaces

The note related to the summing-up of the flights remains valid here as well.

5.5.3. Strategy choice

For this scenario, we composed the general acceptability of a strategy (engage or not engage measure) as follows: in order for the measure to be accepted (enter *Simulated* case), it was mandatory for 5 players to agree to it, under which there needed to be EDUUISA1I, low-cost and traditional AUs (having ”veto power”). Since for this game, we had two strategy choice possibilities and seven players, the number of combination of strategies is $2^8 = 256$ different strategies - due to brevity reasons, we only displayed the first 11 combinations, for Player 5 (LDZOCTA) and Player 9 (other AUs) in the Appendix.

Initial strategy division

For this scenario, the initial strategies were composed in two different manners: *All are neutral*, and *Acceptance by inclination*. For the first, a ’0.5’ will be written both for acception and rejection of the strategy, simbolizing the neutrality in acceptance, while the third is based on our assumption of the acception of the strategy of each player based on the flight onload/offload, as well as the payoff - and is presented in the table below:

	Strategy - accept	Strategy - reject
EDUUCHI1K	0.85	0.15
LIPPCTA	0.3	0.7
LOVVCTA	0.5	0.5
LJLACTA	0.8	0.2
LDZOCTA	0.7	0.3
AU - low-cost	0.5	0.5
AU - trad.	0.5	0.5
AU - other	0.5	0.5

Table 5.11: Initial strategy acceptance for Scenario 2b.

5.5.4. Algorithms used

For the game theoretic representation, we used the algorithm of Lan [58], as it also presented a convenient Python implementation which we could couple with the variable calculations performed on NEST data.

As Lan explains, his algorithm proposes a “smooth strategy updating” as opposed to the current regret matchings for Nash equilibrium. The paper discusses the adequateness of the “smooth” suppression of “unprofitable” pure strategies for the progression of the game towards Nash equilibrium. Lan’s algorithm is based on iterative regret matching, giving a sequence of strategies which eventually evolve towards an equilibrium point.

Short introduction

Lan mentions the iterative regret matching method devised by Hart and Mas-Colell ([66], [67], cited in [58]). He then differentiates it from the traditional algorithms of Lemke-Howson (also used by the

Nashpy library [68]), which require full knowledge of the players' payoff matrices, while the regret matching algorithms only focus on the past experiences of the players, namely the **regrets from previous decisions**. On these regrets, the future strategies are adjusted, assigning higher probabilities to actions with greater positive regret. Another difference from the Lemke-Howson algorithm is that, this algorithm returns a single Nash equilibrium [68], while the regret matching algorithm can output multiple.

Catering to the individuality of players in a game, as discussed before, is the fact that they do not need external information or coordination, as they update their mixed strategies based on their own experience. The strategy evolves towards better responses, making use of the regret resulting from the previous strategy. This might be assimilated to the CDM process in which measures are discussed among the stakeholders, and lessons are learnt from past experiences. Playing by starting with a higher number of re-routed flights, then gradually decreasing it to 0, also simulates the possible acceptance of stakeholders during an actual CDM discussion round.

Regret matching update

The regret matching formula which allows strategy updates is given by:

$$\mathbf{s}'_i = \frac{\mathbf{s}_i + r_i R_i(\mathbf{s}_i)}{1 + r_i \left|R_i(\mathbf{s}_i)\right|}, \text{ where } r_i > 0 \tag{5.6}$$

where:

s_i	Current mixed strategy
$R_i(s_i)$	Regret vector for player i
r_i	adjustment rate
$\lvert \cdot \rvert$	norm of the regret vector

Regret vector calculation

The regret for a pure strategy j is defined as:

$$\phi_{ij}(s_i) = \max\{0, p_i(\pi_{ij}; S) - p_i(s_i; S)\} \tag{5.7}$$

where:

$p_i(s_i; S)$	player payoff under the current mixed strategy
$p_i(\pi_{ij}; S)$	payoff if the pure strategy j were played

Payoff calculation

The player expected value of payoff is highlighted by the following inner product of the strategy vector s_i and the vertex payoff vector v_i:

$$p_i(s_i; S) = \langle s_i, v_i \rangle \tag{5.8}$$

The payoff also appears under the form of a sum, as follows:

$$\text{Payoff}_i = \sum_j s_i[j] \cdot p_i(\pi_{ij}; S) \tag{5.9}$$

where:

$s_i[j]$	is the probability of selecting the j-th pure strategy
$p_i(\pi_{ij}; S)$	is the payoff for the j-th pure strategy π_{ij}, assuming
	the current strategy profile S (strategies of all players).

Deviation calculation
The deviation measures how much better a player could do by unilaterally switching from their current strategy to a specific pure strategy. We recall the definition of the Nash equilibrium, stating that it is reached whenever no player can benefit further from unilaterally changing their strategy - hence, the deviation can give us an indicator on how close we are in reaching the Nash equilibrium. It is expressed through the formula:

$$\text{Deviation}_j = \max(0, p_i(\pi_{ij}; S) - \text{Payoff}_i) \tag{5.10}$$

If the switch to π_{ij} gives a higher payoff than the current mixed strategy, the deviation is the positive difference, otherwise it is 0.

In a nutshell, the main values output by the algorithm are the following:

- **Payoff** is the expected outcome under the current mixed strategy
- **Deviation** represents how much better can a player do by switching to a pure strategy
- **Deviation sum** - quantifies how far the system is from the Nash equilibrium.

5.6. Synthesis

The above research question has attempted to find a method to enable the measurement of stakeholder acceptance in the case of a strategic ATFCM measure issued by the EUROCONTROL Network Manager. The purpose of such a measure was to alleviate the pressure, or congestion, above a sector, generated by the high levels of traffic coupled with a reduced capacity provision.

To mark the reduced capacity provision, a ”stress test” was performed - namely, the capacity was reduced by 20% for each sector in the EDUUUTAS congested airspace. This, in order to appropriately measure the effects of the network measure (i.e., the re-routing of several flights on a chosen traffic flow). The game theoretic model methodology, as well as the import and calculation of necessary variables to determine player payoff (done with NEST), and a detailed description of the four different test scenarios, were given.

In the end of the section, the geometric regret matching (GRM) algorithm which solves the game theoretic model and finds the different degrees of acceptance of all players (ANSPs and AUs alike), is briefly described. This paves the way to the following chapter, which highlights the results obtained through the running of the model and presents underlying graphs which can serve as a justification for the evolution of the player acceptance in the game.

6 Results

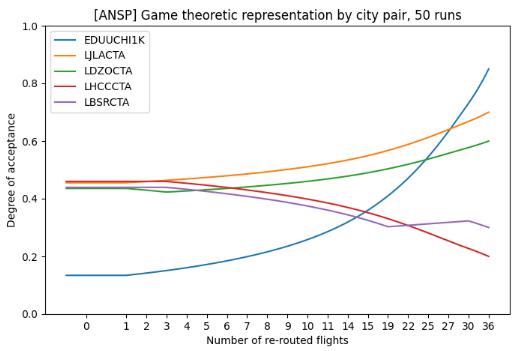
This chapter arrives at the practical part of the thesis, presenting the applicability of the entire work carried out so far. It is divided into the scenarios presented in Research Question 3 and includes the presentation of the baseline ("raw") acceptance of the measure by all stakeholders involved. Next to that, a sensitivity analysis showing the reaction of the model (implicitly, that of the stakeholders) to changes/adjustments in the weights, is also shown and commented upon. This part touches upon the incentivization of stakeholders to accept a certain measure, as yielded by the adjustment of a specific parameter.

For each scenario, the evolution of the acceptance is shown for ANSPs and AUs, with the extraction by city pair on the left, and the extraction by flight on the right.

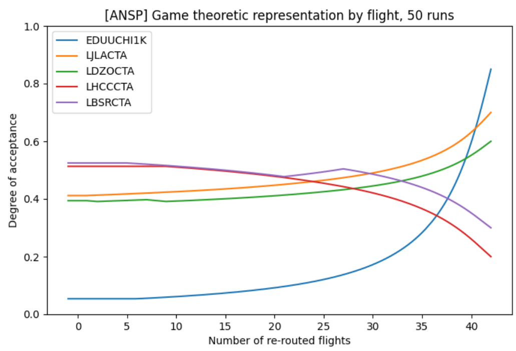
Note: The acceptance calculations, in the game theoretic model, were performed starting with the highest number of re-routed flights (to reflect a negotiation process in which it is started with the best result for the German sector). Then the flights were removed, either by city pair or flight, as explained in section 5.1.7. Choice of flights. In what follows, the figures are inverted, to present a more reader-friendly version and explain the evolution of acceptance as more and more flights are re-routed. Nevertheless, the reader can keep in mind that the negotiation process, or the initial acceptance of all users, starts on the right hand of the figure.

6.1. Scenario 1a. EG-LT flow, avoid EDUUCHI1K sector

6.1.1. Baseline (”raw”) case

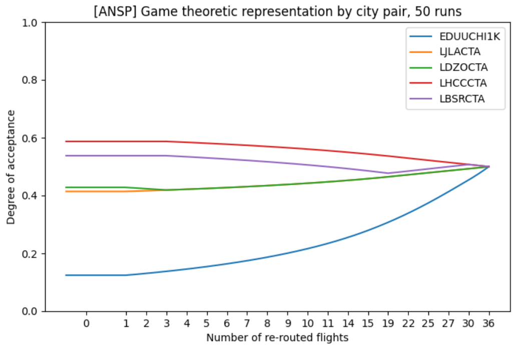


(a) By city pair

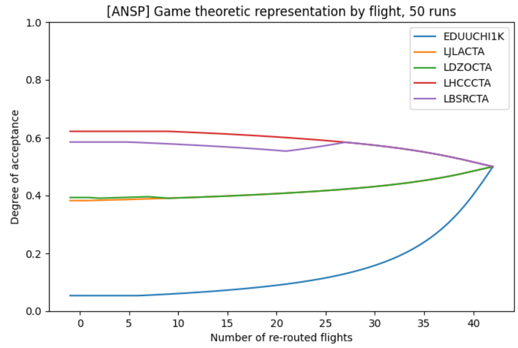


(b) By flight

Figure 6.1: Flight extraction for the ANSPs, on acceptance by inclination

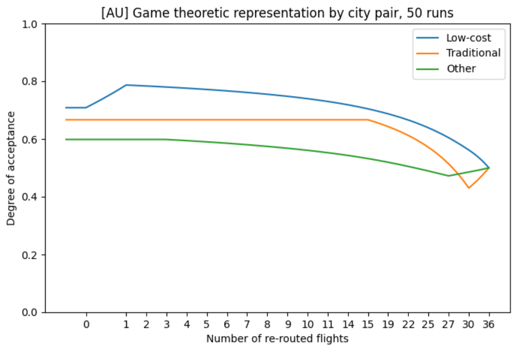


(a) By city pair

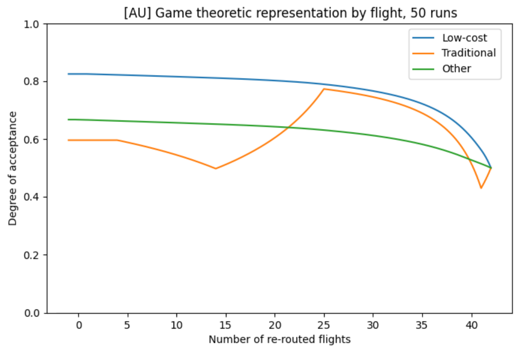


(b) By flight

Figure 6.2: Flight extraction for the ANSPs, on acceptance by inclination/neutral



(a) By city pair



(b) By flight

Figure 6.3: Flight extraction for the AUs, on acceptance by inclination/neutral

In analyzing the acceptance evolution, we can take into consideration two major aspects, namely the number of flights which are offloaded (removed) or onloaded (added) into each airspace, as well as the payoff difference the re-routings generate.

For the first point, we repeat the table giving the effects of the re-routing:

Airspace	Number of flights	Effect
EDUUCHI1K (Germany)	42	Offloaded (removed)
LJLACTA (Slovenia)	14	Offloaded (removed)
LDZOCTA (Croatia)	13	Offloaded (removed))
LHCCCTA (Hungary)	23	Onloaded (added)
LBSRCTA (Bulgaria)	13	Onloaded (added)

Table 6.1: Effects of the simulation on the five considered airspaces

The effects on the player payoffs are the following:

- For EDUUCHI1K, the delay, as well as the route charges, decrease almost linearly and inversely proportionally with the number of re-routed flights
- For LJLACTA, the delay decreases, but the route charges increase as the number of re-routed flights increases

- For LDZOCTA, the delay, as well as the route charges, decrease as the number of re-routed flights increases
- For LHCCCTA, the delay, as well as the route charges, increase as the number of re-routed flights increases
- For LBSRCTA, the delay firstly increases, then decreases again, then ultimately increases with the augmentation in the number of re-routed flights. The route charges experience a similar behaviour.
- For low-cost airlines, the difference in fuel cost increases, the difference in route charges decreases, and the time difference increases together with the augmentation in the number of re-routed flights.
- For airlines of type 'other', the difference in fuel cost increases, the difference in route charges decreases, while the time difference first increases, then decreases in line with the augmentation of the number of flights
- For traditional airlines, the fuel cost increases, while route charges decrease and the time difference increases.

Graphs showing exactly the evolution of these payoffs can be found in the Annex, under section B.1.

It is to be noted that, for the ANSPs, it would be sought to collect more route charges and experience less delay, while for the AUs, to minimize costs related to fuel consumption and delay (measured by the time difference), as well as the route charges paid for crossing various airspaces. The explanations and differences in payoffs above have been presented to enhance the understanding of the underlying causes of the evolution of acceptance.

As such, it is understandable that **EDUUCHI1K** will be in favour of more flight re-routings (which is only natural, as it is the sector for which the measure has been conceived), as the route charges are not an element of importance for them and they wish to minimize the delays. In the same way, **LJLACTA** and **LDZOCTA** tend to agree on more re-routings, however their line is not as steep as the one of EDUUCHI1K, possibly because of the fewer flights they are offloaded in general (14 and 13, respectively, as opposed to 42), as well as the route charges they might lose.

On the other hand, **LBSRCTA** and **LHCCCTA** agree less if more flights are re-routed through their airspace, as they would be loaded with extra flights, generating route charges, but also extra delays in their area of responsibility.

For the airspace users, we notice a rather consistent tendency of agreeing less, if more flights are re-routed.

As the reader may also notice, the tendencies to accept or reject a measure do not vary greatly between the cases measured with *Acceptance by inclination* or *Neutral acceptance*, however more convergence is achieved in the first category (at least for the ANSPs). The extraction by flight, rather than by city pair, tends to offer steeper curves of acceptance/rejection, and brings convergence at a later stage (i.e., at a higher number of re-routed flights, which may prove beneficial for the German EDUUCHI1K sector).

As such, we notice convergence for the ANSPs at around 4 re-routed flights (for city pair extraction — Figure 6.1a, and at around 20 flights for flight extraction — Figure 6.1b, where acceptance is around 50%. A greater or equal acceptance by the AUs for those values of re-routed flights is also found.

6.1.2. Sensitivity analysis

Given the results in the above case, it has been tried to modify the weights in order to incentivize Germany to agree to less re-routed flights, to achieve convergence with the other players. Nevertheless, the model has proven inflexible to a weight adjustment.

It was only when we eliminated the mandatoriness ("veto power") of Germany, that its acceptance towards less re-routed flights did not tend to zero any more, and reached relative convergence with the other ANSPs at around 7 re-routed flights (by city pair), as we can see in the figure on the next page:

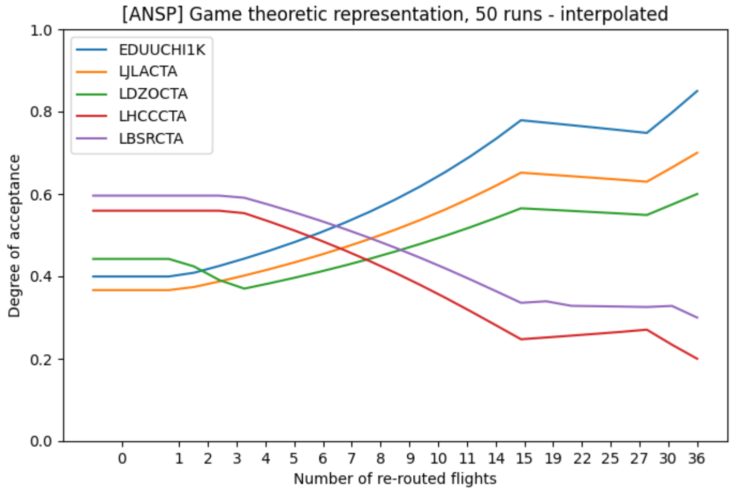


Figure 6.4: Flight extraction by city pair for the ANSPs, on acceptance by inclination [Test 1]

As stated before, if taken by flights, the convergence occurs later and allows the Network Manager to extract more flights:

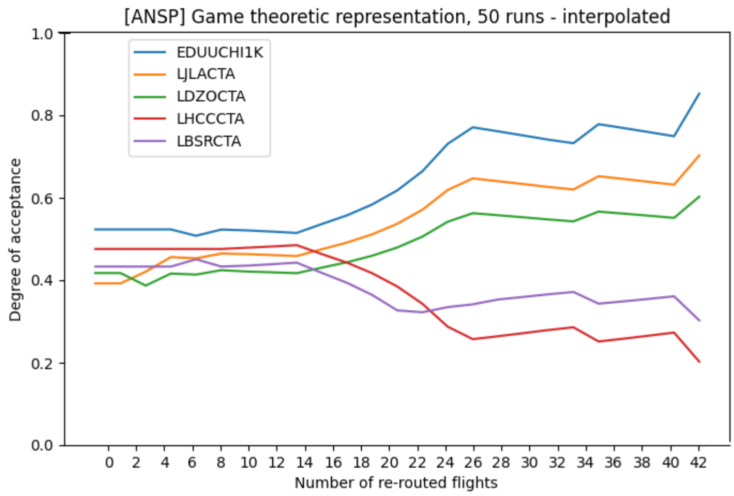


Figure 6.5: Flight extraction by flight for the ANSPs, on acceptance by inclination [Test 1]

To verify whether the airspace user acceptance would change upon adjusting the weights, we considered the traditional airlines to be more interested in keeping reputation and not having delays than paying more route charges/burning fuel and the low-cost airlines more interested in keeping a smaller cost. As such, we devised the adjustments for the payoffs of different airlines as such:

- $w_{\Delta r_{c_{AU}}}$: 40 for low-cost airlines; 25 for traditional airlines
- $w_{\Delta f_{c_{AU}}}$: 50 for low-cost airlines; 20 for traditional airlines
- $w_{\Delta t_{AU}}$: 20 for low-cost airlines; 50 for traditional airlines

The weights of the 'other' type of airline have remained unchanged.

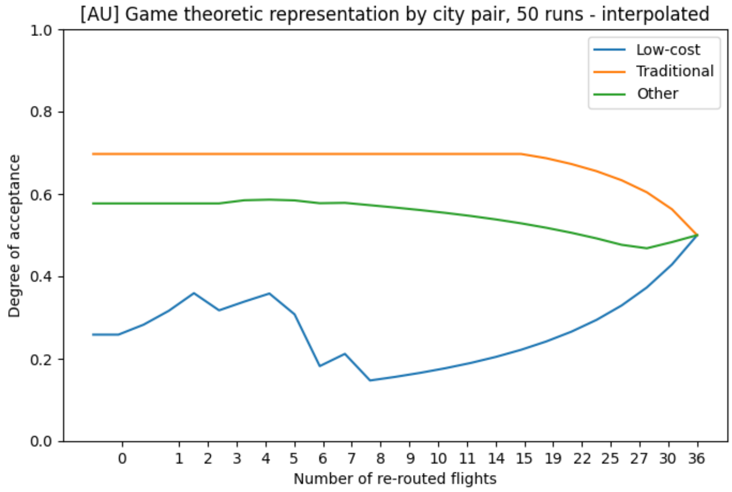


Figure 6.6: Flight extraction by city pair for the AUs, on acceptance by inclination/neutral [Test 2]

In this figure, we can notice the airspace user acceptances diverge, with the traditional airlines accepting more re-routings and the low-cost airlines less, reflecting their balance between delay/reputation — incurred costs.

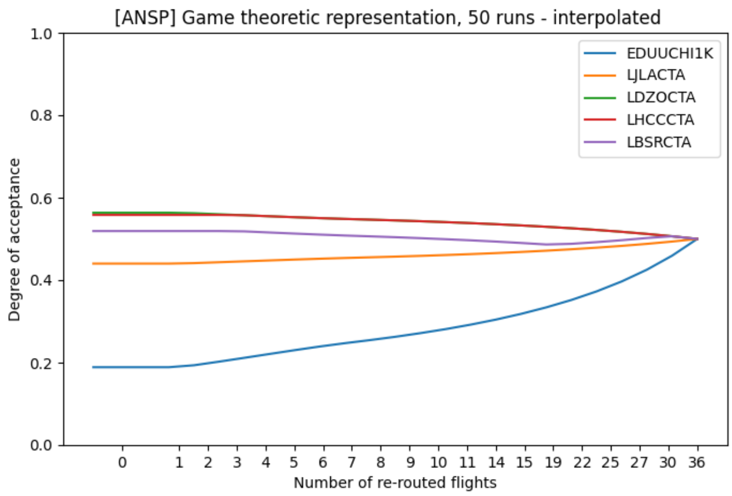
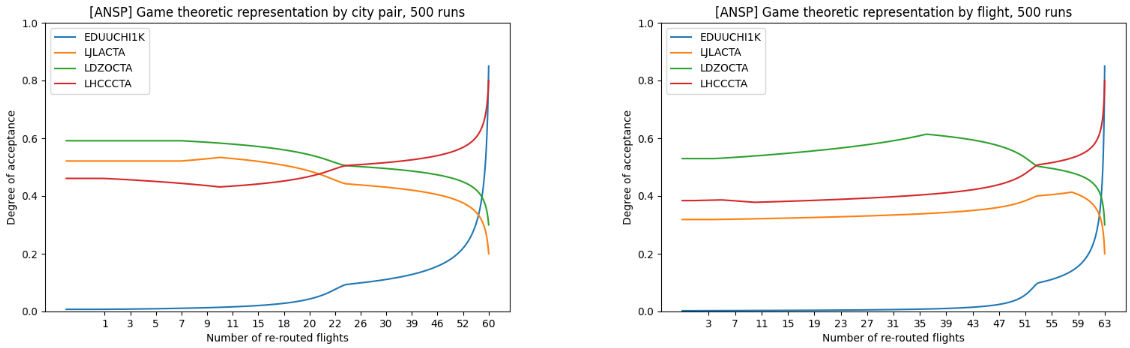


Figure 6.7: Flight extraction by city pair for the ANSPs, on neutral acceptance [Test 3]

The model appears to exhibit again limited flexibility when adjustments are made solely to the delay parameter coefficient, as observed in the cases of LDZOCTA and LJLACTA, similar to the behavior noted with EDUUCHI1K. However, setting w to 15 for route charges, 60 for delay in LJLACTA (14 offloaded flights), and 40 for delay in LDZOCTA (13 offloaded flights) results in improved alignment of LDZOCTA with fewer reroutings. This adjustment shifts the balance in favor of route charges by reducing the relative penalty associated with delays.

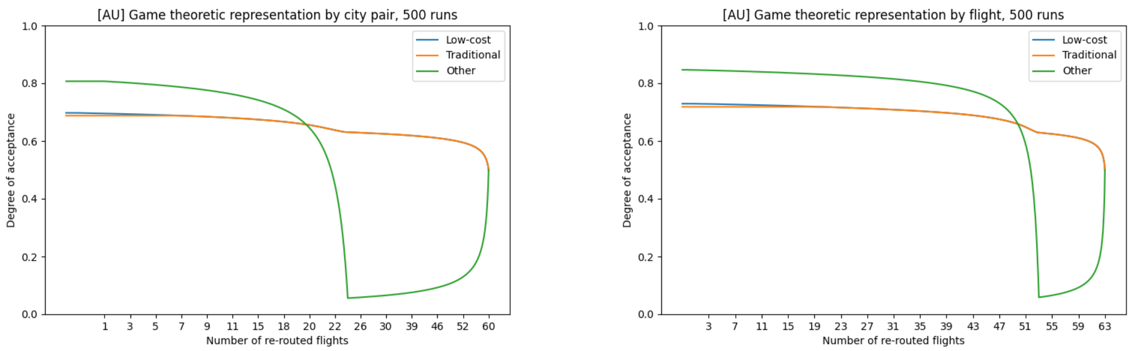
6.2. Scenario 1b. EG-LT flow, avoid EDUUDI3C sector

6.2.1. Baseline (”raw”) case



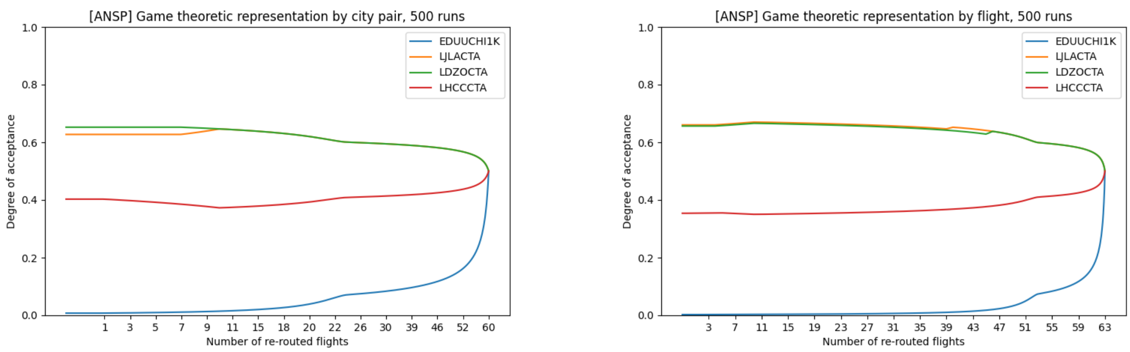
(a) By city pair **(b)** By flight

Figure 6.8: Flight extraction for the ANSPs, on acceptance by inclination



(a) By city pair **(b)** By flight

Figure 6.9: Flight extraction for the AUs, on acceptance by inclination/neutral



(a) By city pair **(b)** By flight

Figure 6.10: Flight extraction for the ANSPs, on neutral acceptance

To comment on the acceptance of the stakeholders in this game, we repeat the procedure described in the first scenario - namely we examine the number of onloaded/offloaded flights in each of the ANSP players' airspace, then discuss the payoff evolution.

Airspace	Number of flights	Effect
EDUUDI3C (Germany)	64	Offloaded (removed)
LJLACTA (Slovenia)	24	Onloaded (added)
LDZOCTA (Croatia)	18	Onloaded (added))
LHCCCTA (Hungary)	18	Offloaded (removed)

Table 6.2: Effects of the simulation on the five considered airspaces

The effects on the player payoffs are the following:

- For EDUUDI3C, the delay, as well as the route charges, decrease almost linearly and proportionally with the number of re-routed flights
- For LJLACTA, the delay, as well as the route charges, increase together with the number of re-routed flights.
- For LDZOCTA, the delay, as well as the route charges, increase, together with the number of re-routed flights (albeit in a non-linear manner).
- For LHCCCTA, the delay, as well as the route charges, decrease as the number of re-routed flights increases.
- For low-cost airlines, the difference in fuel cost increases, the difference in route charges decreases, and the time difference increases together with the augmentation in the number of re-routed flights.
- For airlines of type 'other', the difference in fuel cost increases, the difference in route charges decreases, then increases, then decreases again, while the time difference first decreases, then increases, in line with the augmentation of the number of re-routed flights.
- For traditional airlines, the fuel cost increases, while the route charges decrease, then increase again, and the time difference increases.

Graphs showing exactly the evolution of these payoffs can be found in the Annex, under section B.2.

It is to be noted that, for the ANSPs, it would be sought to collect more route charges and experience less delay, while for the AUs, to minimize costs related to fuel consumption and delay (measured by the time difference), as well as the route charges paid for crossing various airspaces. The explanations and differences in payoffs above have been presented to enhance the understanding of the underlying causes of the evolution of acceptance.

As such, it is explainable that the acceptance of **EDUUDI3C** sharply increases as more flights are re-routed. In the same way, **LHCCCTA** tends to agree on more re-routings, however its line is not as steep as the one of EDUUDI3C, possibly because of the fewer flights it is offloaded, compared to EDUUDI3C (18 vs. 64).

For the airspace users, we notice a rather consistent tendency of agreeing less with more re-routings.

As the reader may also notice, the tendencies to accept or reject a measure do not vary greatly between the cases measured with *Acceptance by inclination* or *Neutral acceptance*, however more convergence is achieved in the first category (at least for the ANSPs). The extraction by flight, rather than by city pair, tends to offer steeper curves of acceptance/rejection, and brings convergence at an earlier stage (i.e., at a higher number of re-routed flights, which may prove beneficial for the German EDUUDI3C sector).

As such, we notice convergence for the ANSPs at around 22 re-routed flights (for city pair extraction — Figure 6.8a, and at around 51 flights for flight extraction — Figure 6.8b, where acceptance is around 50%. A greater or equal acceptance by the AUs for those values of re-routed flights is also found — even for the 'other' type, whose line of acceptance first decreases sharply between the 63 and 51 re-routed flights (possibly because of specific flights which would be more advantageous as re-routed to them), but then makes a comeback.

6.2.2. Sensitivity analysis

Given the results in the above case, it has been tried to modify the weights in order to incentivize Germany to agree to less re-routed flights, to achieve convergence with the other players. Nevertheless, the model has proven inflexible to a weight adjustment.

To verify whether the airspace user acceptance would change upon adjusting the weights, we considered the traditional airlines to be more interested in keeping reputation and not having delays than paying more route charges/burning fuel and the low-cost airlines more interested in keeping a smaller cost. As such, we devised the adjustments for the payoffs of different airlines as such:

- $w_{\Delta r_{c_{AU}}}$: 40 for low-cost airlines; 25 for traditional airlines
- $w_{\Delta f_{c_{AU}}}$: 50 for low-cost airlines; 20 for traditional airlines
- $w_{\Delta t_{AU}}$: 20 for low-cost airlines; 50 for traditional airlines

The weights of the 'other' type of airline have remained unchanged.

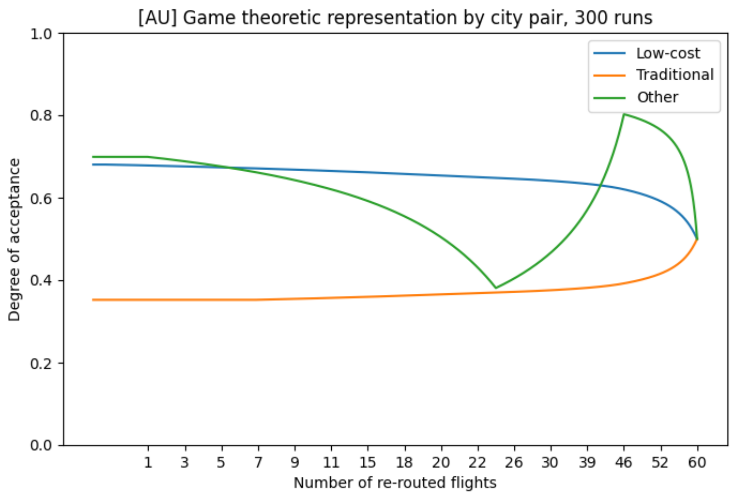


Figure 6.11: Flight extraction by city pair for the AUs, on acceptance by inclination [Test 4]

In this figure, we can notice the airspace user acceptances diverge, with the traditional airlines accepting less re-routings and the low-cost airlines more, reflecting their balance between delay/reputation — incurred costs.

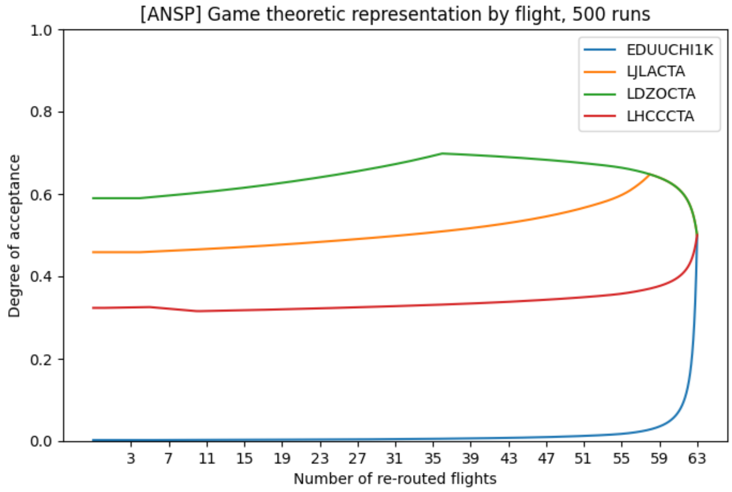
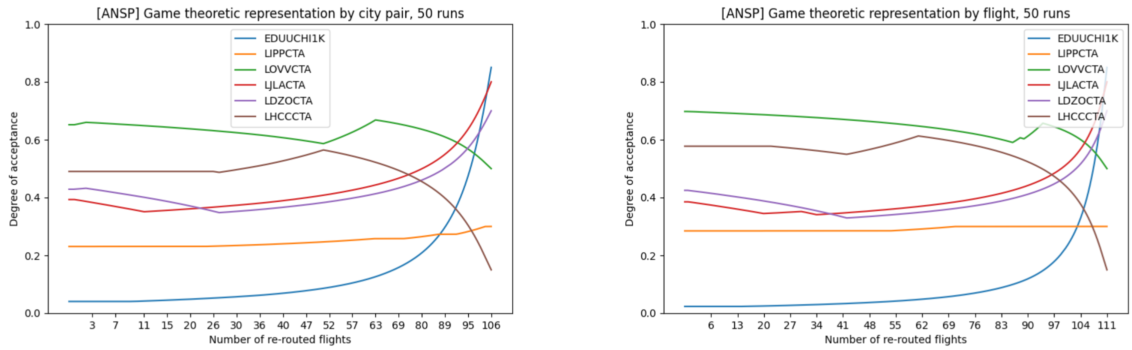


Figure 6.12: Flight extraction by city pair for the ANSPs, on neutral acceptance [Test 5]

By assigning a higher delay penalty (70) to LDZOCTA (18 flights onloaded) and a lower penalty (30) to LJLACTA (24 flights onloaded), we observe that the acceptance rate of LDZOCTA for flights with fewer reroutings initially progresses at a similar rate to that of LJLACTA, before becoming lower towards the end of the graph.

6.3. Scenario 2a. ED airports, avoid EDUUCHI1K sector

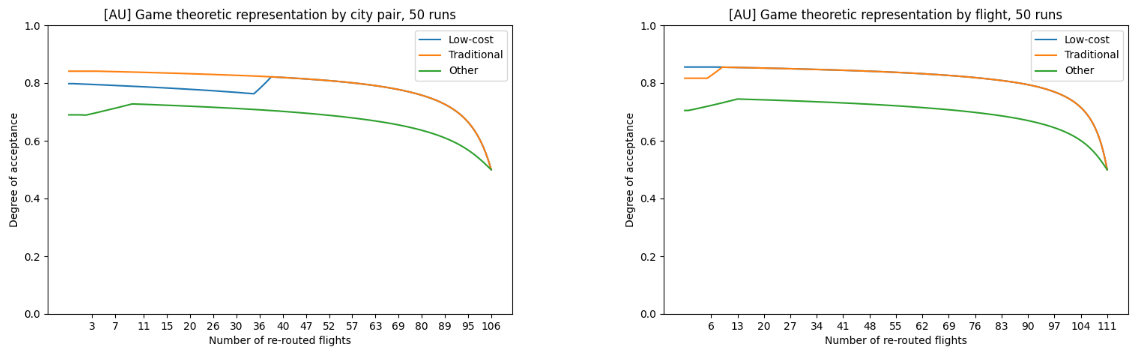
6.3.1. Baseline (”raw”) case



(a) By city pair

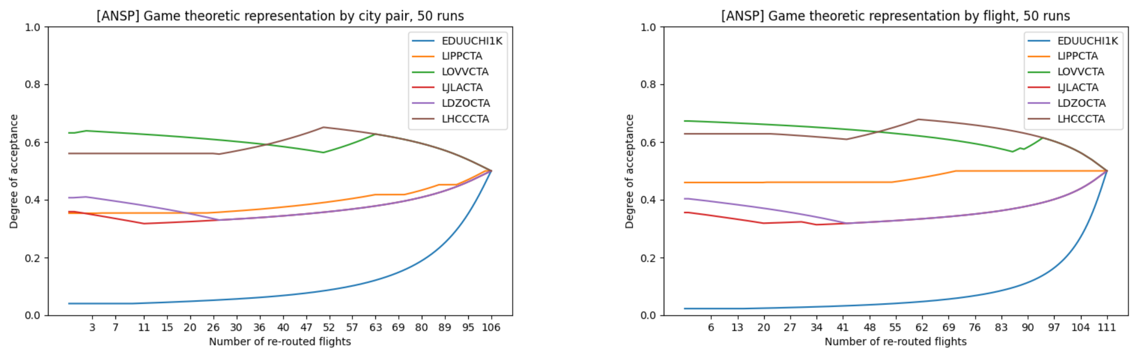
(b) By flight

Figure 6.13: Flight extraction for the ANSPs, on acceptance by inclination



(a) By city pair **(b)** By flight

Figure 6.14: Flight extraction for the AUs, on acceptance by inclination/neutral



(a) By city pair **(b)** By flight

Figure 6.15: Flight extraction for the ANSPs, on neutral acceptance

To comment on the acceptance of the stakeholders in this game, we repeat the procedure described in the first scenario - namely we examine the number of onloaded/offloaded flights in each of the ANSP players' airspace, then discuss the payoff evolution.

Airspace	Number of flights	Effect
EDUUCHI1K (Germany)	111	Offloaded (removed)
LIPPCTA (Italy)	16	Onloaded (added)
LOVVCTA (Austria)	5	Offloaded (removed))
LJLACTA (Slovenia)	24	Offloaded (removed)
LDZOCTA (Croatia)	11	Offloaded (removed)
LHCCCTA (Hungary)	20	Onloaded (added)

Table 6.3: Effects of the simulation on the five considered airspaces

The effects on the player payoffs are the following:

- For EDUUCHI1K, the delay, as well as the route charges decrease almost linearly and proportionally with the number of re-routed flights.
- LIPPCTA is an interesting case, in which both the delays and the route charges remain constant, as in the initial case (zero re-routed flights).

- For LOVVCTA, the delay looks like a step function, being lower than the delay for the initial case (zero re-routed flights), then increases above the delay for the initial case. The route charges, however, first decrease below the value for the initial case, then increase and decrease again.
- For LJLACTA, the delay, as well as the route charges, decrease as the number of re-routed flights increases.
- For LDZOCTA, the delay, as well as the route charges, decrease as the number of re-routed flights increases (albeit in a non-linear manner, but which is more uniform than the one for the two ANSPs above).
- For LHCCCTA, the delay, as well as the route charges, increase as the number of re-routed flights increases.
- For low-cost airlines, the difference in fuel cost decreases similarly to a step function, the difference in route charges decreases, and the time difference increases together with the augmentation in the number of re-routed flights.
- For airlines of type ’other’, the difference in fuel cost remains unchanged, the difference in route charges increases, then decreases, while the time difference increases in line with the reduction of the number of flights.
- For traditional airlines, the fuel cost decreases in a step-wise manner, while route charges decrease and the time difference increases.

Note: Since all the payoff values for the airspace users discussed here are differences, the “initial value” (for zero re-routings) mentioned multiple times, is actually zero.

Graphs showing exactly the evolution of these payoffs can be found in the Annex, under section B.3.

It is to be noted that, for the ANSPs, it would be sought to collect more route charges and experience less delay, while for the AUs, to minimize costs related to fuel consumption and delay (measured by the time difference), as well as the route charges paid for crossing various airspaces. The explanations and differences in payoffs above have been presented to enhance the understanding of the underlying causes of the evolution of acceptance.

As such, it is explainable that the acceptance of **EDUUCHI1K** sharply increases as more flights are re-routed. Other players such as **LHCCCTA** and **LOVVCTA** tend to agree less to more re-routings, as they obtain more delays — route charges also do not seem to be an incentive for them to remain with more re-routings. Since the payoffs of **LIPPCTA** are relatively constant, the rather small modification in acceptance does not come as a surprise.

LDZOCTA and **LJLACTA** appear to agree more if flights are re-routed, as their airspace would become less congested as a result of the measure. Their acceptance evolution seems similar, although the flights offloaded would be 24 for LJLACTA and 11 for LDZOCTA.

For the airspace users, we notice a rather consistent tendency of agreeing less to more flights re-routed. In the baseline cases, the acceptance of the low-cost and the traditional air carriers seems to overlap, this becomes more evident on the graph representing “by flight” extraction.

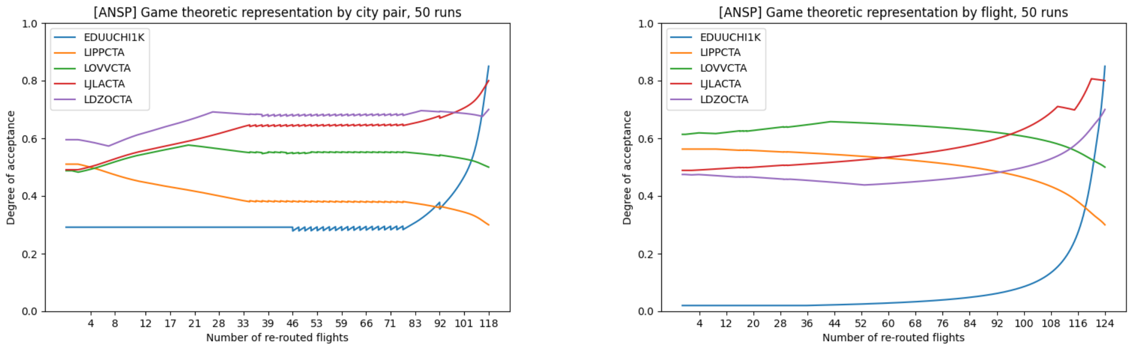
As the reader may also notice, the tendencies to accept or reject a measure do not vary greatly between the cases measured with *Acceptance by inclination* or *Neutral acceptance*, however more convergence is achieved in the first category (at least for the ANSPs). The extraction by flight, rather than by city pair, tends to offer steeper curves of acceptance/rejection, and brings convergence at an earlier stage (i.e., at a higher number of re-routed flights, which may prove beneficial for the German EDUUCHI1K sector).

6.3.2. Sensitivity analysis

Given the closeness of the curves of the traditional and low-cost airlines on the flight extraction simulation, the different payoffs previously discussed have been applied, but the model has remained inflexible.

6.4. Scenario 2b. ED airports, avoid EDUUISA1I sector

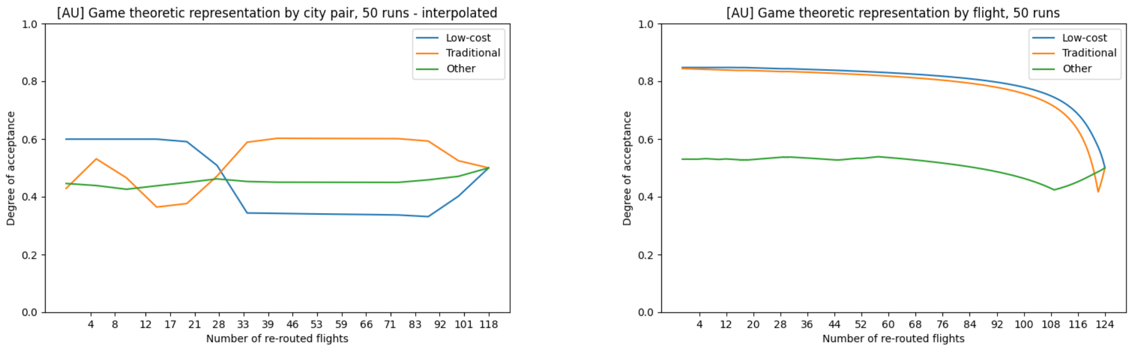
6.4.1. Baseline ("raw") case



(a) By city pair

(b) By flight

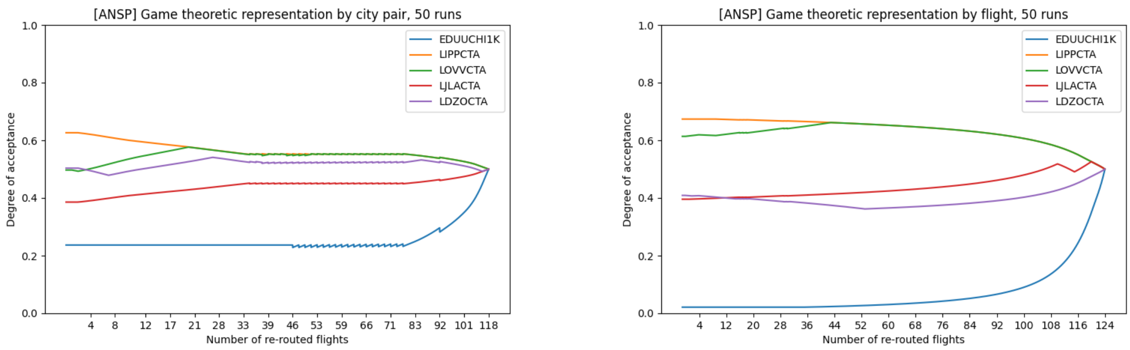
Figure 6.16: Flight extraction for the ANSPs, on acceptance by inclination



(a) By city pair

(b) By flight

Figure 6.17: Flight extraction for the AUs, on acceptance by inclination/neutral



(a) By city pair

(b) By flight

Figure 6.18: Flight extraction for the ANSPs, on neutral acceptance

To comment on the acceptance of the stakeholders in this game, we repeat the procedure described in the first scenario - namely we examine the number of onloaded/offloaded flights in each of the ANSP players' airspace, then discuss the payoff evolution.

Airspace	Number of flights	Effect
EDUUISA1I (Germany)	124	Offloaded (removed)
LIPPCTA (Italy)	21	Onloaded (added)
LOVVCTA (Austria)	5	Offloaded (removed))
LJLACTA (Slovenia)	5	Offloaded (removed)
LDZOCTA (Croatia)	4	Offloaded (removed)

Table 6.4: Effects of the simulation on the five considered airspaces

The effects on the player payoffs are the following:

- For EDUUISA1I, the delay, as well as the route charges decrease under the form of a step function with the number of re-routed flights
- For LIPPCTA, the delay, as well as the route charges, increase with the number of flights re-routed.
- For LOVVCTA, the delay looks again like a step function, being lower than the delay for the initial case (zero re-routed flights), then increasing above the delay for the initial case. The route charges, however, decrease in a more uniform manner.
- For LJLACTA, the delay first decreases, then stays level around 60 re-routed flights, then increases as we reach zero re-routed flights.
- For LDZOCTA, the delay oscillates. The route charges have a relatively more uniform decrease.
- For low-cost airlines, the difference in fuel cost decreases, while the difference in route charges increases, and the time difference oscillates to reach the initial value (of zero re-routed flights) in the end.
- For airlines of type 'other', the difference in fuel cost increases, the difference in route charges stays well above the initial value, then sharply decreases, to increase to the initial value, while the time difference oscillates with the augmentation of the number of flights.
- For traditional airlines, the fuel cost difference oscillates, staying below the initial value, then reaching it, while route charges decrease and the time difference also oscillates, being below the initial value in the beginning, then increasing above it and then decreasing again towards the end.

Note: Since all the payoff values for the airspace users discussed here are differences, the "initial value" (for zero re-routings) mentioned multiple times, is actually zero.

Graphs showing exactly the evolution of these payoffs can be found in the Annex, under section B.4.

It is to be noted that, for the ANSPs, it would be sought to collect more route charges and experience less delay, while for the AUs, to minimize costs related to fuel consumption and delay (measured by the time difference), as well as the route charges paid for crossing various airspaces. The explanations and differences in payoffs above have been presented to enhance the understanding of the underlying causes of the evolution of acceptance.

As such, it is explainable that the acceptance of **EDUUISA1I** sharply increases if more flights are re-routed. **LDZOCTA** and **LJLACTA** appear to agree more with re-routings around their airspace, as the measure would ease the congestion above their controlled area. Their acceptance evolution seems similar, although the flights offloaded would have been 5 for LJLACTA and 4 for LDZOCTA.

For the airspace users, we notice a rather consistent tendency of agreeing less with more flights re-routed. In the baseline cases, the acceptance of the low-cost and the traditional air carriers seems to overlap, this becomes more evident on the graph representing "by flight" extraction.

As the reader may also notice, the tendencies to accept or reject a measure do not vary greatly between the cases measured with *Acceptance by inclination* or *Neutral acceptance*, however more convergence is achieved in the first category (at least for the ANSPs). The extraction by flight, rather than by city pair, tends to offer steeper curves of acceptance/rejection, and brings convergence at an earlier stage (i.e., at a higher number of re-routed flights, which may prove beneficial for the German EDUUISA1I sector).

6.4.2. Sensitivity analysis

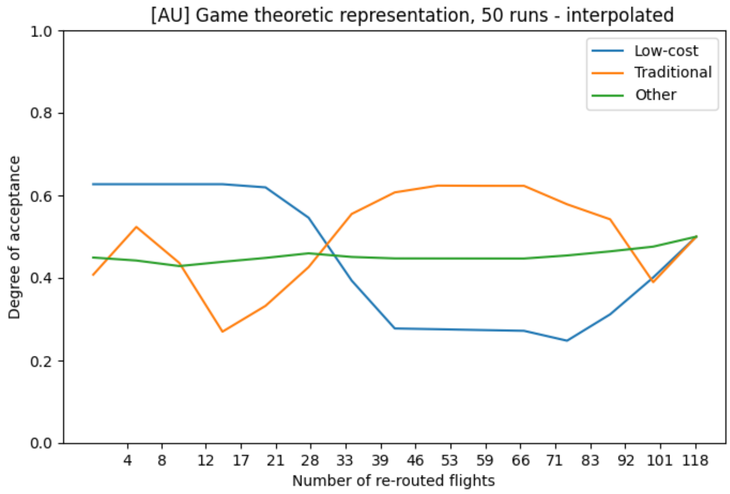


Figure 6.19: Flight extraction by flight for the AUs, on neutral acceptance [Test 6]

For the AU side, instead of seeing convergence towards acceptance for both low-cost and traditional airlines, we see a clear differentiation (even opposition/complementarity between the two lines of acceptance) — this, for the acceptance by inclination. Interestingly, however, we notice a common acceptance of slightly above 0.4 between 28 and 33 re-routed flights.

When looking at the neutral acceptance, Germany's acceptance still does not change upon the adjustment of the weight. It is interesting to notice that, both for this point and the previous point (referring to Scenario 2b – assumed acceptance/acceptance by inclination), the acceptance of Germany does not tend to 0 any more as the number of re-routed flights decreases (which is not in their favour) but rather stabilizes around 0.2. This is in opposition to the previous scenarios, where we experienced a near-0 acceptance of the re-routings, if the number of flights was low.

7 Stakeholder opinion

This chapter presents to the reader excerpts of the opinion of the stakeholders involved in the COCTA project towards their proposition of a new ATM value-chain in which the Network Manager is given more power, and has a higher influence in the airspace user trajectory choice.

The author of the thesis, assisted by the coordinators of COCTA, carried out a meeting in which the work within the thesis (mainly the game theoretic model) was presented to an airline representative, an ANSP representative, as well as members of the academia from different domains, all having contributed to the COCTA project. The conclusions of said meeting are highlighted at the end of this chapter.

7.1. COCTA main stakeholders, discussion, and ideas

As identified by the COCTA consortium within the deliverable *Communication and Dissemination Report and Data Management Update Report* [69], the main stakeholders in this problem are:

1. ATM stakeholders
   (a) EUROCONTROL/SESAR JU
   (b) ANSPs
   (c) Airlines
   (d) Airports
   (e) Employees (represented by unions)
2. Political institutions and regulators
   (a) European level (EC, ECAC)
   (b) State level (civil aviation authorities — CAAs)
3. Researchers and academia
   (a) European Commission research and innovation events
   (b) ATM
   (c) Airline
   (d) General air transport industry
   (e) Operations Research

In the Advisory Board of COCTA, members of ANSPs, airspace users, as well as the EUROCONTROL Network Manager have been present. In the same manner as for our meeting, the opinions will be broken down by the specific stakeholder group.

7.1.1. EUROCONTROL/NM

On predictability, which is a determining parameter in the dynamic ATM environment, NM has stated that it is essential for aircraft operators to effectively manage their operations, for ATM systems to coordinate Europe-wide air traffic, for passengers to plan their travel reliably, and for broader economic efficiency to be maintained. Moreover, it was recognized that the future path to follow would be a shift from the current air traffic flow management (ATFM) to a cooperative traffic management (CTM).

7.1.2. Academia

It was recommended that the airline's choices of different trajectory products should be based on assumptions, while the COCTA mechanism should be aware of the dynamicity of air traffic.

7.1.3. Airlines

Most airlines express resistance to peak-load pricing and generally remain cautious toward the introduction of new charging schemes. This skepticism is partly driven by concerns over the potential need to modify or adapt existing flight management systems.

7.1.4. Other

Other opinions were also deemed relevant and aggregated for this chapter. For example, during the second stakeholder COCTA workshop in Brussels in 2018, participants raised comments and questions regarding specific aspects of the current COCTA concept. Notably, there was a recommendation to provide a more detailed elaboration of the negotiation process between the Network Manager and Air Navigation Service Providers (ANSPs), potentially including relevant legal considerations. The balance between the "flexibility given to the NM versus the flexibility resting with airspace users" [69] was also mentioned — the reader can recognize it both from the literature study and Research Question 2.

7.2. Input from the stakeholders during our meeting

During our meeting, which took place thanks to the generosity and assistance of the professors from COCTA, and the valuable time of the ANSP and airline representatives (the latter two being modelled as players in the thesis with their reaction to a traffic measure being tested), the following ideas were proposed:

7.2.1. ANSP

The model offers a promising approach to optimize traffic flows based on real congestion data. It would be valuable to carefully consider how to maintain regional balance when shifting traffic, as well as how to identify and monitor heavy users of congested sectors. A major strength would be the ability to predict how likely airspace users are to accept rerouting proposals. Positioning the tool within the Network Manager's decision-making structure is definitely the right choice. Additionally, considering dynamic real-world disruptions like weather, staff shortages and route charges would further enhance the model's robustness.

7.2.2. Airline

Segmenting airlines into low-cost, traditional, and special operations is very realistic. Airlines would benefit greatly if the model could show a clear trade-off between rerouting costs and delay savings. Enabling some level of feedback or consultation from airspace users, even in fast operational timelines, would strengthen acceptance and usability.

7.2.3. Academia

It would be encouraged to map out the current CDM processes very clearly and show exactly where and how the model enhances them. Including sensitivity analyses on different decision priorities (e.g., cost versus delay) will make the results even more compelling. Mentioning how the concept could align with future developments like SESAR could also give additional strategic relevance to the project.

7.3. Synthesis

To recapitulate, this chapter has presented the reader with the opinion of parties who are central to the development of such research projects. In the first part, the reaction of stakeholders to the COCTA project, who were consulted on the matter, were revealed. In the second part, the response of a more restricted, but nevertheless essential stakeholders (also viewed from the standpoint of them being the game model's participants).

8
Conclusion

This chapter summarizes the path that the thesis has followed, from its incipient idea and stages, up to the results and their meaning for the readers, as well as potential users of the model it employs.

8.1. Overview

The thesis has been developed under the supervision, from the company part, of the EUROCONTROL Operations Planning Unit, within the Airspace & Capacity Division of the Network Management Directorate. Among other duties, within their responsibilities lies conducting the Collaborative Decision-Making (CDM) process with capacity providers (mainly air navigation service providers — ANSPs) and demand (airspace users, used interchangeably with aircraft operators throughout the thesis).

The CDM is a process providing stakeholders with the opportunity to influence choices made by relevant authorities based on accurate and up-to-date information, which allows decisions to be taken jointly. It precedes a decision to develop and apply an air traffic flow and capacity management (ATFCM) measure. Such a measure is normally activated during the strategic capacity planning phase, which concentrates on the examination of noteworthy occurrences or annual peak periods (such as the summer or winter holidays), where a sharp rise in demand or a decrease in ACC or airport capacity is anticipated.

This is what the main objective of the thesis discusses. It is pointed out, based on previous academic experience and industry needs, that yielding a higher decision power to the Network Manager within the CDM process in regard to various types of measures, would improve the overall network performance. In the literature review, the academic point of view is exposed on the matter, accompanied by economic considerations — the latter being analysed in correlation with the fairness towards the parties involved in the air traffic management (ATM) process. Afterwards, different game theoretic model types are discussed and evaluated on the basis of their applicability in air traffic management (ATM). The ending of the literature review also serves as a justification of the choice of game theory for the analysis of the way in which equilibrium is reached between the parties involved in the CDM process. One of the most renowned game theory states, the Nash equilibrium, is used for this evaluation.

The reader is then taken gradually through the research objective, namely what the current capacity of the Network Manager is to take decisions and how this power can be increased. The NM's positioning and relationship with the current stakeholders is discussed, along with the manner in which the surrounding processes are built. Further, the proactivity of the NM is analysed, and concrete ways in which its reach regarding decisions can be expanded, are shown. This paves the way for the final research question, which presents the game model setup, highlighting how relevant data for the player payoffs was extracted using the EUROCONTROL Network Strategic Tool (NEST), then applied to the model.

8.2. Comment on research

The method of evaluation of stakeholder acceptability is presented in the last research question: there are multiple players of the game — air navigation service providers and airspace users, which have two options — either to accept, or reject a measure re-routing traffic above a congested sector, issued by the NM. The strategies of each player are based on the combinations of acceptance/rejecting of the measure, taken by the player — the result will be a line indicating the initial, and final acceptance of the model participants. As the model allows it, two types of initial acceptance are used — one in which values are assigned based on our assumption of each player's needs, and the other on neutrality — all begin with 0.5. The final result is also a value between 0 and 1.

In the chapter before the last, the simulation outcomes are presented and commented upon, and a sensitivity analysis shows how the model responds to a change in the payoff weights. The weights are first given a value to try to represent the evolution in acceptance more realistically, then are adjusted to simulate possible effects in the incentivization of the stakeholders to change their behaviour.

The primary objective of the thesis was to identify a proper way to introduce changes to stakeholders, with the aim of improving overall network performance. In the process, both fairness and stakeholder acceptance of the proposed measures were taken into consideration.

The simulations across multiple scenarios (UK-Türkiye and German outbound flows) demonstrated that:

- Fairness can be measured through how utility (payoff) is redistributed among stakeholders. The game-theoretic model allowed stakeholders' benefits and losses to be quantified under different routing strategies. Players with high offload were more likely to support the re-routing measure extracting flights out of their airspace, while players receiving onloaded traffic were less inclined—unless their payoff was managed favourably — here, we could speak of a balance between the two main payoffs for an ANSP — route charges and delay.
- Stakeholder acceptance is conditional, largely dependent on the perceived payoff and the presence of veto-power players (e.g., traditional and low-cost AUs, key congested sectors). Acceptance thresholds and player inclinations illustrated how critical stakeholder configurations and their weight in decision-making affect the outcome of network-wide strategies.
- Incentivization of stakeholders was feasible by adjusting the weights in their payoff functions. This means stakeholders could be theoretically encouraged to accept more flights through their airspace — e.g., via offering a reduction in their monetary impact of delay, modelled through setting a smaller payoff on the delay for a specific player. The game setup thus offers a predictive framework for testing policy levers before implementation.

8.3. Stakeholder input

A stakeholder point of view on the increase in decision power of the Network Manager is given, both as a response to a previous academic model discussing this topic and to our thesis. On the current model, the review is generally favourable — it is acknowledged that it can be evolved into a tool for use in the decision-making structure of the Network Manager. The integration of the thesis's work and findings into other research frameworks, such as the SESAR program, is also emphasized, all while making sure that the advantages the model offers to the Collaborative Decision-Making process are well explained.

8.4. Limitations and way forward

In evaluating the stakeholder acceptance towards the measure issued by the Network Manager, the geometric regret matching (GRM) algorithm of Lan [58] was used. It is based on the previous experiences of the players, the "regrets", which they use to improve their future strategy — this process is akin to learning from past experiences.

There were several shortcomings in obtaining the results presented. To ensure a coherent evolution of the strategies, more than one game run (as initially planned) had to be performed. For several cases, as described in the Results chapter, the model proved inflexible to both small and large adjustments in the weights.

The first idea would be to research and evaluate multiple game theoretic algorithms and check their performance against each other, based on the same payoff data. Along the geometrical regret matcher, the Lemke-Howson algorithm which a common Python library (Nashpy) is based on, would be a start. It is however advised that, the nashpy library limits itself to two players — it would need an expansion to cater to our stakeholder system. The area of study can also be magnified — from several ANSPs on the traffic flow, as our study highlighted, it would be advisable to extend to larger portions of the European ATM Network, even the entire Network itself.

The weights were defined in a relatively raw way — to obtain the same unit of measurement in calculating the payoff function [EUR], only the cost of delay was used. There were two different cost units, applying to airlines and ANSPs (measured at network level and only synthetically as an indicator of ANSP performance). A broader weight definition, together with more properly documented weight adjustments, is advised for more realism. A statistical analysis more precisely measuring the differences in acceptance, on the baseline and adjusted case, could also be carried out.

In the broader context of monitoring the regional balance while rerouting traffic, heavy users of congested areas could be discovered and tracked. By taking into account and simulating real-life disruptions such as bad weather or staff shortages, the realism would be improved. The suggestions made by the stakeholders would help enhance the realism of the model.

Integration of the game theoretic model and its outcomes within larger research projects, such as COCTA and its successor CADENZA, would help the industry benefit from the current work and its future possible improvements. Aligning the concept with “future developments like SESAR”, as the stakeholders mentioned, could magnify its visibility and strategic relevance.

8.5. Final remarks

The experiment provides a proof-of-concept for applying game theory to model fairness and incentivization in ATFCM-related decision-making, as well as visualize stakeholder acceptance. For EUROCONTROL and similar bodies, such models can serve as decision-support tools in identifying stakeholder responses and strategically shaping incentive mechanisms. In shaping future research on this topic, it is essential to stay connected to the industry, in a continuous discussion and feedback with the involved stakeholders, to identify their needs, adjust and improve the model accordingly, and present them with relevant solutions through the research.

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A
Relevant data

A.1. Scenario 1a. EG-LT, avoid EDUUCHI1K sector

Player	Strategy	Payoff
1 - EDUUCHI1K	11111111	$w_{Rc_1} * Rc_{11} + w_{\delta_1} * \delta_{11}$
	11111110	$w_{Rc_1} * Rc_{11} + w_{\delta_1} * \delta_{11}$
	11111101	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11111100	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11111011	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11111010	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11111001	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11111000	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	11110111	$w_{Rc_1} * Rc_{11} + w_{\delta_1} * \delta_{11}$
	11110110	$w_{Rc_1} * Rc_{11} + w_{\delta_1} * \delta_{11}$
	11110101	$w_{Rc_1} * Rc_{10} + w_{\delta_1} * \delta_{10}$
	...	...

Table A.1: Strategies and payoff functions for Player 1 (EDUUCHI1K)

Player	Strategy	Payoff
6 - AU - low-cost	11111111	$w_{\Delta r_{cAU}} * \Delta r_{cAU} + w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11111110	$w_{\Delta r_{cAU}} * \Delta r_{cAU} + w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11111101	0
	11111100	0
	11111011	0
	11111010	0
	11111001	0
	11111000	0
	11110111	$w_{\Delta r_{cAU}} * \Delta r_{cAU} + w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11110110	$w_{\Delta r_{cAU}} * \Delta r_{cAU} + w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11110101	0
	...	...

Table A.2: Strategies and payoff functions for Player 6 (AU — low-cost)

A.2. Scenario 1b. EG-LT, avoid EDUUDI3C sector

Player	Strategy	Payoff
2 - LJLACTA	1111111	$w_{Rc_2} * Rc_{21} + w_{\delta_2} * \delta_{21}$
	1111110	$w_{Rc_2} * Rc_{21} + w_{\delta_2} * \delta_{21}$
	1111101	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1111100	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1111011	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1111010	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1111001	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1111000	$w_{Rc_2} * Rc_{20} + w_{\delta_2} * \delta_{20}$
	1110111	$w_{Rc_2} * Rc_{21} + w_{\delta_2} * \delta_{21}$
	1110110	$w_{Rc_2} * Rc_{21} + w_{\delta_2} * \delta_{21}$
	1110101	$w_{Rc_2} * Rc_{21} + w_{\delta_2} * \delta_{21}$
	...	...

Table A.3: Strategies and payoff functions for Player 2 (LJLACTA)

Player	Strategy	Payoff
5 - AU - low-cost	1111111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	1111110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	1111101	0
	1111100	0
	1111011	0
	1111010	0
	1111001	0
	1111000	0
	1110111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	1110110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	1110101	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	...	...

Table A.4: Strategies and payoff functions for Player 5 (AU - low-cost)

A.3. Scenario 2a. ED airports, avoid EDUUCHI1K sector

Player	Strategy	Payoff
4 - LOVVCTA	111111111	$w_{Rc_4} * Rc_{41} + w_{\delta_4} * \delta_{41}$
	111111110	$w_{Rc_4} * Rc_{41} + w_{\delta_4} * \delta_{41}$
	111111101	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111111100	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111111011	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111111010	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111111001	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111111000	$w_{Rc_4} * Rc_{40} + w_{\delta_4} * \delta_{40}$
	111110111	$w_{Rc_4} * Rc_{41} + w_{\delta_4} * \delta_{41}$
	111110110	$w_{Rc_4} * Rc_{41} + w_{\delta_4} * \delta_{41}$
	111110101	$w_{Rc_4} * Rc_{41} + w_{\delta_4} * \delta_{41}$
	...	...

Table A.5: Strategies and payoff functions for Player 4 (LOVVCTA)

Player	Strategy	Payoff
8 - AU - traditional	111111111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	111111110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	111111101	0
	111111100	0
	111111011	0
	111111010	0
	111111001	0
	111111000	0
	111110111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	111110110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	111110101	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	...	...

Table A.6: Strategies and payoff functions for Player 8 (AU - traditional)

A.4. Scenario 2b. ED airports, avoid EDUUISA1I sector

Player	Strategy	Payoff
6 - LDZOCTA	11111111	$w_{Rc_6} * Rc_{61} + w_{\delta_6} * \delta_{61}$
	11111110	$w_{Rc_6} * Rc_{61} + w_{\delta_6} * \delta_{61}$
	11111101	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11111100	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11111011	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11111010	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11111001	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11111000	$w_{Rc_6} * Rc_{60} + w_{\delta_6} * \delta_{60}$
	11110111	$w_{Rc_6} * Rc_{61} + w_{\delta_6} * \delta_{61}$
	11110110	$w_{Rc_6} * Rc_{61} + w_{\delta_6} * \delta_{61}$
	11110101	$w_{Rc_6} * Rc_{61} + w_{\delta_6} * \delta_{61}$
	...	...

Table A.7: Strategies and payoff functions for Player 6 (LDZOCTA)

Player	Strategy	Payoff
9 - AU - other	11111111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11111110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11111101	0
	11111100	0
	11111011	0
	11111010	0
	11111001	0
	11111000	0
	11110111	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11110110	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	11110101	$w_{\Delta f_{cAU}} * \Delta f_{cAU} + w_{\Delta t_{AU}} * \Delta t_{AU}$
	...	...

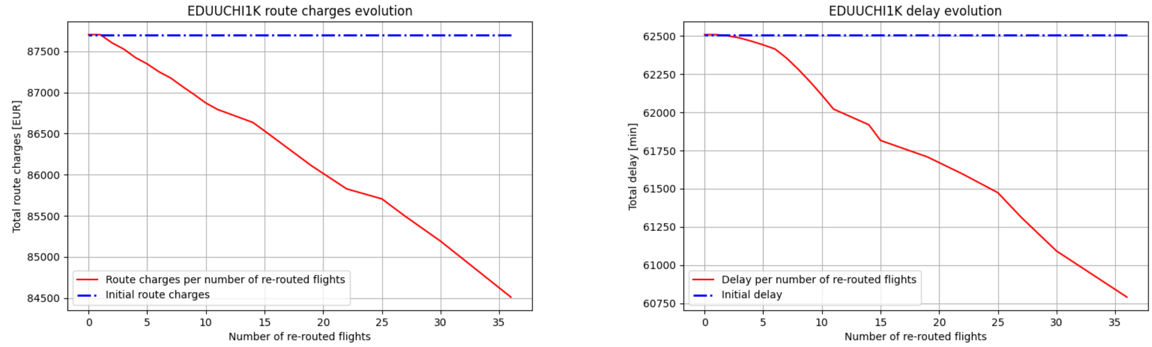
Table A.8: Strategies and payoff functions for Player 9 (AU - other)

B

Relevant figures

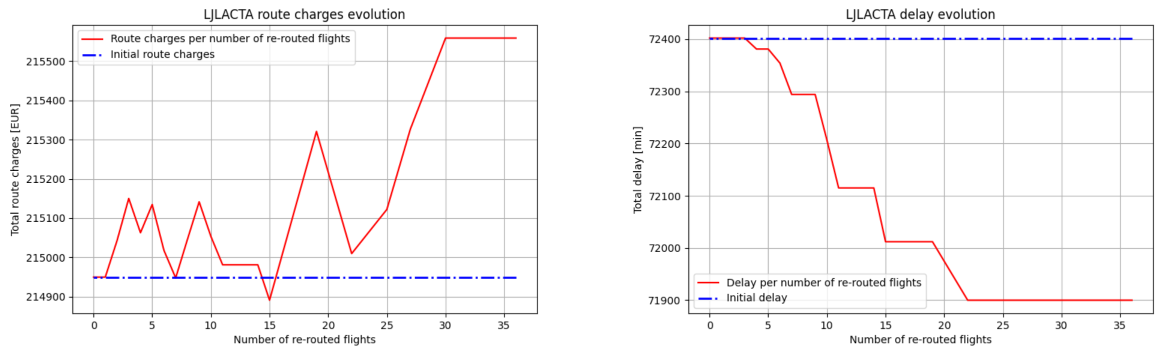
B.1. Scenario 1a. EG-LT, avoid EDUUCHI1K sector

B.1.1. ANSP payoff evolution



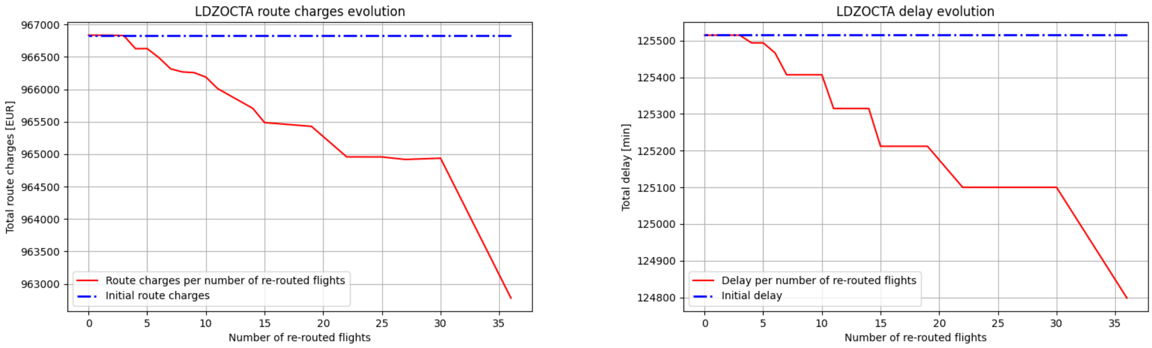
(a) Route charges evolution **(b)** Delay evolution

Figure B.1: Payoff evolution for EDUUCHI1K



(a) Route charges evolution **(b)** Delay evolution

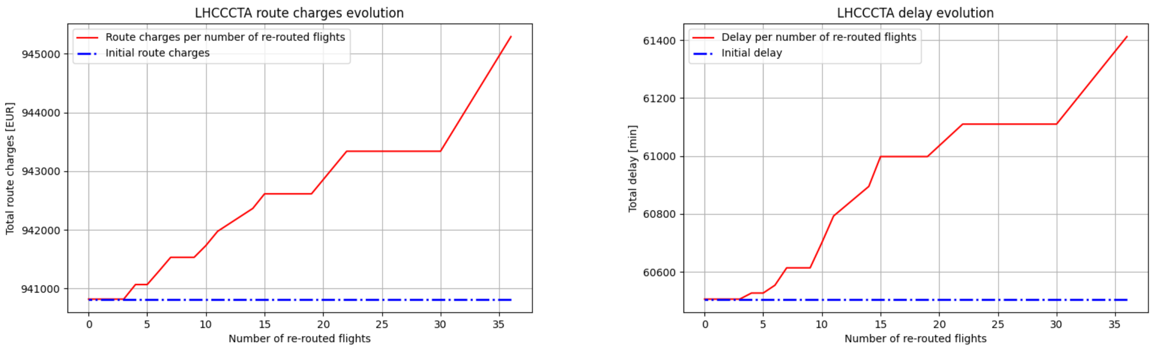
Figure B.2: Payoff evolution for LJLACTA



(a) Route charges evolution

(b) Delay evolution

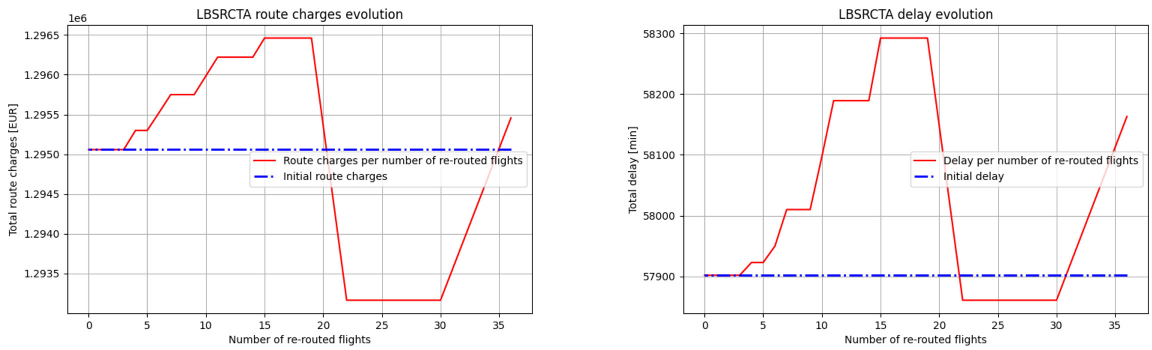
Figure B.3: Payoff evolution for LDZOCTA



(a) Route charges evolution

(b) Delay evolution

Figure B.4: Payoff evolution for LHCCCTA



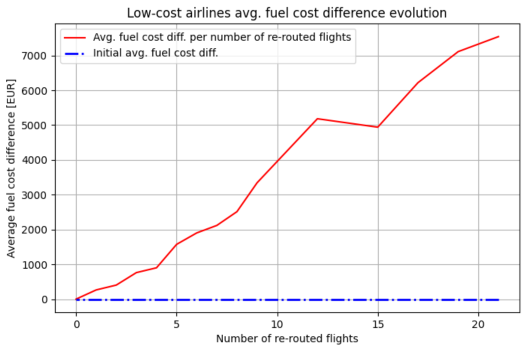
(a) Route charges evolution

(b) Delay evolution

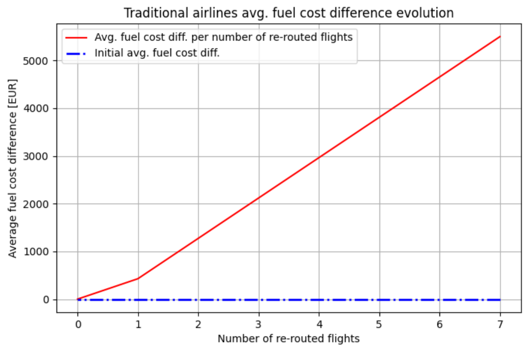
Figure B.5: Payoff evolution for LBSRCTA

B.1.2. AU payoff evolution

Fuel cost difference evolution



(a) Fuel cost difference evolution for low-cost airlines



(b) Fuel cost difference evolution for traditional airlines

Figure B.6: Fuel cost difference evolution

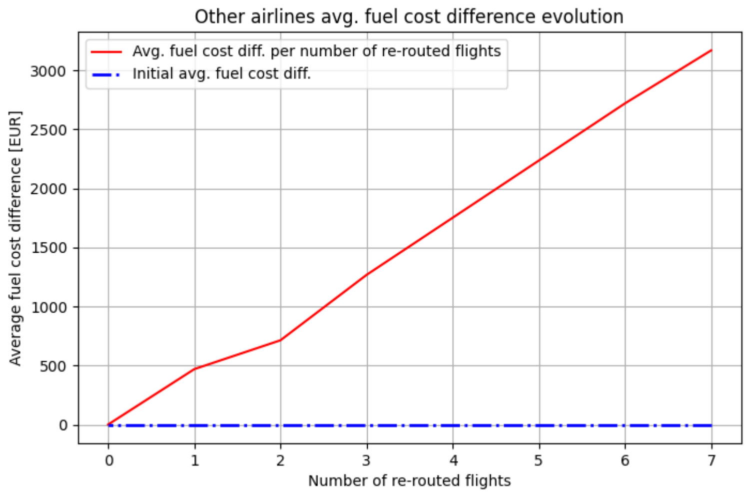
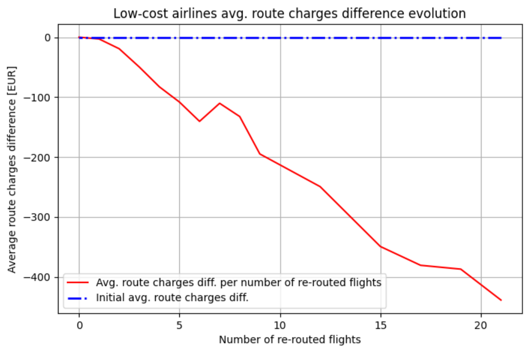
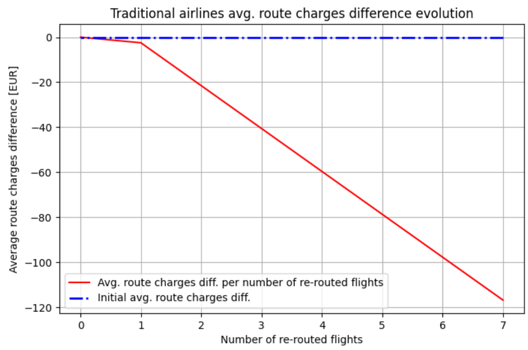


Figure B.7: Fuel cost difference evolution for airlines of type ’other’

Route charges difference evolution



(a) Route charges difference evolution for low-cost airlines



(b) Route charges difference evolution for traditional airlines

Figure B.8: Route charges difference evolution

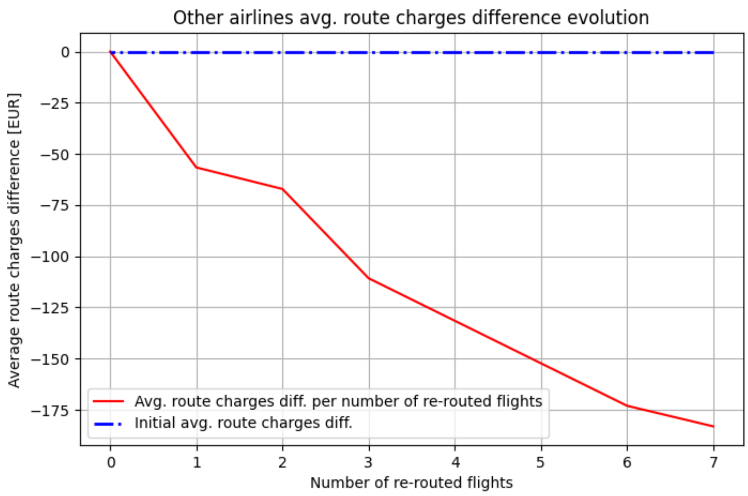
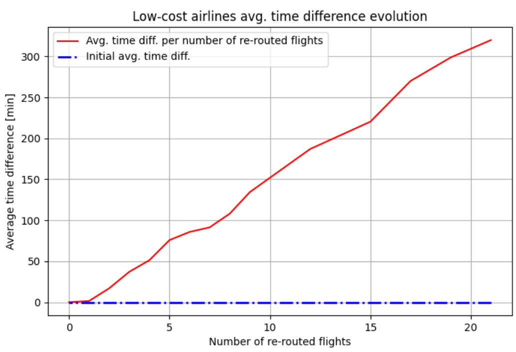
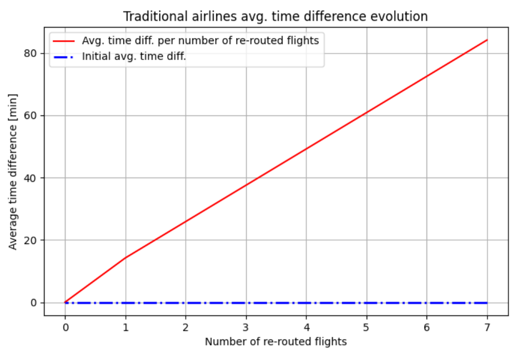


Figure B.9: Route charges difference evolution for airlines of type ’other’

Time difference evolution



(a) Time difference evolution for low-cost airlines



(b) Time difference evolution for traditional airlines

Figure B.10: Time difference evolution

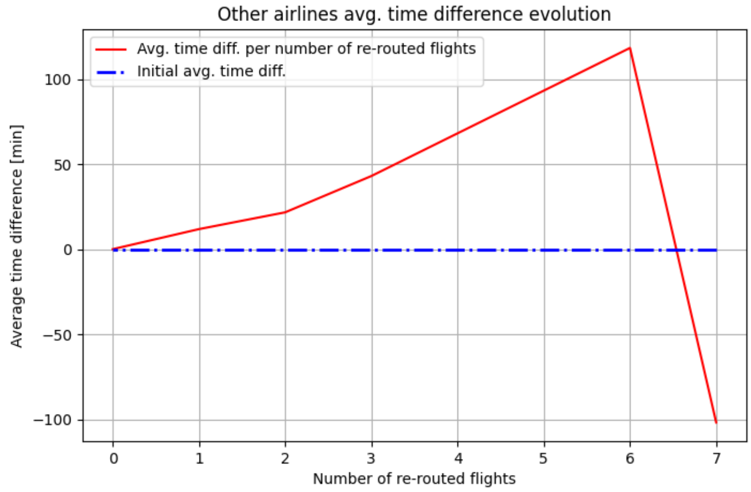
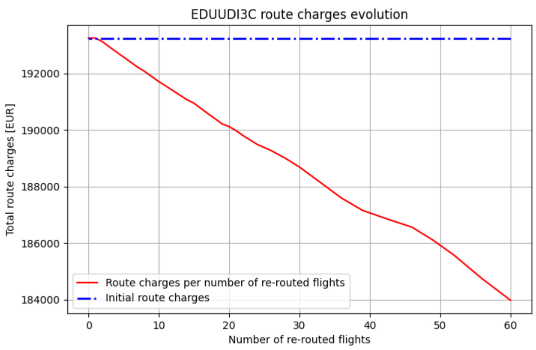


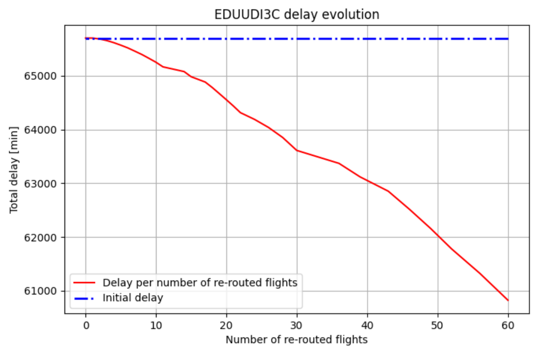
Figure B.11: Time difference evolution for airlines of type 'other'

B.2. Scenario 1b. EG-LT, avoid EDUUDI3C sector

B.2.1. ANSP payoff evolution

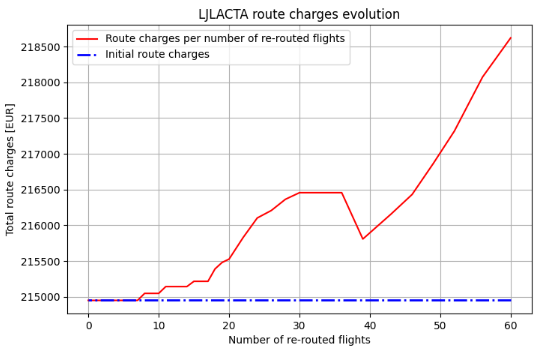


(a) Route charges evolution

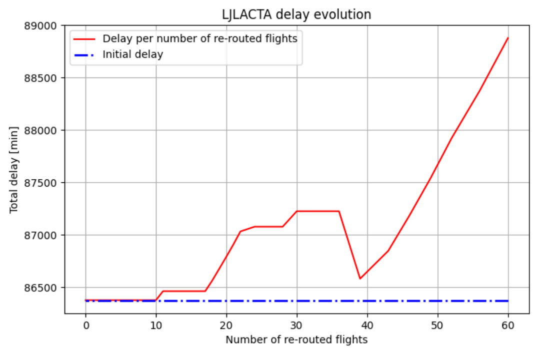


(b) Delay evolution

Figure B.12: Payoff evolution for EDUUDI3C

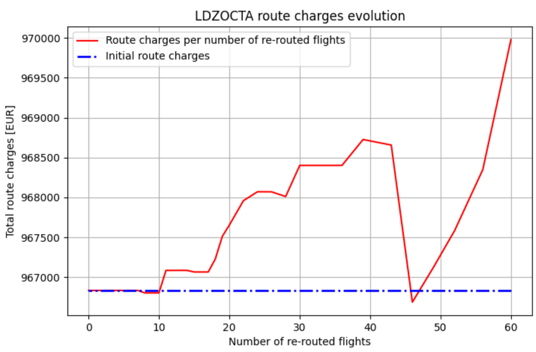


(a) Route charges evolution

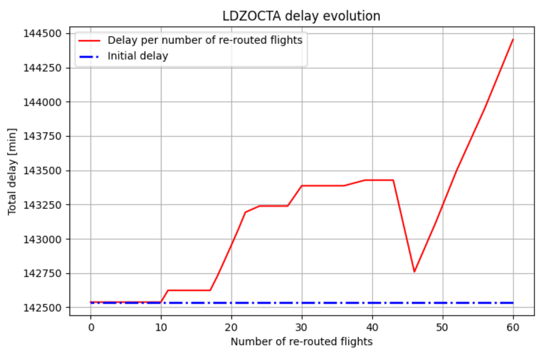


(b) Delay evolution

Figure B.13: Payoff evolution for LJLACTA

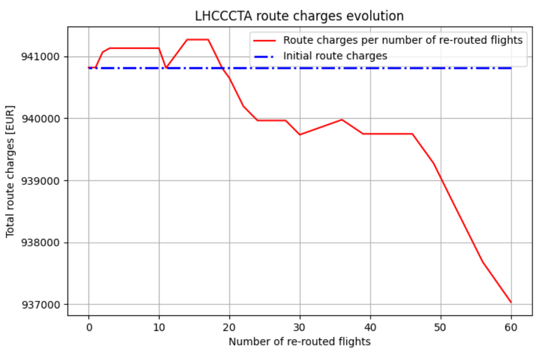


(a) Route charges evolution

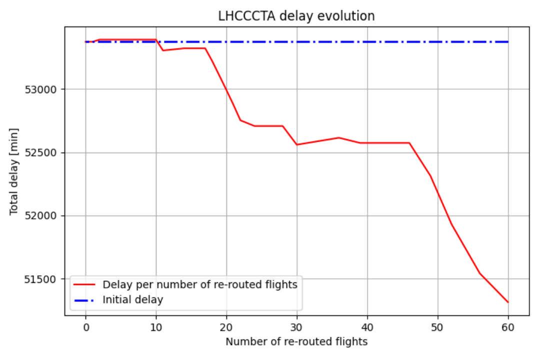


(b) Delay evolution

Figure B.14: Payoff evolution for LDZOCTA



(a) Route charges evolution

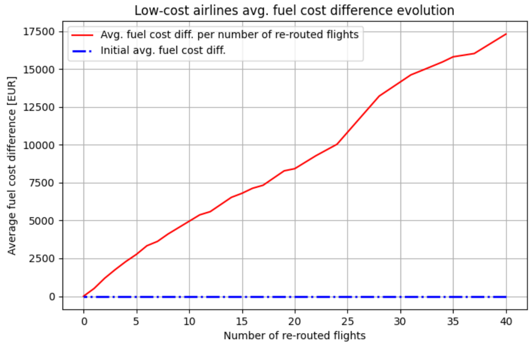


(b) Delay evolution

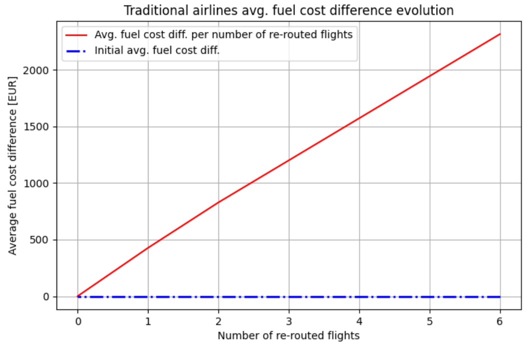
Figure B.15: Payoff evolution for LHCCCTA

B.2.2. AU payoff evolution

Fuel cost difference evolution



(a) Fuel cost difference evolution for low-cost airlines



(b) Fuel cost difference evolution for traditional airlines

Figure B.16: Fuel cost difference evolution

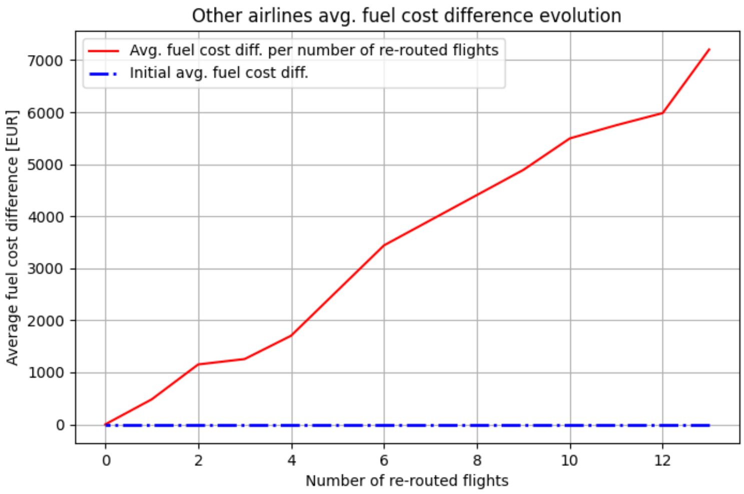
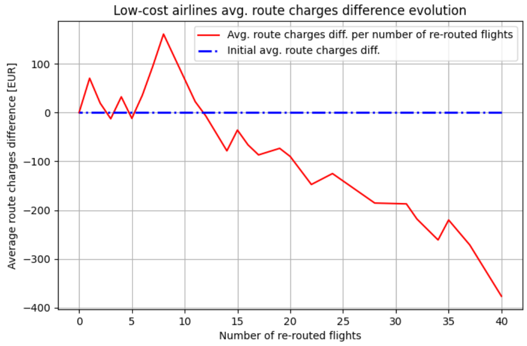
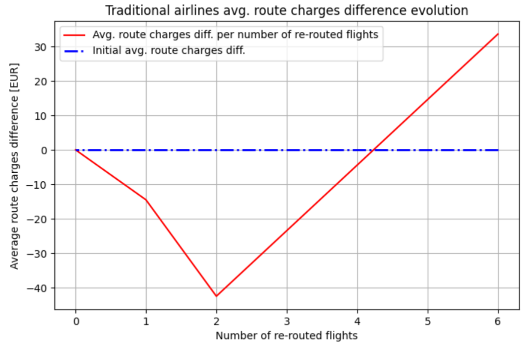


Figure B.17: Fuel cost difference evolution for airlines of type 'other'

Route charges difference evolution



(a) Route charges difference evolution for low-cost airlines



(b) Route charges difference evolution for traditional airlines

Figure B.18: Route charges difference evolution

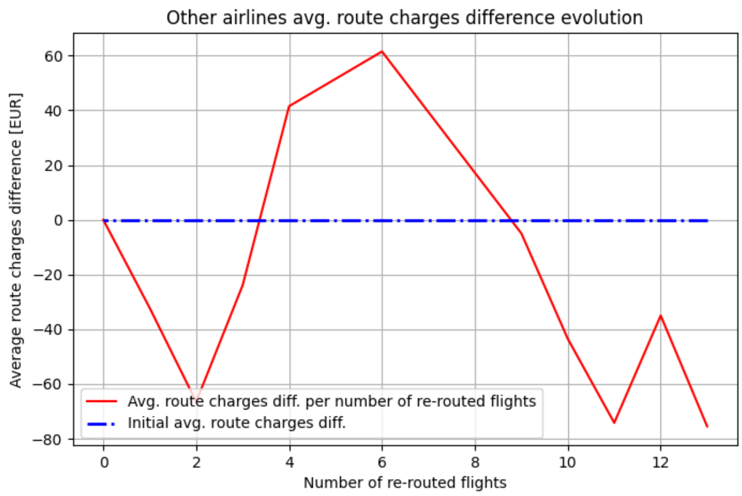
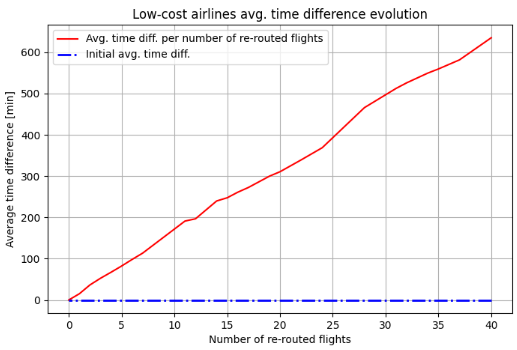
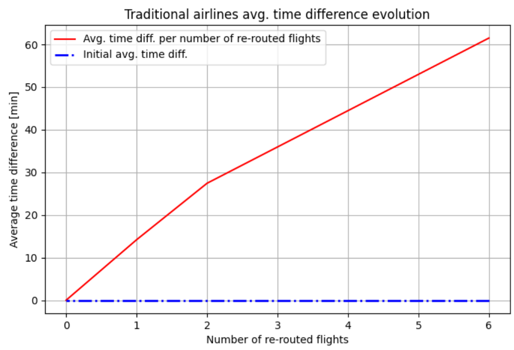


Figure B.19: Route charges difference evolution for airlines of type 'other'

Time difference evolution



(a) Time difference evolution for low-cost airlines



(b) Time difference evolution for traditional airlines

Figure B.20: Time difference evolution

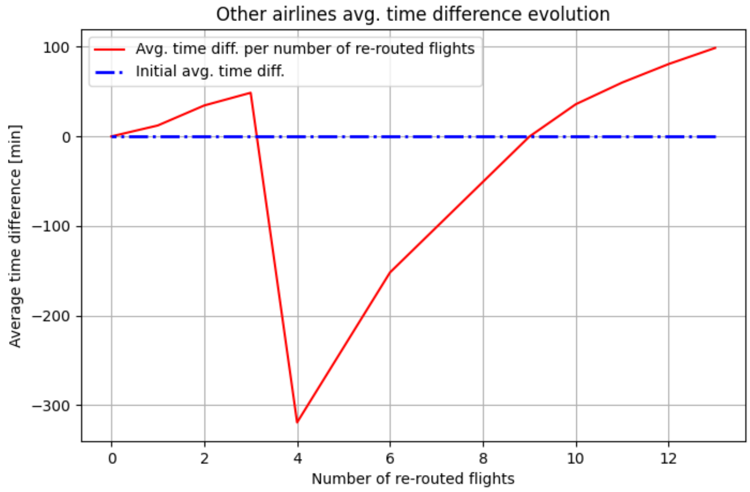
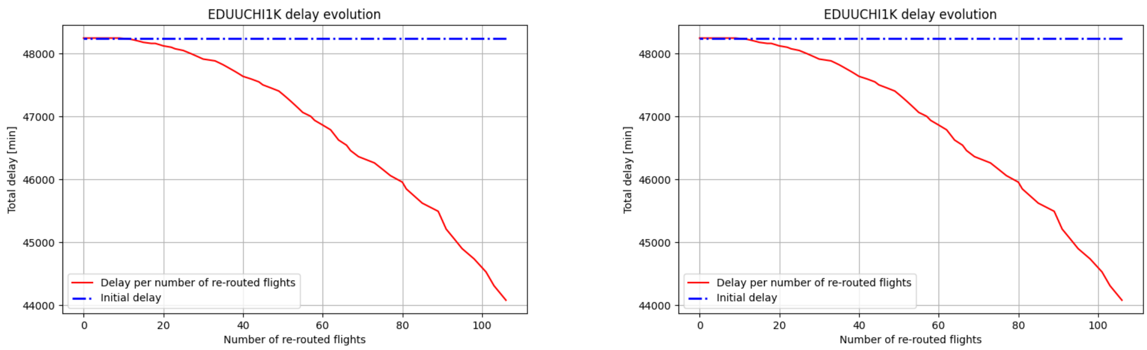


Figure B.21: Time difference evolution for airlines of type 'other'

B.3. Scenario 2a. ED airports, avoid EDUUCHI1K sector

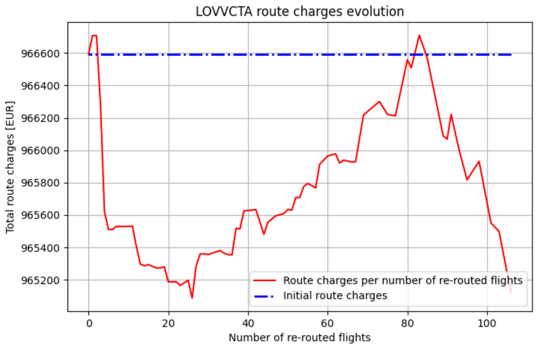
B.3.1. ANSP payoff evolution



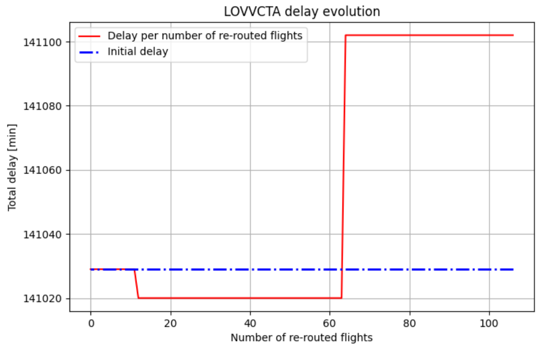
(a) Route charges evolution

(b) Delay evolution

Figure B.22: Payoff evolution for EDUUCHI1K

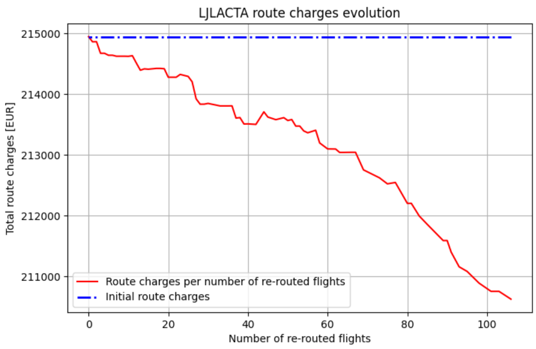


(a) Route charges evolution

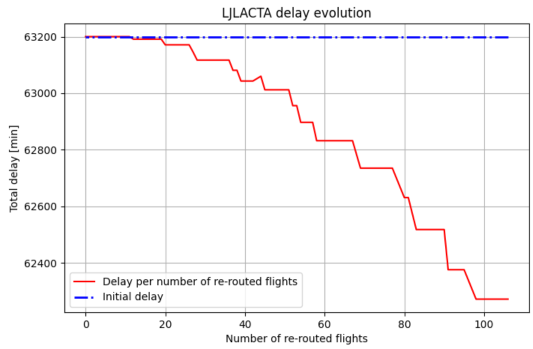


(b) Delay evolution

Figure B.23: Payoff evolution for LOVVCTA

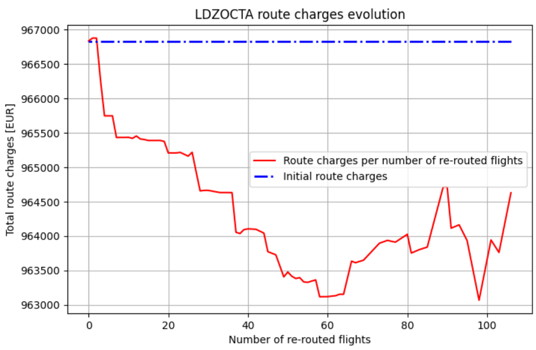


(a) Route charges evolution

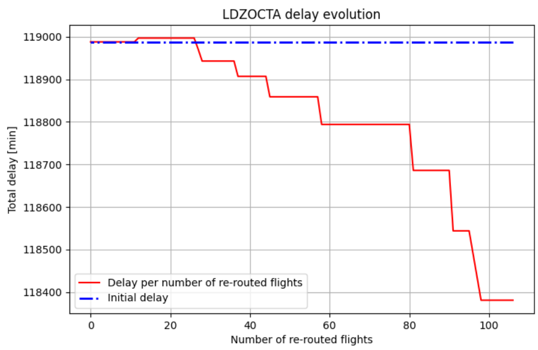


(b) Delay evolution

Figure B.24: Payoff evolution for LJLACTA

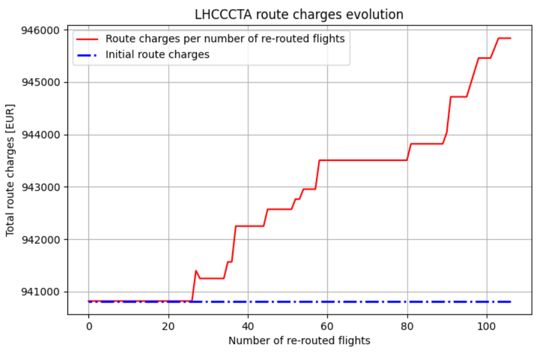


(a) Route charges evolution

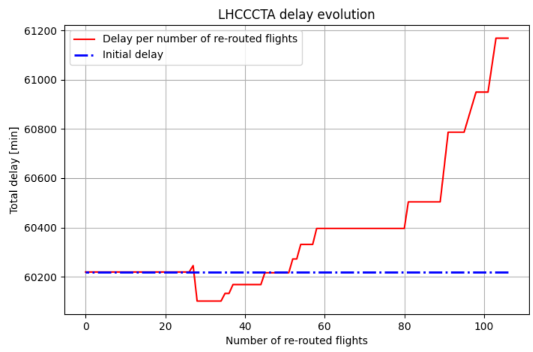


(b) Delay evolution

Figure B.25: Payoff evolution for LDZOCTA



(a) Route charges evolution

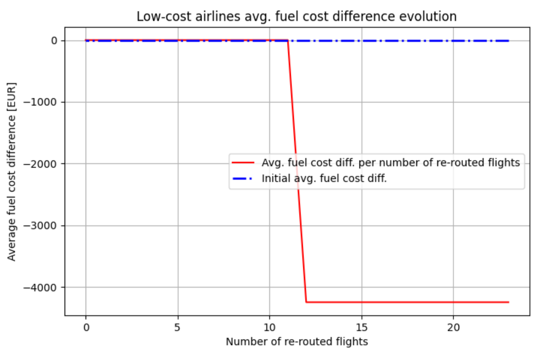


(b) Delay evolution

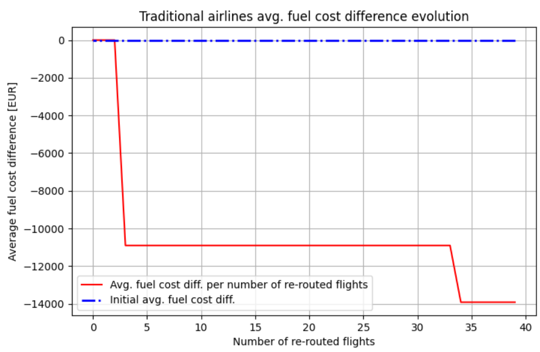
Figure B.26: Payoff evolution for LHCCCTA

B.3.2. AU payoff evolution

Fuel cost difference evolution



(a) Fuel cost difference evolution for low-cost airlines



(b) Fuel cost difference evolution for traditional airlines

Figure B.27: Fuel cost difference evolution

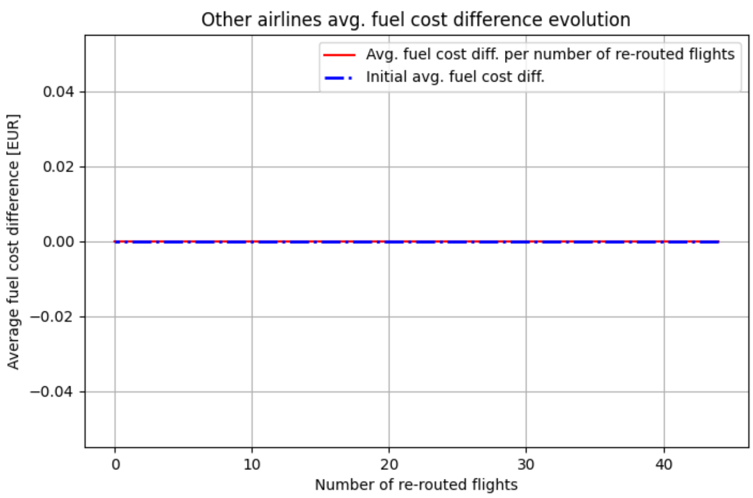
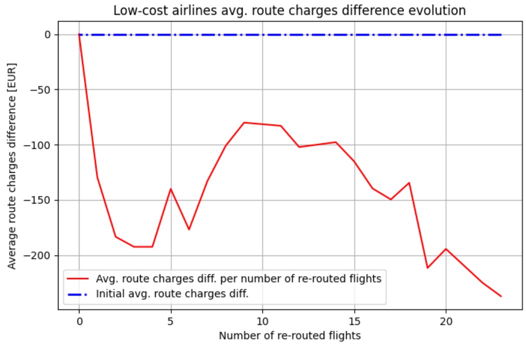
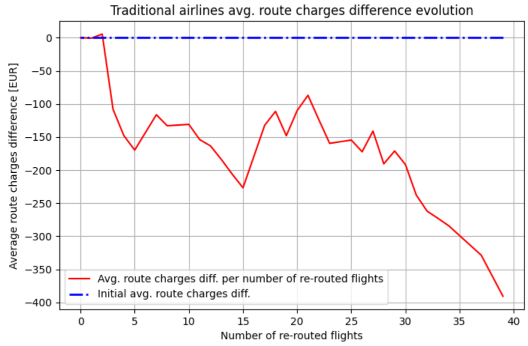


Figure B.28: Fuel cost difference evolution for airlines of type 'other'

Route charges difference evolution



(a) Route charges difference evolution for low-cost airlines



(b) Route charges difference evolution for traditional airlines

Figure B.29: Route charges difference evolution

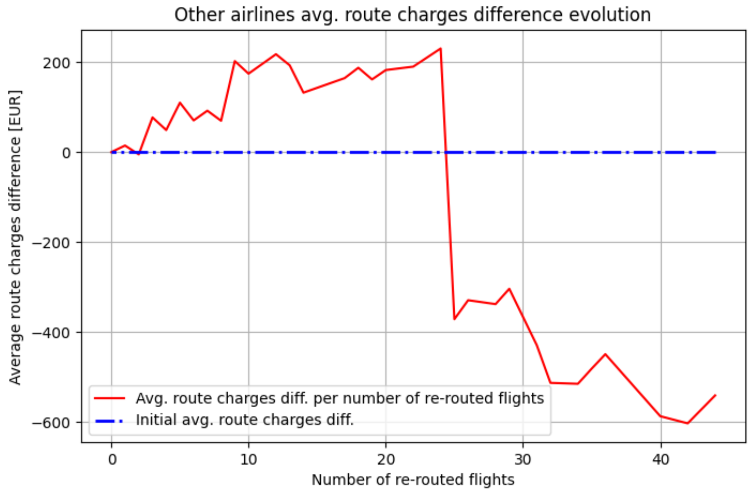
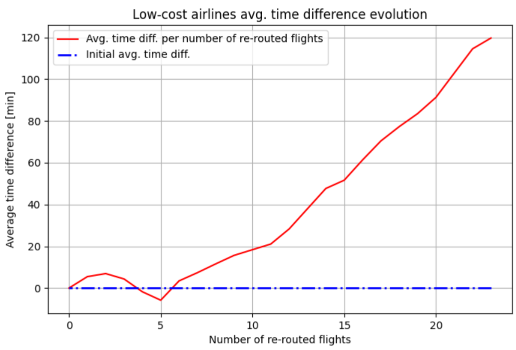
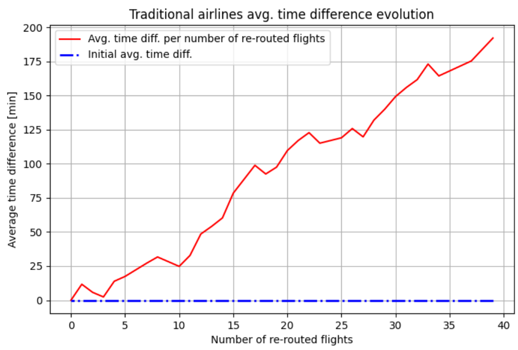


Figure B.30: Route charges difference evolution for airlines of type 'other'

Time difference evolution



(a) Time difference evolution for low-cost airlines



(b) Time difference evolution for traditional airlines

Figure B.31: Time difference evolution

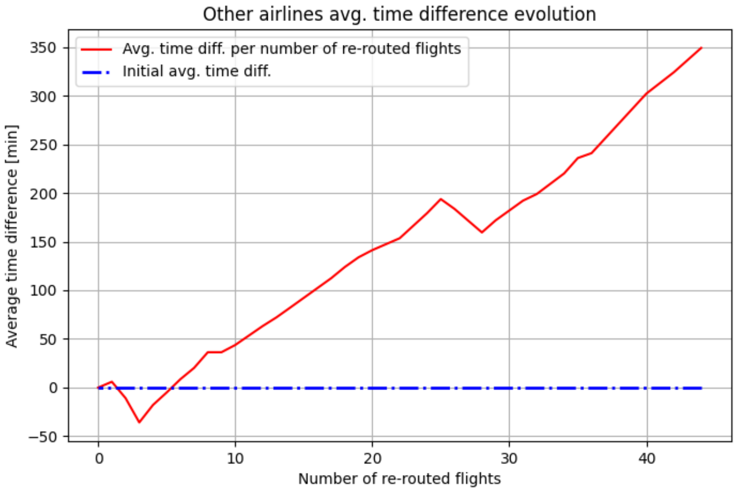
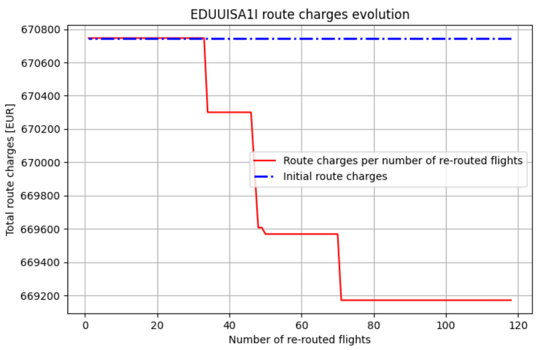


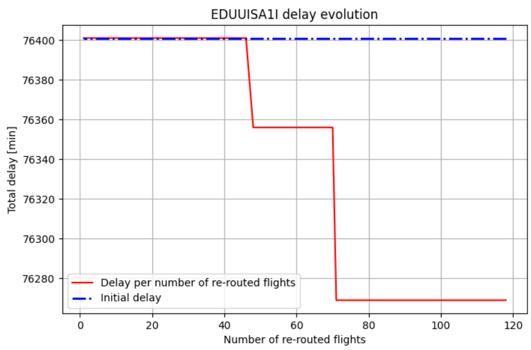
Figure B.32: Time difference evolution for airlines of type 'other'

B.4. Scenario 2b. ED airports, avoid EDUUISA1I sector

B.4.1. ANSP payoff evolution

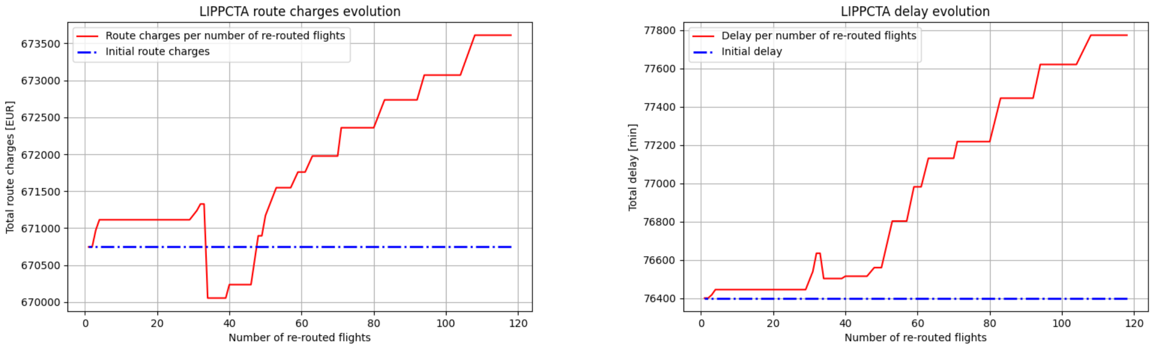


(a) Route charges evolution



(b) Delay evolution

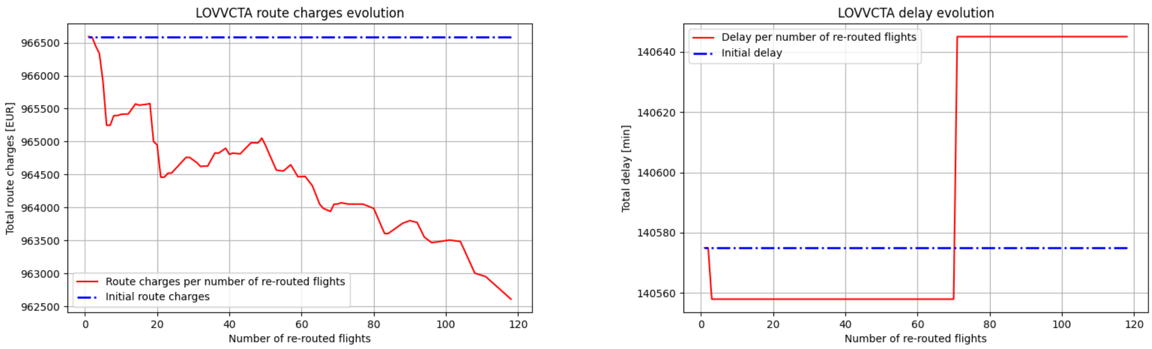
Figure B.33: Payoff evolution for EDUUISA1I



(a) Route charges evolution

(b) Delay evolution

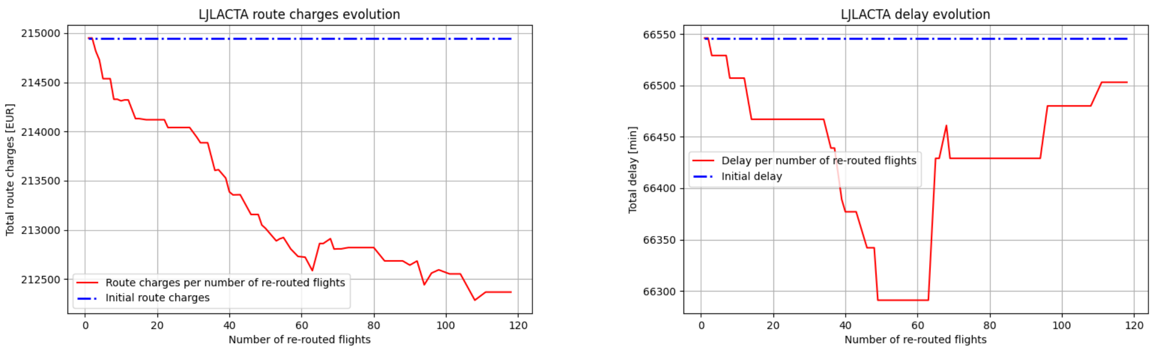
Figure B.34: Payoff evolution for LIPPCTA



(a) Route charges evolution

(b) Delay evolution

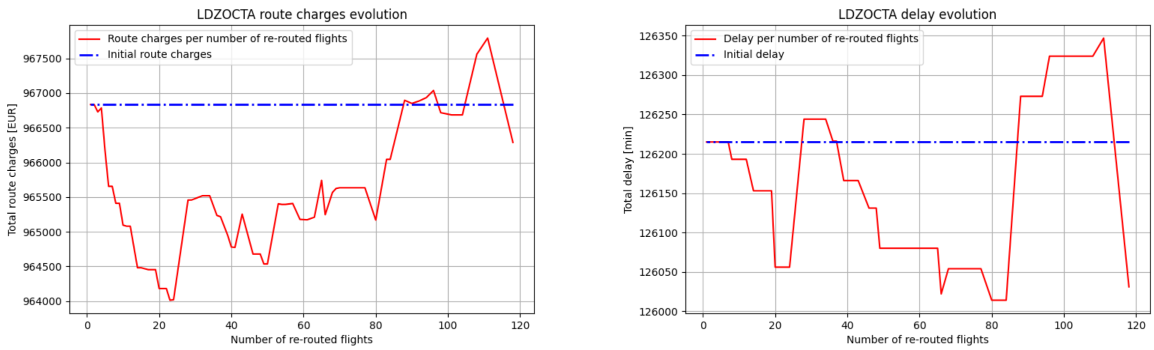
Figure B.35: Payoff evolution for LOVVCTA



(a) Route charges evolution

(b) Delay evolution

Figure B.36: Payoff evolution for LJLACTA



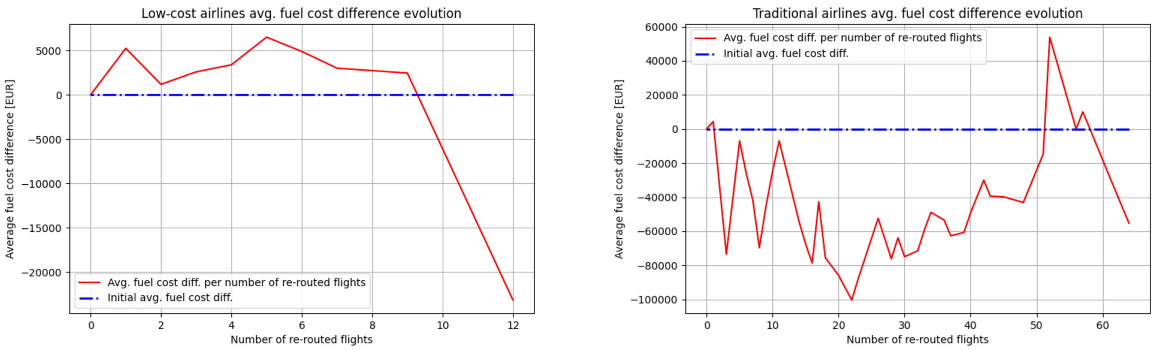
(a) Route charges evolution

(b) Delay evolution

Figure B.37: Payoff evolution for LDZOCTA

B.4.2. AU payoff evolution

Fuel cost difference evolution



(a) Fuel cost difference evolution for low-cost airlines

(b) Fuel cost difference evolution for traditional airlines

Figure B.38: Fuel cost difference evolution

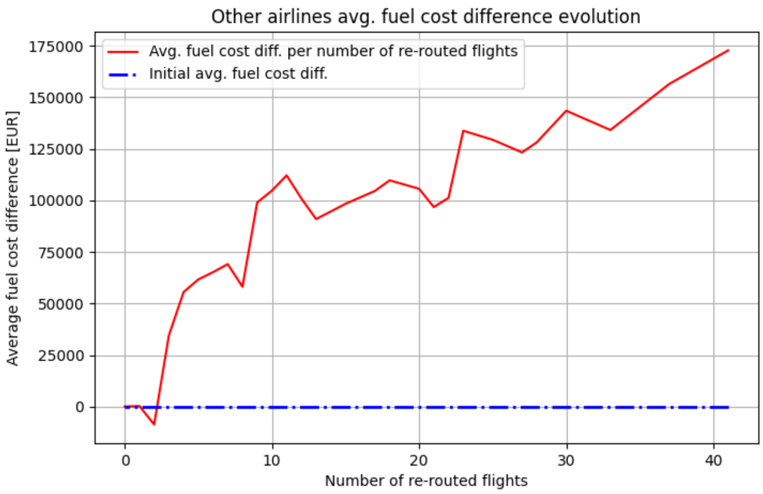
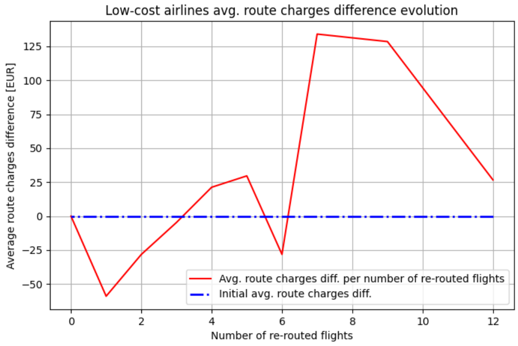
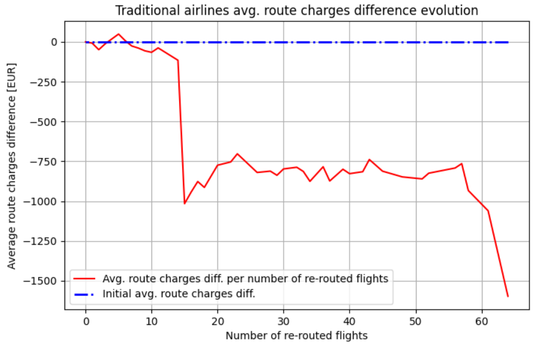


Figure B.39: Fuel cost difference evolution for airlines of type 'other'

Route charges difference evolution



(a) Route charges difference evolution for low-cost airlines



(b) Route charges difference evolution for traditional airlines

Figure B.40: Route charges difference evolution

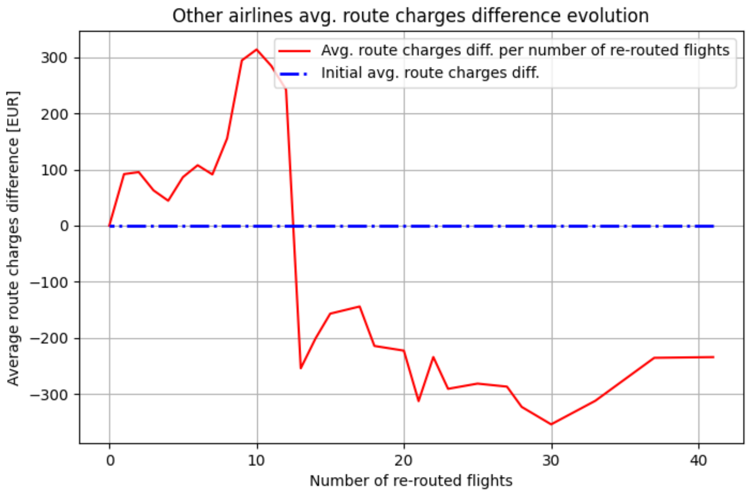
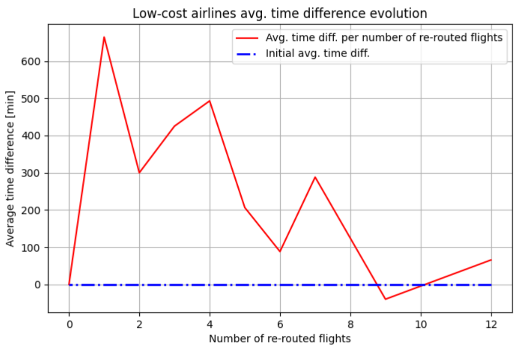
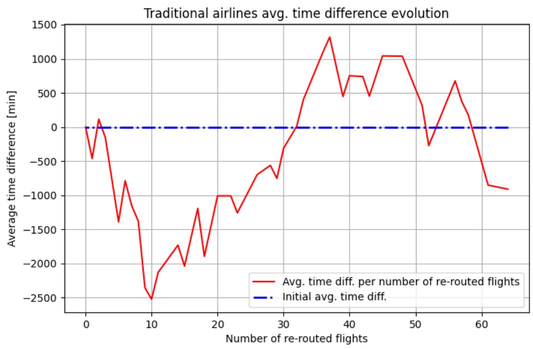


Figure B.41: Route charges difference evolution for airlines of type 'other'

Time difference evolution



(a) Time difference evolution for low-cost airlines



(b) Time difference evolution for traditional airlines

Figure B.42: Time difference evolution

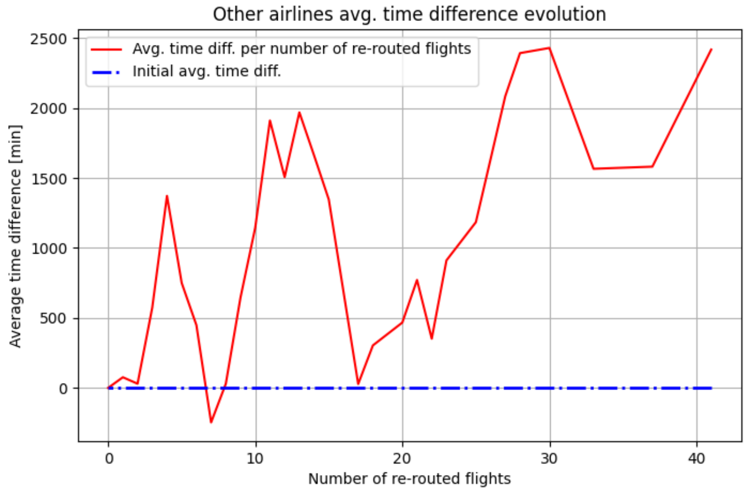


Figure B.43: Time difference evolution for airlines of type 'other'