Universitat Autònoma de Barcelona

escola d'enginyeria

Design of an Algorithm for UDPP (User Driven Priorisation Process) Based on Combinatorial Auctions.

Final Degree Project Report

Bachelor's Degree in Aeronautical Management

Written by **Antonio Redondo Rodríguez**

Directed by **Dr. Sergio Ruiz Navarro**

Sabadell, July 10th 2014

FULL DE RESUM – TREBALL DE FI DE GRAU DE L'ESCOLA D'ENGINYERIA

Títol del Projecte: Design of an Algorithm for UDPP (User Driven Priorisation Process) Based on Combinatorial Auctions.

Autor: Antonio Redondo Rodríguez	**Data:** 10 de Juliol de 2014

Director: Dr. Sergio Ruiz Navarro

Titulació: Grau en Gestió Aeronàutica

Paraules Clau

- **Català:** *Congestió a l'Aeroport, CDM, Cel Únic Europeu, DCB, SESAR, Sequències d'aterratge òptimes, UDPP, Utilitat.*
- **Castellà:** *Congestión en Aeropuertos, CDM, Cielo Único Europeo, DCB, Secuencias de aterrizaje óptimas, SESAR, UDPP, Utilidad.*
- **Anglès:** *Airport Congestion, CDM, DCB, SESAR, Single European Sky, Optimum landing sequences, UDPP, Utility.*

Resum del Projecte

- **Català:** *Es presenta un algoritme basat en subhastes combinatòries per al protocol UDPP (User Driven Priorisation Process), on els recursos són assignats als usuaris que més els valoren, maximitzant el benestar social i distribuïnt els costos de manera equitativa.*

- **Castellà:** *Se presenta un algoritmo basado en subastas combinatorias para el protocolo UDPP (User Driven Priorisation Process), en el cual los recursos son asignados a los usuarios que más los valoran, maximizando así el bienestar social y distribuyendo los costes de manera equitativa.*

- **Anglès:** *An algorithm for the UDPP (User Driven Priorisation Process) based on combinatorial auctions is presented, in which the resources are allocated to those users who value them the most, thus maximizing social welfare and distributing costs in an equitable way.*

Contents

ABSTRACT **1**

1. INTRODUCTION **2**

1.1 The Single European Sky (SES) 3

1.1.1 The SESAR Programme 4

1.2 Demand & Capacity Balancing Through UDPP 7

1.3 Motivation of the Research: Design of a Market Based UDPP Mechanism 8

1.4 Objectives 9

1.5 Project Scope & Document Structure 10

2. LITERATURE REVIEW. **11**

2.1 New ATM Concepts Introduced by SESAR 12

2.2 Uncertainty in ATM 15

2.3 Market Mechanisms for UDPP 17

3. DESIGN OF THE ALGORITHM. **20**

3.1 Definition of Variables and Parameters 21

3.2 Market Mechanism Rules 25

3.3 Incentive Alignment for Collaborative Behavior of the Market Agents . 28

3.4 Algorithm Complexity During the Calculation of the Feasible Landing Sequences 29

3.5 Congestion Fees and Compensation Refunds 31

3.6 Cash Flows Among Agents in the UDPP Market 32

4. CASE STUDIES AND RESULTS. 32

4.1 Scenario 1: Normal Market Performance 33

4.2 Scenario 2: One User Places False Bids 35

5. CONCLUSIONS. 37

Bibliography 39

Nomenclature 41

List of Figures

2.1 Business Trajectory Life-Cycle. 14

2.2 Relations Between Different Sources of Uncertainty. 16

3.3 Dual time dimension between current time and the UDPP Time Window. 21

3.4 Matrix of separations. 22

3.5 Representation of a flight range (aircraft cannot land between t_{start} and ELT_i, but can land in t_{end} or even after). 23

3.6 Example of a vector of utilities creation. 24

3.7 Utilities within different ranges. 24

3.8 Information Flows in the UDPP Process 27

3.9 Example of Compensations. 32

ABSTRACT

Due to the current growth in air transport, the European Air Management System soon will reach its capacity limits, thus generating a serious impact on passenger delays, costs for airlines and CO_2 emissions. To solve the problem, in 2004, the European Commission launched the Single European Sky (SES) initiative, aiming to reform the European airspace and the way it is managed.

The SESAR (Single European Sky ATM Research) Programme is the mechanism that coordinates and concentrates all research and development activities in order to achieve the SES goals. Two of the concepts introduced by SESAR are **Collaborative Decision Making (CDM)**, which aims at users to optimize their decisions in collaboration with other partners, and **Demand and Capacity Balancing (DCB)**, which is a process that aims to maintain the balance between demand and capacity during the course of the daily traffic operations.

UDPP (User Driven Priorisation Process) is a CDM-based process for DCB which allows AUs to reflect a prioritization of flights which best respects their business interests. It is activated during periods in which an **imbalance between capacity and demand is predicted** at some local sectors of the ATM (generally due to a sudden capacity fall caused by the presence of adverse weather not correctly forecast). The service provider declares the available capacity and users, interacting collaboratively and collectively with the provider, propose specific flights to update it.

UDPP is described in the SESAR documents, but in a high level of abstraction. **As no specific algorithm is available for UDPP, the challenge of the proposed project is to better understand the different parameters and constraints that affect the DCB process in airports in order to specify in detail a new particular concept of how the UDPP algorithm should be.**

The project outcome is an UDPP market mechanism based on **combinatorial auctions**, where users and airports can place bids for the available resources, which will be allocated to those **users who value them the most**, thus achieving the **maximum social welfare** possible whereas the costs derived from the potential negative externalities of the resource allocation will be supported by all the users in an equitable way.

an UDPP market mechanism based on combinatorial auctions where users and airports can "bid" for the available resources, which will be allocated to those users who value them most, thus achieving the maximum social welfare possible whereas the costs derived from the potential negative externalities of the resource allocation will be supported by all the users in an equitable way.

1. INTRODUCTION

European Air Traffic Management (ATM) is an extremely complicated system. Its airspace is among the busiest in the world with over 33,000 flights daily, with a very high airport density. The traffic forecasts [10] predict a growth of 2,7% from 2015 onwards. The 2008 peak of 10.1 million flights is forecast to be reached again in 2016 and in 2020, 11.8 million flights, 19% more than in 2013.

The shortcomings of the European ATM system are estimated to cost billions of Euros annually. That is a threat to the sustainable growth of the air transport sector. Without any change in the way that the air transport is currently managed, the European ATM soon will reach its capacity limits, thus generating a serious impact on passenger delays, costs for airlines and CO_2 emissions.

1.1 The Single European Sky (SES)

The Single European Sky (SES) is an initiative launched by the European Commission (EC) in 2004 to reform the European ATM. The European airspace will no longer have national boundaries, on behalf the Functional Airspace Blocks (FAB), which are trans-European cross-border airspaces, designed as a function of the air traffic needs, instead of the national borders.

Besides restructuring European airspace structure, the SES key objectives are the generation of additional ATM capacity and the increase of the overall ATM system efficiency, altogether without ever neglecting safety.

In order to meet these objectives, the EC sets a Performance Scheme, that defines the required performance levels (compared to 2005) in the following areas.

- **Safety:** Improve safety by a factor of 10.
- **Capacity:** Enable an increase in capacity by a factor of 3 which will also reduce delays both on the ground and in the air.
- **Cost-Effectiveness:** Provide ATM services to the airspace users at a cost of at least 50% less.
- **Environmental Impact:** Enable a 10% reduction in the effects flights have on the environment.

In addition, Eurocontrol[1] has been established as the European **Network Manager (NM)**, who assumes a set of different ATM functions, among which the most important one with regards to this work is the **Air Traffic Flow and Capacity Management (ATFCM)**.

1.1.1 The SESAR Programme

A new ATM infrastructure needs to be deployed in Europe in order to achieve SES objectives and targets. It requires active and constructive cooperation in a coordinated and synchronized manner between a wide range of stakeholders. **The SESAR (Single European Sky ATM Research) initiative is the mechanism which seeks to coordinate and concentrate all EU research and development activities in ATM.** It is the technological dimension of SES, supported by state-of-the-art and innovative technology.

SESAR is organized in three phases:

- **Definition Phase (2005-2008)**. During this period, the European ATM Master Plan [17] was delivered, in which the technological steps and the modernization for the implementation of a new ATM concept are defined. It was co-financed by the EC and Eurocontrol.
- **Development Phase (2008-2016).** This phase was managed by SESAR Joint Undertaking, a European public-private partnership, in which the required new

[1] Eurocontrol is the European Organization for the Safety of Air Navigation. Founded in 1960, it is an international organization working for seamless, pan-European air traffic management. Eurocontrol is a civil organization and currently has 40 member states. Its headquarters are in Haren, City of Brussels.

generation of systems and components was produced as defined in the previous phase. SESAR Joint Undertaking is the guarantee for a single management structure for the project, as well as a governance model associating all actors involved.

- **Deployment Phase (2014-2020).** It will seek to build the new infrastructure at a wide scale both in Europe and in partner countries. This will be carried out under the responsibility of the industry.

By making full use of existing and newly developed technologies, SESAR concept is based on the following new key features:

- **Moving from Airspace to 4D Trajectory Management**, reducing the constraints of airspace organization to a minimum. **The key concept is the 4D Trajectory**, under which the Airspace Users (AU) and Air Navigation Service Providers (ANSP) define together, through a collaborative process, their optimum flight trajectory.

- **Network Collaborative Management & Dynamic Capacity Balancing.** Introduction of the **Network Operations Plan (NOP)**, a dynamic updated plan that ensures a common view of the network situation. 4D Trajectories are used in ATFCM, by means of the concept of Business Trajectories (BT). Definition of the **CDM (Collaborative Decision Making)** concept and UDPP (User Driven Priorisation Process) protocol. **UDPP is a process or protocol activated during periods in which an imbalance between capacity and demand is predicted at some local sectors of the ATM (generally due to a sudden capacity fall caused by the presence of adverse weather not correctly forecast). The service provider declares the available capacity and users, interacting collaboratively and collectively with the provider, propose specific flights to update it** [11].

- **Airport Integration & Throughput.** Full integration of airport operations as part of ATM and the planning process. A key enabler for a closer integration of network and airport operations is the implementation of Airport Collaborative Decision Making (A-CDM)**.** A-CDM improves ATFCM at airports by reducing delays and improving the predictability and efficiency. It allows each partner to optimize decisions in collaboration with other partners, knowing their preferences and constraints as well as the actual and planned future situation.

- **System Wide Information Management (SWIM)** [8], securely connecting all the ATM stakeholders, guaranteeing that they share the same data. It consists of standards, infrastructure and governance enabling the management of ATM information and its exchange between qualified parties. It will enable the stakeholders in the European ATM community to collaborate in a federated manner, at the pan-European, regional and local levels. Information will be available to all parties, except if specific policies restrict access to it. In other words, SWIM can be understood as a future European ATM intranet.

- **Conflict Management & Automation.** ANSP and pilots will be assisted by new automated functions to reduce their workload and easing to handle complex decision-making processes. **Conflict Detection & Resolution (CD&R)** [16] tools will be used to organize the ATM in a safe way, both in strategic and in tactical phase.

- **Traffic Synchronization.** Integration of Departure Manager (DMAN) and Surface Manager (SMAN) systems at airports and their collaboration with **Arrival Management systems (AMAN)** to optimize the sequencing of aircraft surface movements, arrivals and departures at airports.

In order to achieve the target concept and key features, SESAR is divided in three phases, called Steps. These steps are capability-based and not fixed in time. Each step brings the ATM system closer to the target concept.

- **Step 1: Time Based Operations.** It is the basis for the implementation of the SESAR concept and it focuses on flight efficiency, predictability and the environment. It introduces time prioritization for arrivals at airports by initial Trajectory-Based operations, through the use of temporal landmarks. Datalink is widely used.

- **Step 2: Trajectory Based Operations.** It defines a trajectory-based ATM system where the AU optimize their Business Trajectories and define their priorities in the network. SWIM is used for 4D trajectory management and air/ground trajectory exchange to enable tactical planning and de-confliction.

- **Step 3: Performance Based Operations.** It will achieve the high performance needed to satisfy the SESAR target concept, through the total use of SWIM and collaboratively planned network operations with UDPP.

1.2 Demand & Capacity Balancing Through UDPP

Two of the ATM changes proposed by SESAR are the Collaborative Decision Making and the Dynamic Capacity Balancing.

The concept of **Collaborative Decision Making** introduced in SESAR aims at users to optimize their decisions in collaboration with other partners, knowing their preferences and constraints, improving predictability and efficiency. In this context, all users progressively share more and more precise data to build the NOP, a common traffic and operational environment picture, that can be updated in real time and must reflect any changes that may affect the ATM operations.

Demand & Capacity Balancing (DCB) is a process that takes place on the day of operations and aims to maintain the balance between demand and capacity during the course of daily traffic operations. Through the life-cycle of the flights, the traffic demand and capacity are monitored. When an imbalance occurs, capacity shortfall scenarios are collaboratively solved and reimplemented.

UDPP is a CDM-based process for DCB which allows AUs to reflect a prioritization of flights which best respects their business interests. It is activated during periods in which an **imbalance between capacity and demand is predicted** at some local sectors of the ATM (generally due to a sudden capacity fall caused by the presence of adverse weather not correctly forecast). The service provider declares the available capacity and users, interacting collaboratively and collectively with the provider, propose specific flights to update it.

Since SESAR Definition Phase is a dynamic and changing process, **UDPP definition in the different Steps is slightly different**. The documents containing the definitions of all the concepts introduced in each SESAR Step are the Concept of Operations (ConOps) documents [7, 9]. Only the Step 1 and Step 2 ConOps have been published so far. Next, the different definitions of UDPP are described.

UDPP in Step 1. UDPP is first used to address reduced airport capacity, with a primary focus on addressing departure congestion. However, it is also available in any normal situation on departure and arrival, and even en-route. It is directly linked to slot allocations in the Network Operations planning during periods of reduced capacity. The CDM process mainly relies on the existing system (Slot Swapping) using current techniques adapted to SWIM-compliant information sharing.

In all cases, NM assesses the impact of the AU's UDPP proposals on the network, makes sure that all concerned parties are aware of them and react with new measures in order to minimize the impact of the proposal on the network. Two roles are defined in UDPP Step 1:

- **UDPP Arbitration at Airport Level.** In case of departures from the same airport, NM delegates to the Airport the responsibility to make sure that the agreed UDPP rules are respected and that an acceptable solution is available in due time.
- **UDPP Referee at Network Level.** NM publishes the results and facilitates collaborative dialogue to resolve traffic DCB issues. In particular, it records the results of UDPP requests over time, in accordance to the UDPP principles and rules.

UDPP in Step 2. As in Step 1, UDPP is primarily for use during periods of capacity constraint, but available at all times in order to support business efficiency. **The concept of business efficiency is first mentioned in Step 2.** UDPP is available at both planning and execution phases and is enabled by NM.

It is an input into the DCB process and the management of sequences with the aim of respecting at best the priorities and business interests of AUs. **The concept of sequences is also new in Step 2.** It also mentions that AMAN/DMAN is linked to DCB and UDPP through the use of automation and decision making support tools. **AUs provide a traffic prioritization order to determine their preferred way to match with the new capacity constraints.**

1.3 Motivation of the Research: Design of a Market Based UDPP Mechanism

The SESAR ConOps documents provide high level guidance and serve as a common reference for all operationally related SESAR tasks, describing the ATM operations foreseen in Europe so that all the airspace users gain common understanding. UDPP is described in the ConOps documents, but in a high level of abstraction. **As no specific algorithm is available for UDPP, the challenge of the proposed project is to better understand the different parameters and constraints that affect the DCB process in airports in order to specify in detail an own concept of how the UDPP algorithm should be.**

Seven different indicators, called Key Performance Areas (KPA), are used in SESAR in order to verify compliance with the performance achievable by the SESAR operational concept. These KPA are **Capacity**, **Flexibility**, **Predictability**, **Efficiency**, **Cost Effectiveness**, **Safety** and **Environmental Sustainability**. The innovative concept of CDM, and more precisely UDPP, will generate an important impact on all SESAR KPAs, with an improvement specially on Capacity, Flexibility and Efficiency and also introducing the concepts of Equity and Fairness. In my point of view, **UDPP will be of special interest in the target ATM, specially at airports**, as it will be an important part of a new paradigm in which users will be involved in sharing their priorities, democratically and seeking network efficiency.

1.4 Objectives

The main objective of this project is to **design an algorithm for the UDPP protocol based in an ATM resources market system, so that these resources can be allocated to those airspace users who value them most, thus achieving the most socially beneficial resource allocation.**

In order to achieve the main objective, a series of **partial objectives** are defined. These will form a set of short-term milestones, necessary to define an efficient methodology to face the problem. Next, the partial objectives of the project are listed.

1. Study the concepts introduced in SESAR and become familiar with how the operations will be in the SES, in order to get a model that can be coupled in those requirements and limitations.
2. Identify the parameters that affect in a resources reallocation, the involved parties and other aspects to consider.

3. Analyze different economic theories and justify that a market mechanism is the best method to use in the algorithm design. Describe the threats that deviate a market from the optimal result.

4. Understand the difference between discrete and time-spatial resources and ensure that economic theories are still met.

5. Analyze the concepts of efficiency, equity and fairness and study how to consider and ensure them in the model

6. Specify the market performance and its variables and parameters.

7. Check the validity of the model by developing different case studies.

8. Analyze the results and make conclusions.

9. Define the model limitations and the future work.

1.5 Project Scope & Document Structure

SESAR provides slightly different definitions of UDPP in Step 1 and Step 2 ConOps Documents. In Step 1, UDPP is defined to primarily be used in airports, specially in departure congestion. It defines different arbitration roles for airport and en-route supervision.

In Step 2, UDPP definition is broader. UDPP is available at any situation, in airports and en-route, in strategic and tactical phases.

This project considers that the greatest potential of the UDPP protocol lies in moments of congestion, after an unexpected perturbation has produced an imbalance between demand and capacity, specially at airports in a tactical level. Therefore, the proposed model will only consider the case of UDPP activated under NM enablement, being used for the resolution of mismatches between demand and capacity for **arrivals at airports** at a **tactical level**. The algorithm will be a utility-based market for allocation of resources (landing slots) through a **combinatorial auction**. This model may be adaptable to other flight stages like departures or en-route and also to strategic phase, with the convenient changes. The project will only cover the modeling stage, presenting a **theoretical model of the algorithm**.

In Chapter 2, a detailed **Literature Review** is presented, with a comparison between the current ATM system and the ATM expected in SES, an analysis on the different sources of uncertainty that may lead to the appearance of a perturbation provoking the activation of UDPP and a review on the different concepts necessary for the design of a market.

In Chapter 3, the **Design of the Algorithm** is detailed. First, the variables and parameters are described, and then, the market mechanism rules. Next, the different steps in the algorithm design phase are described in detail, such as the **incentive alignment for collaborative behavior or agents**, the calculation of **feasible landing sequences**, the **congestion fees** and **compensation refunds** used to guarantee an **equitable situation** and finally, the **cash flows** between users.

Chapter 4 presents 2 different **Case Studies** to facilitate the understanding of the algorithm. The first one describes the normal algorithm performance and the second one, a situation in which one user places false bids in order to get a resource.

Finally, in Chapter 5, the final conclusions are done.

2. LITERATURE REVIEW

2.1 New ATM Concepts Introduced by SESAR

At first glance, current and target ATM systems may seem similar. However, operational and conceptual changes are huge. With the aim of showing the key differences, an abstract of the flight planning process in both systems is presented.

The current ATM planning begins with the publishing of the available network resources (airways and sectors) capacity, by the use of information derived from long term predictions. It determines the maximum airspace capacity at the day of operations. Airlines use this information to issue their Flight Plans (FPL). FPL is a document that, regarding a scheduled flight or a part of it, is submitted to ANSP to inform that the flight is going to take place. Contains information about aircraft identification, origin and destination, waypoints, etc. It must be approved before the flight execution.

Eurocontrol CFMU (Central Flow Management Unit) is responsible for matching capacity and demand, in order to avoid unsafe overloaded sectors. **CFMU makes a prediction of the airspace demand from the information of each individual FPL and compares it to the pre-declared capacity released by ANSP.** Those predictions are refined as the day of operations becomes closer and the quantity and quality of information increases. If any imbalance between the predicted traffic and the available capacity is detected at the day of operations in a sector, **CFMU applies regulations** (delays, re-routings or flight level changes) to some selected flights. This selection is not made taking into account the ATC (Air Traffic Control) sectors workload.

ANSP are responsible of the ATC function, preserving safety distances among all aircraft during the flight execution, guiding and facilitating the navigation of each individual aircraft through the airspace sectors. ANSP are also responsible of CD&R at a tactical level, usually with an advance of 20 minutes maximum and with no global ATM perspective of how the decisions made at a local sector may affect the rest of the network through domino effects.

However, in the target ATM, one of the fundamental elements is the **4D Business Trajectory Management.** The traffic flow management is replaced by trajectories management. The BT represents the intended trajectory in a time-space dimension for each flight. It evolves out of a collaborative planning process through its life-cycle, in 3 sequential phases:

- **Business Development Trajectory (BDT).** It is internally generated by the AU based on their business planning goals and their own optimization parameters. BDT are not shared with the rest of the ATM community, as their development may start even years before the day of operations.

- **Shared Business Trajectory (SBT).** It evolves out of a BDT and is shared for planning and negotiation purposes with all involved stakeholders. As long as some potential constraints and discrepancies between the network and the SBT may be detected, AU are involved in the process of DCB, by modifying the trajectory. This phase can start several months before the day of operations and finishes a few minutes before the flight execution.

- **Reference Business Trajectory (RBT).** It is the one that the AU agrees to fly and the ANSP and Airport agree to facilitate. The RBT becomes instantiated before the first ATC clearance, just minutes before the flight execution. Since the RBT is a goal to be achieved, it will be progressively authorized. Thus, **RBT may evolve during flight execution in order to reflect all the applicable clearances and constraints of current state of the network.** The progressive authorizations made over an RBT are the **4D contracts**. Before flight time, the RBT is published by airline and accessed by aircraft. When the take-off time is known, the first airborne segment of the RBT will be cleared through a 4D contract. Successive segments of RBT will be progressively cleared by means of new 4D contracts. RBT may be recalculated or updated from ground or air, for different reasons (separation provision, sequencing, new AUs needs, weather, changing arrival constraints or inability to comply with RBT).

Figure 2.1 shows how Business Trajectory evolves over time and how it is used in the different planning phases.

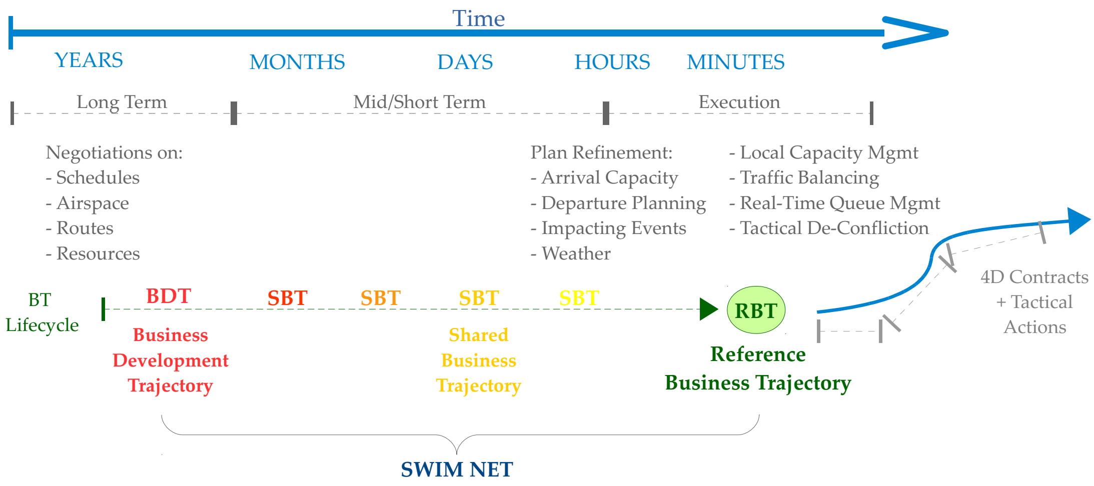

Figure 2.1: Business Trajectory Life-Cycle.

4D Trajectories are also composed of different temporal landmarks, either imposed by ATM or calculated by AU, which control the operation of the flight through the trajectory. This landmarks or milestones are introduced in SESAR Step 1 (Time Based Operations) [7].

- **Target Time of Arrival (TTA).** An ATM computed arrival time. It is not a constraint but a progressively refined planning time that is used to coordinate between arrival and departure management applications.
- **Estimated Time of Arrival (ETA).** The time computed by the FMS (Flight Management System)[2] for the flight arriving at a point related to the destination airport.
- **Controlled Time of Arrival (CTA).** An ATM imposed time constraint on a defined merging point associated to an arrival runway.
- **Controlled Time Over (CTO).** An ATM imposed time constraint over a point. Similar to CTA but used en-route.

A possible problem is that the trajectory held in aircraft systems and the trajectory calculated for that flight by the ground ATM system may be different because of limited

[2] An integrated system, consisting of an airborne sensor, receiver and computer with both navigation and aircraft performance databases, which provides performance and navigation guidance to a display and automatic flight control system.

reconciliation or different assumptions, purposes, sophistication or performance models. However, in SESAR, both aircraft and ground systems will be using shared data, including trajectories, to build and maintain **a common understanding of trajectory evolution, via SWIM**.

During flight execution, both the executed and predicted trajectories will slightly deviate from the RBT, as it was computed using forecasted winds, which include a level of uncertainty and may differ to actual winds. Trajectory Management Requirements (TMR) specify the requirements on the aircraft to share the updated trajectory in the event of that the flight detects a deviation from previous predictions on a cyclical basis. It will allow to set time-spatial deviation tolerances (buffers) or even, CD&R process if necessary.

Airspace stakeholders will use the NOP as a single portal access to ATM information. AU will declare their trajectory intentions and preferences and ANSP will declare their expected capacity and resources. NM will facilitate dialogue to resolve demand and capacity imbalances in a collaborative manner. In case of a sudden capacity shortfall the NM initiates a UDPP process, allowing resource trading among stakeholders to solve the imbalance situation. **NM can impose decisions in case of no agreement is reached in timely-critical situations.**

2.2 Uncertainty in ATM

UDPP protocol will be activated during periods of reduced capacity, when a perturbation unexpectedly affects the system, generally provoking a reduction of capacity in the ATM or in **particular local sectors** and, as a consequence, impeding the normal execution of operations as scheduled. That means that every situation has a component of uncertainty, that should be understood in order to keep track of the different sources of uncertainty that may lead to the occurrence of a perturbation. Several authors and researchers have conducted studies on uncertainty, but using different approaches. There is a lack of a common language that facilitates collaboration towards common objectives and dissemination of their work. Therefore, the ATM scientific community has recently provided with a framework that eases the study of how different levels and sources of uncertainty affect the ATM system [6]. Five different sources of uncertainty are described, arranged in a hierarchical way.

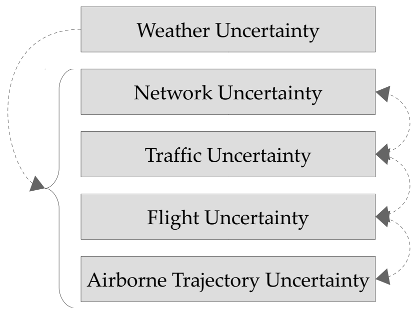

Figure 2.2: Relations Between Different Sources of Uncertainty.

- **Airborne Trajectory Uncertainty.** Only the airborne phase of the 4D trajectory is considered. It quantifies potential feasible deviations of the aircraft with respect to the planned nominal 4D trajectory. The model used to determine the most probable position of the aircraft is the region of confidence, whose center lies at the expected value of the position of the aircraft and includes around it a region of space where the aircraft could be located with a certain degree of probability.

- **Flight Uncertainty.** It encompasses all the uncertainties present at the different stages of the flight (Strategic, Pre-Departure, Gate-to-Gate and Post-Arrival. Flight delay is a very important phenomenon that affects and propagates to other scales.

- **Traffic Uncertainty.** Trajectories interact with management procedures, separation rules and uncertain atmospheric conditions. This generates a dynamic, rapidly changing environment where air traffic control has to take decisions trying to fulfill the conflicting objectives of optimization and safety.

- **Network Uncertainty.** An air transport network can be summarized as a set of airports and flights, represented by a graph with airports as nodes and flights as directed links between those nodes. Their structure and relations are irregular, uncertain and dynamically evolving in time. Uncertainties in all the other inferior levels may lead to a perturbation in the network level, creating domino effects.

- **Weather Uncertainty.** It is situated at the highest level not because it encompasses all of the above, but because it can affect them all. It is the most arbitrary and difficult to foresee source of uncertainty.

Figure 2.2 whows the relations between the different sources of uncertainty.

The article, in addition to the sources of uncertainty, also defines its scope. It distinguishes three levels:

- **Microscale** - A single flight. Of particular interest within this scale is the study of the aircraft trajectory.
- **Mesoscale** - Air traffic. This intermediate scale allows focus on a given area that contains many individual aircraft that interact among themselves following a given set of rules, for instance a Terminal Maneuvering Area (TMA) or sector.
- **Macroscale** - Air transport network. This scale integrates the state of the various ATM elements and allows focus on the network properties, giving a high-level view of the system.

UDPP will be activated after the occurrence of a perturbation, whose uncertainty mainly will be affecting the ATM system in the Mesoscale scope. The lack of **runway capacity is the primary constraint** in the busiest airports in Europe and the available capacity at runways is often reduced because of the presence of bad weather, thus generating important delays on the traffic affected. Thus, this project will focus on airports, as these are the ATM's main bottleneck.

2.3 Market Mechanisms for UDPP

A capacity drop in an airport can be summarized as a reallocation of landing slots or landing times, where some users will get the right of landing at the airport, until capacity is fulfilled, and the rest will be forced to divert to their alternative airports. Several authors have conducted studies on the use of market mechanisms to allocate aeronautical resources.

In 1982, Rassenti et. al. [15] proposed a sealed-bid combinatorial auction for the allocation of airport time slots to competing airlines. This procedure permits airlines to submit various contingency bids for combinations of individual airport landing or take-off slots. Later in 2006, Ball et. al. [2] established the necessary evolutions in the system design in order to keep meeting the goals of economic viability, safety and efficiency. The article explains how market-clearing mechanisms might be able to rectify many of the shortcomings of the current system. More recently, in 2009, Ranieri et. al. [14] described a market mechanism based on auctions to assign ATFM delays to flights at a tactical level, when a mismatch between demand and capacity is detected for a specific system resource.

In order to design a market mechanism to implement the UDPP algorithm, the characteristics and performance of markets should be analyzed. The first concept to understand is the Pareto optimality [3]. **An allocation is Pareto Optimal if there is no way to arrange production or reallocate goods so that someone is made better off without making someone else worse off.** This theory also stands that individuals are the best judges of their own welfare. Fundamental Theorems of Welfare Economics [18] stand that under certain conditions, an allocation achieved by a market economy will be Pareto Optimal. However, there might be some circumstances that deviate allocation from the optimum.

- **Externalities.** When a consumption or production of an agent changes the production or consumption possibilities of other agents. Externalities can be good or bad.
- **Asymmetric Information.** Occurs when information is dispersed in society.
- **Bounded Rationality.** In decision making, individuals rationality is limited by the available information, their cognitive limitations and the finite time they have to make decide.
- **Market Incompleteness.** When markets do not supply a good or a service, even when its supply cost is lower than what users are willing to pay.

In order to design a market whose result is the optimum, or as close as possible to the optimum, the threats that deviate the result from the Pareto optimum must be understood. Coase [5] claims that if the ownership of the goods is clear and **the transaction cost of reaching a contract between the parties is small or nonexistent**, the parties will reach a private agreement that is socially beneficial. The social optimum is achieved regardless of how the property rights are distributed, they simply change who pays and who charges. If agents are not able to reach an agreement, that is a sign that externalities are smaller than transaction costs. Then, externalities in the market can be minimized or even eliminated if the transaction costs are low enough and the remaining externalities are compensated.

With the use of SWIM [8], transaction costs between parties wishing to collaborate will be practically null. As the Coase Theorem argues, under these conditions the agents will reach agreements resulting in the social optimum. Secondly, the use of SWIM also allows the reduction in the impact of other threats. There will be no asymmetric information, as all the ATM users will have the same updated and verified information. Also, bounded rationality will be reduced, as there is no asymmetric information.

Any aircraft flying must always land, thus market incompleteness is not an option in the proposed model. Even when access to saturated or congested resources is structured through a market system, in which resources will be assigned to users who value them the most, no user will stop receiving service, for logical reasons. It is true that deviating an aircraft to an alternative airport will produce externalities, but taking into account that the market meets the Coase Theorem, the users that are outside of the resource access are the ones who generate less impact in the social benefit (lower externalities). These remaining externalities can be reduced by the use of compensations.

In economics, utility is a measure of satisfaction. It is the concept that explains the reason why the consumers acquire goods of any kind, they assign them a value. Assuming that this measure is valid, it makes sense the fact of increasing or decreasing utility, and thereby explaining economic behavior in terms of attempts to increase the utility [4].

Utilitarianism is an economic theory that established the maximization of utility as a moral criterion for the organization of society. From this point of view, it is suggested that an economy is efficient if it produces the highest satisfaction for participants in its activities [12].

Using a utility-based market, it can be stated that **a set of goods can be optimally allocated to the users who value them the most**. Furthermore, if a compensation system is used, where users who have been assigned a good, and consequently having more utility, compensate users who did not obtain a good, a fair and equitable situation can be achieved.

In an airport congestion situation, besides expanding resources, the problem can be solved by allocating them more efficiently. Current system for airport resource allocation encourages waste of resources, as slot allocation uses First Planned, First Served

(FPFS) policy. Aircraft operators, who place different values on airport resources, cannot differentiate themselves by indicating the price they are willing to pay to use the airport (their utility).

A comparison can be used to better understand the concept, for instance, between a business flight and a recreational flight. Assume that the business flight hopes to land at an airport in order to close a multi-million business transaction. Meanwhile, assume that the recreational one has decided to land at the same airport at the same time to pick up a drink. With the first come, first served policy, so long as the recreational flight gets in line to land before the business flight, it could delay the business flight in the air or even cause its diversion to an alternative airport. This outcome is true regardless of whether the business flight places a much higher value on the same landing time [13].

When an airport becomes congested, equity and fairness would be better served if airports employed some method to identify the value placed on use by all aircraft and used this information to arrange the queue, prioritizing higher values.

Once analyzed the concepts and technologies that enable the use of A-CDM, and consequently UDPP, for the allocation of ATM resources and the economic parameters that affect the design of a market, it can be concluded that a market system can achieve a result close to the optimum. Note that the economic theories discussed are valid for discrete goods and instead, the model proposed in this project consists of time-spatial resources. Even so, the main bases of the theories are thus validating the model and in its design the possible differences will be taken into account.

3. DESIGN OF THE ALGORITHM

3.1 Definition of Variables and Parameters

Let assume an airport A in which a capacity drop occurs and UDPP protocol is activated, which will to be active for the **time window (TW) between instants t_{start} and t_{end}**. Users must renegotiate their landing slots within TW limits. Figure 3.3 shows how a new temporal dimension is created, as TW first instant is set to 1 while t_{start} and t_{end} are in function of current time (UTC time). Then, TW can be defined as $TW = \{1, ..., t\}$, where $\boldsymbol{t}$ is the TW duration in seconds. In this model, TW time is discretized in units of 1 second of duration, that can be considered as different spatial-temporal resources. These discrete portions of time are referred in this model as $\boldsymbol{Time - space\ Valuable\ Units\ (TVUs)}$.

The set of flights that are arriving to A and are affected by the capacity reduction is represented by $\boldsymbol{F = \{1, ..., f\}}$, where f is the number of flights. Each flight will have a RBT associated, with an arrival time constraint to accomplish, i.e., a TTA or CTA. Not all of these RBTs will be able to be met, as some flights will get the right of landing at A,

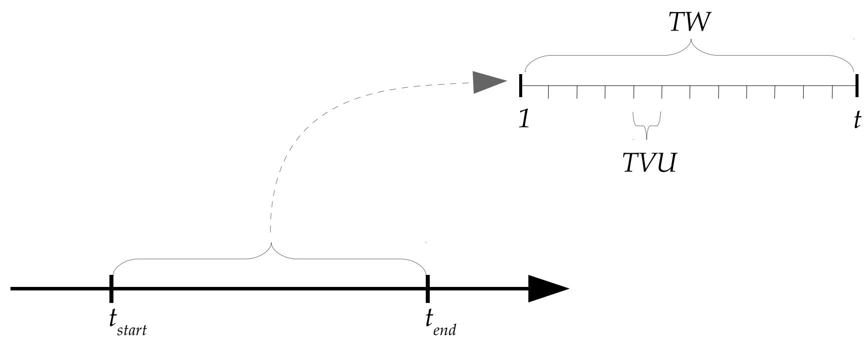

Figure 3.3: Dual time dimension between current time and the UDPP Time Window.

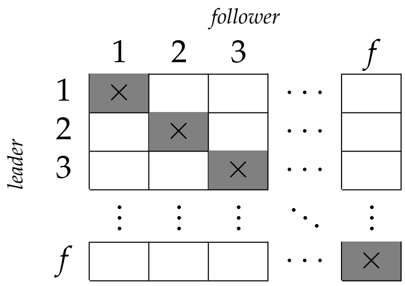

Figure 3.4: Matrix of separations.

getting a landing slot allocated during renegotiation, and some others will be diverted to their alternative airports. In this model, it is considered that **the beginning of any landing slot can start at any discrete second**, i.e., at any TVU, which are the resources that will be traded in the UDPP market, since **a landing slot slot will be composed by a bunch of $TVUs$**. The end of the landing slot will depend on the minimum safety time-based distance separation required between the actual landing aircraft **($leader$)** and the aircraft landing next **($follower$)**. Separations between pairs of aircraft will be stored in a matrix called ***Sep***, whose size is $f \times f$. Each element of the matrix is defined as Sep_{ij}, $\forall ij \in F$, where i represents the leader aircraft and j the follower aircraft. Note that the diagonal of the matrix contains no values, since a flight can not be paired with itself in a landing sequence. Figure 3.4 describes the matrix of time-based minimum separation between pairs of aircraft.

In this model, the property of the time-space resources is assumed to be of the airport. However, for the airport to be able to operate in the ATM system, the NM may force to obey some regulations on the use and allocation of landing slots, for safety reasons. If a traffic mix with different aircraft models and weight categories is considered, the required time-based separations between flights will lead to different runway capacities, depending on the landing sequence executed. Thus, since the airport charges a price for each slot, the revenues of the airport may be affected by the priorisation of the landing sequences. This model proposes that **airports should also participate in the negotiation of the landing slots.** The prices charged to flights for the landing slots, i.e., $LndFee_i$, $\forall i \in F$, are previously established and usually depend on the weight category of the aircraft.

Another constraint in the allocation process is the **range** of each flight. It is a temporal constraint and represents the farthest instant until the aircraft can continue flying safely and also the earliest instant at which the aircraft could reach A by increasing its speed or changing the trajectory. It will depend on multiple factors as remaining fuel, weight,

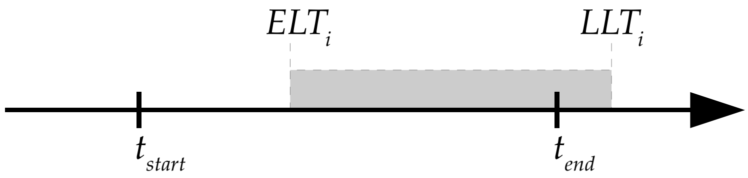

Figure 3.5: Representation of a flight range (aircraft cannot land between t_{start} and ELT_i, but can land in t_{end} or even after).

winds, etc. The range of a flight will be used to know the autonomy of the aircraft and **to determine its feasible landing times**. The time limits that determine the range of a flight are $\boldsymbol{ELT_i}$ (**Earliest Landing Time of flight** $\boldsymbol{i}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$) and $\boldsymbol{LLT_i}$ (**Latest Landing Time of flight** $\boldsymbol{i}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$). Note that a flight range may exceed the TW limits if the aircraft can arrive before UDPP activation or after the protocol is stopped and situation has returned to normal conditions. Figure 3.5 shows an example.

The monetary unit used by users to submit their bids for those resources will be **any common currency that allows representing their utility** valued for each of the $TVUs$ of TW assuming they land at each respective TVU and after taking into account the payment of the $LndFee$. For simplicity, this model assumes that the utility curves of users are concave and continuous, although the model is flexible to any shape. AUs utility is obtained from their own business optimization function, which will be different for every user and even for every flight. This function is a very sensitive and confidential information, so **users will not be willing to share their optimization function**. The method proposed in this model, to protect the confidentiality of information, is that users provide directly the rating for each of the $TVUs$, regardless of the method used by them to obtain such information. The utility of a user i for a specific time step j is defined as $\boldsymbol{U_{i \to j}}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$, $\forall \boldsymbol{j} \in \boldsymbol{TW}$. The set of utilities of a user will be stored in a vector, referred as $\boldsymbol{Bid_i = \{U_{i \to 1}, ..., U_{i \to t}\}}$, which represents the bid of the user for the resources. Figure 3.6 shows an example of how the vector of utilities of a user is created and initialized.

Considering the range restriction, it makes no sense that users provide a utility for those $TVUs$ in which they can not land. Thus, Bid_i vector will be marked with $\times$ in those positions outside the time range. An example is shown in Figure 3.7.

Some users may not get a resource allocated and they will be forced to divert to a time window posterior to TW or to an alternative airport. Therefore, the model must include the costs associated with not being able to land at A. The cost of not landing

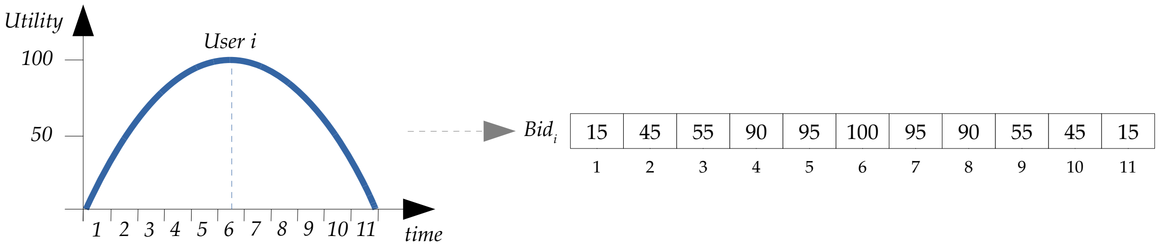

Figure 3.6: Example of a vector of utilities creation.

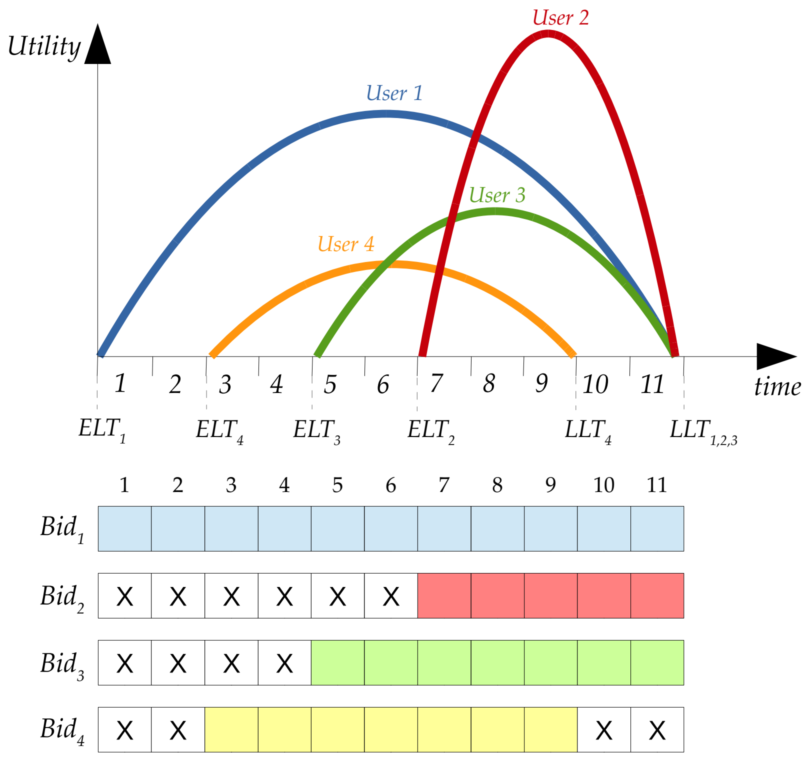

Figure 3.7: Utilities within different ranges.

in an airport can be equivalently described as the utility of diverting to an alternative airport (which not necessarily must be negative) and is identified as $\boldsymbol{DivAlt_i}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$.

As the airport will also participate in the negotiation process, its utility also has to be taken into account. The airport will directly provide the utility that perceives from a series of landing sequences ($\boldsymbol{LSeq}$). Landing sequences will be expressed as a list of landing slots, which are referred as $(i \rightarrow j)$, where i is a flight and j its TVU associated (the start time of the landing slot). Thus, a sequence could be $LSeq = [(i \rightarrow j), (k \rightarrow l)...]$.

Utility perceived by the airport for each sequence will be the amount received from the fees charged to flights included in the sequence and it is described as $\boldsymbol{U_{Apt}}$. The landing sequences are suggested by the **AMAN** and are optimal from the point of view of the airport internal business logic. However, some sequences which could be socially beneficial for the system, may remain outside the airport evaluation, if these are not covered by the AMAN optimization function. Thus, **some sequences generated from the preferences expressed by the AU will be provided to be assessed by the airport**.

The sudden loss of capacity in the airport might generate costs to all the airspace users and also to the airport, thus causing a loss of social welfare in relation to the situation previous to the loss of capacity. For that reason, the model includes a **compensation system, where the winners of the auction pay a congestion fee** ($\boldsymbol{CongFee_i}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$) to use the congested resources, which will be used to **compensate users with negative externalities**, by use of a **compensation refund** ($\boldsymbol{Comp_i}$, $\forall \boldsymbol{i} \in \boldsymbol{F}$). The compensation system is described in detail in Section 3.5.

Table 3.1 presents a summary of all the defined variables and parameters.

3.2 Market Mechanism Rules

Once presented and described the variables and parameters that will be used in the model, the rules and information flows that will regulate the market must be detailed.

Summary of Variables and Parameters

Variable	Description
Bid_i	Bid (vector of utilities) of user i, $\forall i \in F$. $Bid_i = \{U_{i\to 1}, ..., U_{i\to t}\}$.
$Comp_i$	Compensation refund received by user i, $\forall i \in F$.
$CongFee_i$	Congestion fee paid by user i, $\forall i \in F$.
$DivAlt_i$	Utility of flight i for diverting to an alternative airport, $\forall i \in F$.
ELT_i	Earliest Landing Time of flight i, $\forall i \in F$.
f	Number of affected flights.
F	Set of affected flights. $F = \{1, ..., f\}$.
LLT_i	Latest Landing Time of flight i, $\forall i \in F$.
$LSeq$	Landing sequence.
$LndFee_i$	Landing fee for flight i, $\forall i \in F$.
Sep_{ij}	Time-based separation between flights i (leader) and j (follower).
t	TW duration in seconds.
t_{end}	UDPP end time in UTC format.
t_{start}	UDPP start time in UTC format.
TVU	Time-space Valuable Unit.
TW	UDPP Time Window. $TW = \{1, ..., t\}$.
U_{Apt}	Utility of airport for a landing sequence.
$U_{i\to j}$	Utility of user i for TVU j, $\forall i \in F$, $\forall j \in TW$.

Table 3.1: Summary of Variables and Parameters.

UDPP will be activated when a capacity shortage occurs. The perturbation causing the capacity drop may have several origins, like a sudden storm, weather not correctly forecasted, accidents or incidents, infrastructure problems or maintenance, etc. The probability of occurrence of perturbations will have different scopes and sources of uncertainty. When the perturbation is detected the NM is responsible for evaluating the situation and considering the need for activation of the protocol.

UDPP activation will be published in the NOP, as it will be a new state of the network, and also broadcasted to all users and stakeholders, via SWIM. NM acts as an arbitrator or supervisor. Although UDPP is a collaborative negotiation process, the allocation result must be finally revised and approved by the NM, to ensure it complies with the safety principles and avoid compromising the proper operation and performance of the network.

The first step is the UDPP activation announcement and TW limits setting, and once the temporal range is defined, the set of users affected F can be determined. When they are informed of the situation, the process of calculating their utilities must be started. Each user will use **their own secret business optimization function** and initialize a

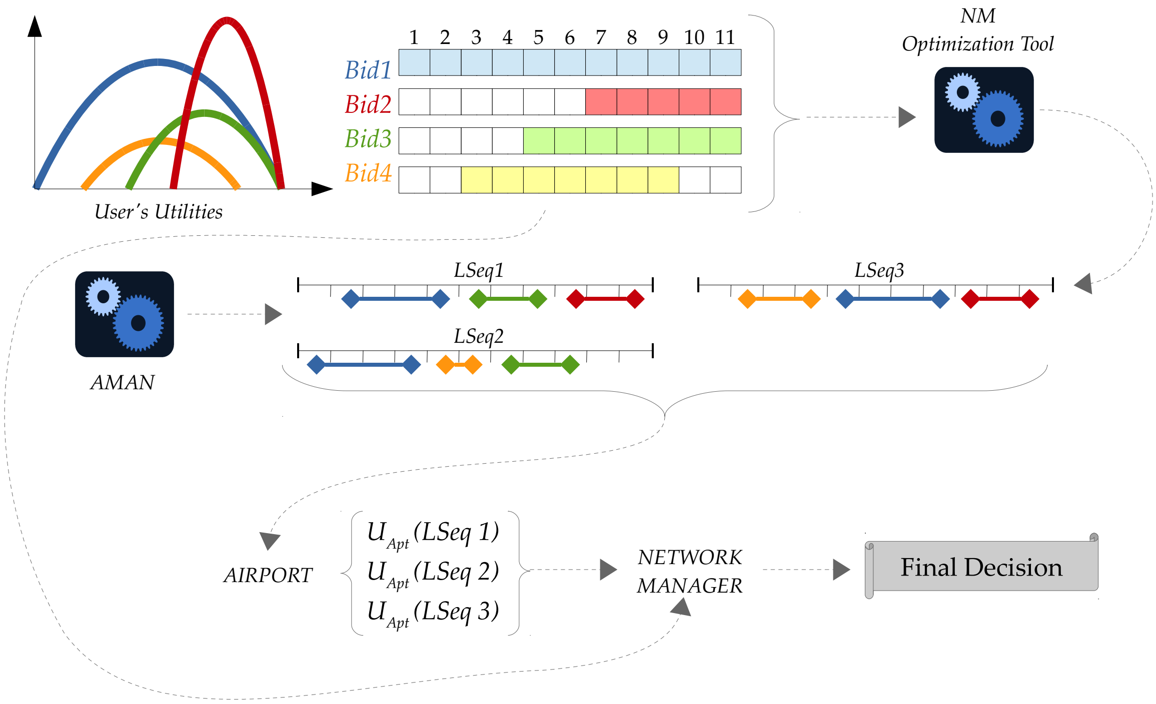

Figure 3.8: Information Flows in the UDPP Process

vector of utilities (Bid_i) with the results of their computations. This vector Bid_i will be submitted to NM and it represents the user's bid for each of the $TVUs$ available, i.e., the amount they are willing to pay for landing at each of these instants.

Alongside, the airport must also begin a computation process. Using its AMAN, it must calculate **a set of landing sequences** which are optimal from the point of view of the airport. These sequences will have to be evaluated and then assigned an airport utility (U_{Apt}), along with another set of sequences that will be provided by the NM, which would be calculated from the preferences expressed by users. The entire set of sequences, along with their associated utilities, will be returned to NM, and represents the bid of the airport.

The NM, once has collected the information from the users and the airport, is able to allocate the resources to users and provide the final landing sequence. To do that, the total utility or welfare associated to each available sequence is calculated, and then, sequences are sorted as a function of its associated utility. Thus, the chosen landing sequence will be the one with a greater social utility. **The final decision will be published in the NOP**.

Figure 3.8 shows a schematic summary of the information flows in the proposed UDPP model. Note how users fill Bid_i vectors from their utility function, creating their bid for each TVU. This information is then submitted to the NM, which creates, a set of landing sequences from the preferences expressed by users. Alongside, the AMAN creates sequences that are optimum from the point of view of the airport. Note that such sequences will determine how many aircraft/slots can be fit in TW, as well as their duration, order and the flight that gets allocated each landing slot. Once all sequences are created, the airport assesses each sequence and associates them an utility. Finally, the NM with utilities from users and the airport chooses the sequence that results in a higher social welfare/total utility.

3.3 Incentive Alignment for Collaborative Behavior of the Market Agents

This model will assign the TVU resources to the users that value them the most, but to be valid, **the valorations and information provided by users and the airport must be real (i.e., they tell the truth)**. There are at least three main forces that preserve an user from deviating from cooperative and collaborative behavior.

- **The goodwill towards CDM.** It is a powerful force to support cooperation and it has been vital in the process of design and development of the new paradigms in ATM. However, in a long term perspective, it is too weak, given the competitiveness within the industry.
- **The Peer Pressure.** Concept described in the Contestability Theory [1]. This theory states that an oligopoly company will never raise its prices too high to attract market entries nor cut its prices too low to provoke price wars in other markets. An user will keep a cooperative behavior to avoid non-cooperative reprisals from competitors.
- **Supervision.** The NM will act as a supervisor or arbitrator on top of the system, so decisions in the negotiation process will be monitored by the NM.

Despite these forces, in the long term the only method to keep users within a collaborative behavior is to **align individual user's interests with the interest of the overall**

system. The fairness policies adopted by the use of Congestion Fees and Compensation Refunds are a key element for guaranteeing collaboration among users and ensuring the disclosure of true information. Socialization of the costs allows the system to always reach an equitable situation, that, with false information, would never be possible, creating surreal utilities and more costs to all users. In chapter 4 an example of how dishonest behaviors and false biddings cause imbalances in the system, and therefore higher costs, is shown.

3.4 Algorithm Complexity During the Calculation of the Feasible Landing Sequences

Assuming a landing sequence as an allocation of time-space resources, to find the optimal solution (i.e., the landing sequence that maximizes the social welfare) or to generate feasible landing sequences, the following model can be used.

Parameters

$F = \{1, ..., f\}$	Set of flights affected by UDPP.
$TW = \{1, ..., t+1\}$	Time Window of UDPP, i.e., the set of available $TVUs$. The last element represents $DivAlt$.
ELT_i , $\forall i \in F$	Earliest Landing Time of flight i.
LLT_i , $\forall i \in F$	Latest Landing Time of flight i.
$LndFee_i$, $\forall i \in F$	Landing Fee charged to flight i.
Sep_{ik} , $\forall i, k \in F$	Time-based minimal separation between flights i and k.
$U_{i \to j}$, $\forall i \in F$, $\forall j \in TW$	The bid placed by user i on TVU j.

Variables

Lnd_{ij} , $\forall i \in F$, $\forall j \in TW$	Binary variable. 1 if flight i lands at TVU j, 0 otherwise.

$$maximize \quad U_s = \sum_{i \in F} \sum_{j \in TW} Lnd_{ij} \cdot U_{i \to j} + \sum_{i \in F} \sum_{j=1}^{t} Lnd_{ij} \cdot LndFee_i \tag{1}$$

subject to:

$$\sum_{j \in TW} Lnd_{ij} = 1 \, , \; \forall i \in F \tag{2}$$

$$\sum_{i \in F} Lnd_{ij} \leq 1 \, , \; \forall j \in \{1, ..., t\} \tag{3}$$

$$\sum_{j=1}^{ELT_i - 1} Lnd_{ij} = 0 \, , \; \forall i \in F \, , \; \forall ELT_i > 1 \tag{4}$$

$$\sum_{j=LLT_i+1}^{t} Lnd_{ij} = 0 \, , \; \forall i \in F \, , \; \forall LLT_i < t \tag{5}$$

$$Lnd_{ij} \cdot Lnd_{kl} \cdot [(l - j) - Sep_{ik}] \geq 0 \, , \; \forall i,k \in F \, , \; \forall i \neq k \, , \; \forall j,l \in \{1, ..., t\} \, , \; \forall l > i \tag{6}$$

The optimization function (1) is a summatory of the utilities associated to their landing slots (or the deviation to an alternative airport) plus the utility of the airport.

Constraint (2) ensures that each user has no more than one TVU allocated (which will be the starting time of the landing slot) and constraint (3) that each TVU is only allocated to maximum one user. Constraints (4) and (5) guarantee that any user gets a TVU allocated outside of its range. Finally, constraint (6) guarantees that the time-based separation between flights is within the minimums.

However, this problem is NP-Hard (which is the main problem attributed to combinatorial auctions) and therefore the number of feasible combinations can rapidly become untreatable. Therefore, **the proposed UDPP model will assume the landing sequences as given.** On the one hand, the airport, by the use of AMAN, will generate landing sequences in which the capacity and the revenues are maximized. On the other hand, the NM will generate landing sequences by exploring the Pareto efficient solutions frontier (i.e., feasible landing sequences in which any user can improve without making worse to others).

Further research is required in order to determine a method to generate feasible landing sequences by the use of heuristics and Pareto efficient solutions frontier exploration.

3.5 Congestion Fees and Compensation Refunds

The sudden loss of capacity in the airport might generate costs to all the airspace users and also to the airport, thus causing a loss of social welfare in relation to the situation previous to the loss of capacity. Let define the social utility of the sequence scheduled before the perturbation occurrence and UDPP activation as U_S^*, and the social utility obtained after negotiation and reallocation of resources as $U_S^{'}$. The social welfare reduction ratio is defined as $\nabla U_s = \frac{U_S'}{U_S^*}$, $\in \{0,1\}$, which gives information about the percentual reduction of social welfare (expressed in parts per unit).

In order to reach an equitable situation, these individual costs and externalities should be socialized and shared equally among all the agents that are affected directly or indirectly by the capacity reduction.

In addition to the price ($LndFee$) charged to users for the landing slot, which is assumed to be previously established and negotiated with the airport, some users will also be charged with a Congestion Fee ($\boldsymbol{CongFee_i}$, $\forall i \in F$), imposed by the NM in order to ensure the efficient allocation of $TVUs$ and to compensate the other airspace users and the airport, that might be affected by negative externalities caused by the consumption of $TVUs$. The NM could be in charge of calculating the Congestion Fees imposed on each of the auction winners. Each of the flights will be charged with different Congestion Fees, as they will be computed taking into account their utility for the allocated slot or the amount they are willing to pay for it.

The revenues obtained by the NM from the Congestion Fees will be used to pay a Compensation Refund ($\boldsymbol{Comp}$) to the users affected by negative externalities, in order to compensate the individual costs derived from the allocation of $TVUs$ to other users, thus **distributing the total social welfare loss in an equitable way**. The idea is that **all the airspace users affected and the airport must assume an individual welfare loss of the same proportion as the social welfare reduction**. For that reason, a virtual utility is calculated, which is expressed as $U_i^E = U_i^* \cdot \nabla U_S$, $\forall i \in F$, and referred as the Equitable Utility for flight i. It represents the utility that the users should obtain after the UDPP protocol to be fair.

Figure 3.9 shows an example of how the Congestion Fees charged to users may compensate other users in order to achieve an equitable reduction in utility.

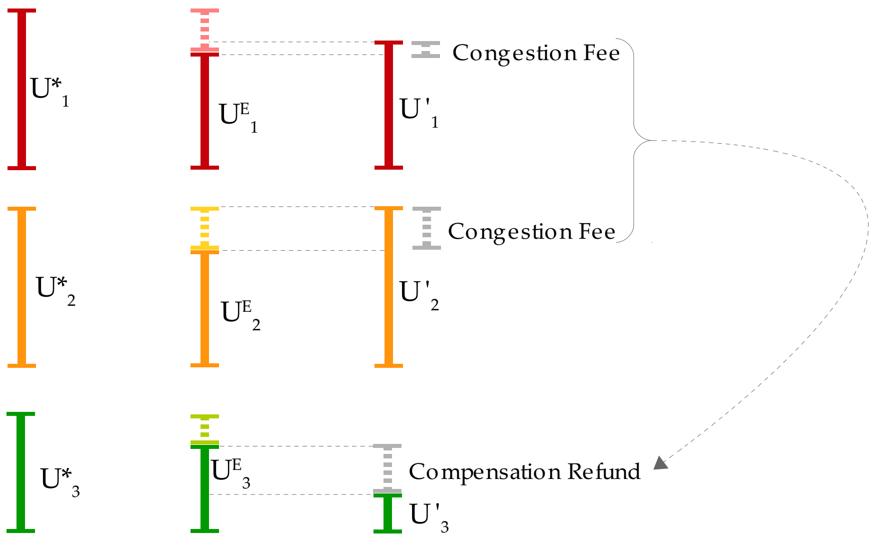

Figure 3.9: Example of Compensations.

3.6 Cash Flows Among Agents in the UDPP Market

In this model, some economic concepts like utility, fees and compensations are addressed. In this work, the utility of an user means the representation of the amount that the user would be willing to pay to get the allocation of a good. A fee is the price that a user pays as a remuneration for services and/or for the right to use a resource. In this model, $LndFee$ (i.e., the fee that a user has to pay in order to get the right to use a runway) and $CongFee$ (i.e., a fee paid in order to guarantee the equitable and efficient allocation of resources) concepts are treated. A refund, like $Comp$, is a restitution, sometimes partial, of a value used to reach a fair equilibrium and to align incentives.

These concepts need to be expressed in currency units. In this model, the unit used will be **Monetary Units (**$m.u.$**)**.

The payment and charge of taxes or refunds generates a flow of $m.u.$ between the agents involved in the UDPP market (NM, Airport, AU). This payments and charges can be cash or credit, within different payment terms. It is out of the scope of the this project to determine the payment methods, being allowed any legal or virtual currency without loss of model validity.

4. CASE STUDIES AND RESULTS

In this chapter, two scenarios are provided, representing two different possible situations, with an exhaustive detail on the steps taken in the algorithm in each case.

4.1 Scenario 1: Normal Market Performance

The proposed scenario consists of 4 flights affected by a capacity fall. The TW is 8 $TVUs$ long.[3]

Suppose that the airport charges the following landing fees to flights:

Flight	1	2	3	4
LndFee	150	100	100	50

Each flight submits the utility values for each TVU after paying the landing fees and also for the option of diverting to an alternative airport:

	$TVUs$								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	$DivAlt$
Flight 1	875	1000	1250	1200	1000	1000	875	800	180
Flight 2	1000	875	750	625	680	750	940	1000	125
Flight 3	905	925	950	960	1000	900	800	625	125
Flight 4	280	300	325	350	375	375	300	280	125

[3]Units are not realistic in this example as they are expressed only for explanatory purpose.

Suppose that the original landing sequence before the capacity reduction was $LSeq* = [(2 \rightarrow 1), (1 \rightarrow 3), (4 \rightarrow 4), (3 \rightarrow 6)]$. According to the values given by the airspace users, the social welfare or utility can be calculated as:

$$U_S^* = U_{2\rightarrow 1} + U_{1\rightarrow 3} + U_{4\rightarrow 4} + U_{3\rightarrow 6} + U_{Apt}(LSeq*)$$
$$U_S^* = 1000 + 1250 + 350 + 900 + (150 + 100 + 100 + 50) = 3900\, m.u.$$

Next, an exploration on different combination of landing sequences has to be done, i order to find the new optimal. Suppose that AMAN of the airport suggests landing sequences $LSeq1$, $LSeq2$, and $LSeq3$, which are optimal from the point of view of the airport. Also, NM suggests $LSeq4$, which has been calculated from the preferences expressed by users. The landing sequences are:

$$LSeq1 = [(4 \rightarrow 1), (2 \rightarrow 3), (1 \rightarrow 6)]$$
$$LSeq2 = [(1 \rightarrow 1), (3 \rightarrow 5), (4 \rightarrow 8)]$$
$$LSeq3 = [(3 \rightarrow 1), (4 \rightarrow 5), (2 \rightarrow 7)]$$
$$LSeq4 = [(1 \rightarrow 3), (2 \rightarrow 8)]$$

The utility that the airport perceives from this sequences are:

$$U_{Apt}(LSeq1) = LndFee_4 + LndFee_2 + LndFee_1 = 50 + 100 + 150 = 300\, m.u.$$
$$U_{Apt}(LSeq2) = LndFee_1 + LndFee_3 + LndFee_4 = 150 + 100 + 50 = 300\, m.u.$$
$$U_{Apt}(LSeq3) = LndFee_3 + LndFee_4 + LndFee_2 = 100 + 50 + 100 = 250\, m.u.$$
$$U_{Apt}(LSeq4) = LndFee_1 + LndFee_2 = 150 + 100 = 250\, m.u.$$

Once all information is collected, the social utility corresponding to each sequence can be calculated:

$$U_S^{LSeq1} = U_{4\rightarrow 1} + U_{2\rightarrow 3} + U_{1\rightarrow 6} + U_{3\rightarrow DivAlt} + U_{Apt}(LSeq1)$$
$$U_S^{LSeq1} = 280 + 750 + 1000 + 125 + 300 = 2455\, m.u.$$

$$U_S^{LSeq2} = U_{1\rightarrow 1} + U_{3\rightarrow 5} + U_{4\rightarrow 8} + U_{2\rightarrow DivAlt} + U_{Apt}(LSeq2)$$
$$U_S^{LSeq2} = 875 + 1000 + 280 + 125 + 3500 = 2580\, m.u.$$

$$U_S^{LSeq3} = U_{3\rightarrow 1} + U_{4\rightarrow 5} + U_{2\rightarrow 7} + U_{1\rightarrow DivAlt} + U_{Apt}(LSeq3)$$
$$U_S^{LSeq3} = 905 + 375 + 940 + 180 + 250 = 2650\, m.u.$$

$$U_S^{LSeq4} = U_{1\rightarrow 3} + U_{2\rightarrow 8} + U_{3\rightarrow DivAlt} + U_{4\rightarrow DivAlt} + U_{Apt}(LSeq4)$$
$$U_S^{LSeq4} = 1250 + 1000 + 125 + 125 + 250 = 2750\, m.u.$$

The maximum social utility is given by $LSeq4$, so it is going to be the sequence implemented. However, some users have a higher individual cost, so compensations have to be calculated to socialize this costs.

$$U_S' = U_S^{LSeq4}$$
$$\nabla U_S = \frac{U_S'}{U_S^*} = \frac{2750}{3900} = 0,7$$

All users and the airport should assume an individual welfare loss of the same proportion as the social welfare reduction. The utility that users and airport should obtain after UDPP protocol to be fair (Equitable Utility) is:

$$U_1^E = U_1^* \cdot \nabla U_S = 1250 \cdot 0,7 = 875\, m.u.$$
$$U_2^E = U_2^* \cdot \nabla U_S = 1000 \cdot 0,7 = 700\, m.u.$$
$$U_3^E = U_3^* \cdot \nabla U_S = 900 \cdot 0,7 = 630\, m.u.$$
$$U_4^E = U_4^* \cdot \nabla U_S = 350 \cdot 0,7 = 245\, m.u.$$
$$U_{Apt}^E = U_{Apt}^* \cdot \nabla U_S = 400 \cdot 0,7 = 280\, m.u.$$

Finally, balancing Equitable with current utilities, the Congestion Fees are calculated:

$$CongFee_1 = U_1' - U_1^E = 1250 - 875 = 375\, m.u.$$
$$CongFee_2 = U_2' - U_2^E = 1000 - 700 = 300\, m.u.$$
$$CongFee_3 = U_3' - U_3^E = 125 - 630 = -505\, m.u.$$
$$CongFee_4 = U_4' - U_4^E = 125 - 245 = -120\, m.u.$$
$$CongFee_{Apt} = U_{Apt}' - U_{Apt}^E = 250 - 280 = -30\, m.u.$$

Note that users 1 and 2 have a positive $CongFee$. That means that their current utility is higher than it should be for the UDPP protocol to be fair. Then, they will pay this amount in order to compensate users with individual costs (externalities). Users 3 and 4 and the airport have a negative $CongFee$. That means that their current utility is lower than it should be for UDPP protocol to be fair, so user they will receive a compensation from the other users. Note that $CongFee = -Comp$.

4.2 Scenario 2: One User Places False Bids

This scenario is the same than the previous example, but consider that user 4 cheats in the biding process in order to avoid the implementation of $LSeq4$ (in which the user 4 is forced to divert to an alternative airport) and lead the system to the implementation of *LSeq*3, which is a scenario that reports higher utility to user 4, i.e., 375.

First, user 4 cheats in the bidding of diverting to an alternative airport:

$$U_{4\to DivAlt}^{False} = 50\, m.u. < U_{4\to DivAlt}^{*} = 125\, m.u.$$

The consequence of this is that the social welfare or utility calculated by the NM for *LSeq*4, is lower than the real one:

$$U_S^{False\ LSeq4} = 2675 < U_S^{True\ LSeq4} = 2750\, m.u.$$

Second, user 4 also places false bids in the valuation of the $TVUs$, giving higher values:

$$U_{4\to 5}^{False} = 440 > U_{4\to 5}^{*} = 375$$

The consequence of this higher valuation is that the social welfare or utility calculated by the NM for *LSeq*3, is higher than the real one:

$$U_S^{False\ LSeq3} = 2715 > U_S^{True\ LSeq3} = 2650$$

Since $U_S^{False\ LSeq3} > U_S^{False\ LSeq4}$, the NM takes the *LSeq*3 as the better option to maximize the social welfare or utility.

$$\nabla U_S^{False} = \frac{U_S^{\prime\, False}}{U_S^{*}} = \frac{2715}{3990} = 0,68$$

Now, the equitable utilities are calculated:

$$\begin{aligned}
U_1^{E\ False} &= U_1^{*} \cdot \nabla U_S^{False} = 1250 \cdot 0,68 = 850\, m.u. \\
U_2^{E\ False} &= U_2^{*} \cdot \nabla U_S^{False} = 1000 \cdot 0,68 = 680\, m.u \\
U_3^{E\ False} &= U_3^{*} \cdot \nabla U_S^{False} = 900 \cdot 0,68 = 612\, m.u \\
U_4^{E\ False} &= U_4^{*} \cdot \nabla U_S^{False} = 440 \cdot 0,68 = 299\, m.u \\
U_{Apt}^{E\ False} &= U_{Apt}^{*} \cdot \nabla U_S^{False} = 400 \cdot 0,68 = 272\, m.u
\end{aligned}$$

Finally, the Congestion Fees are calculated:

$$
\begin{aligned}
CongFee_1^{False} &= U_1'^{\,False} - U_1^{E\,False} = 180 - 850 = -670\,m.u\\
CongFee_2^{False} &= U_2'^{\,False} - U_2^{E\,False} = 940 - 680 = 260\,m.u\\
CongFee_3^{False} &= U_3'^{\,False} - U_3^{E\,False} = 905 - 612 = 293\,m.u\\
CongFee_4^{False} &= U_4'^{\,False} - U_4^{E\,False} = 440 - 299 = 141\,m.u\\
CongFee_{Apt}^{False} &= U_{Apt}'^{\,False} - U_{Apt}^{E\,False} = 250 - 272 = -22\,m.u
\end{aligned}
$$

Note that after the compensation, user 4 obtains a real utility of:

$$U_4^{Real} = 375 - 141 = 234$$

In this case, user 4 obtains a loss. In scenarios in which some agents do not tell the truth, real utility will also be lower than the normal performance (true bids) and also lower to the Equitable Utility.

5. CONCLUSIONS

This work has presented a **model based in combinatorial auctions for Demand and Capacity Balancing through the UDPP protocol**, where users and airports can bid for the available resources, which are allocated to those **users who value them the most**, achieving the **maximum social welfare** and an equitable distribution of negative externalities produced by the resource allocation.

As seen in the case studies, the algorithm achieves an optimum allocation, within the existing constraints (i.e., the time-based separation minimums between aircraft and the autonomy range of flights), if users provide real valorations. The compensation system can be used to socialize the costs, thus guarenteeing an equitable allocation, but also acts as a force to align user's incentive to act in a collaborative way and to always reveal their true willingness to pay for the achievement of the resource allocation with higher social utility. More research is needed to better understand the forces that affect the behavior of market agents.

Also, an integer programming model is provided, which allows creating feasible landing sequences, however, it is an NP-Hard problem, which indeed is a common shortage of combinatorial auctions. Therefore, to solve this problem, landing sequences are considered in the model as given by AMAN and the NM. More research has to be done in order to analyze different ways of how the NM can explore the Pareto efficient solutions frontier to generate landing sequences.

Bibliography

[1] E. Bailey and J. Panzar. The contestability of airline markets during the transition to deregulation. *Law and Contemporary Problems*, (44):809–822, 1981.

[2] M. Ball, G. L. Donohue, and K. Hoffman. "Auctions for the Safe, Efficient and Equitable Allocation of Airspace System Resources". *Combinatorial Auctions, MIT Press Ed.*, 2006.

[3] N. Barr. *"3.2.2 The relevance of efficiency to different theories of society, in Economics of the Welfare State"*. Oxford University Press, 2012.

[4] M. D. Bayles. *"Contemporary Utilitarianism"*. Anchor Books, 1968.

[5] R. H. Coase. "The Problem of Social Cost". *The Journal of Law and Economics.*, 1960.

[6] ComplexWorld Wiki. "Uncertainty in ATM". `http://complexworld.eu/wiki/Uncertainty_in_ATM`.

[7] EUROCONTROL. "SESAR Concept of Operations Step 1", May 2012.

[8] EUROCONTROL. "SWIM Concept of Operations.", June 2012.

[9] EUROCONTROL. "SESAR Concept of Operations Step 2", April 2013.

[10] EUROCONTROL. "EUROCONTROL Seven-Year Forecast", February 2014.

[11] EUROCONTROL Lexicon. "UDPP". `www.eurocontrol.int/lexicon/lexicon/en/index.php/UDPP`.

[12] John Stuart Mill. *"Utilitarianism"*. Oxford University Press, 1998.

[13] D. R. Polsby. "Airport Pricing of Aircraft Takeoff and Landing Slots: An Economic Critique of Federal Regulatory Policy". *California Law Review*, 2001.

[14] A. Ranieri and L. Castelli. "A Market Mechanism to Assign Air Traffic Flow Management Slots.". In *Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM 2009)*.

[15] S. J. Rassenti, V. L. Smith, and R. L. Bulfin. "A Combinatorial Auction Mechanism for Airport Time Slot Allocation". *The Bell Journal of Economics*, 13, 1982.

[16] S. Ruiz. *"Strategic Trajectory De-Confliction to Enable Seamless Aircraft Conflict Management."*. PhD thesis, Universitat Autònoma de Barcelona, 2013. (director M. A. Piera).

[17] SESAR Consortium. "European ATM Master Plan Edition 2", October 2012.

[18] Hal R. Varian. *"Intermediate Microeconomics: A Modern Approach."*. W. W. Norton & Company, 2009.

Nomenclature

A-CDM	Airport CDM
AMAN	Arrival Manager
ANSP	Air Navigation Service Providers
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
AU	Airspace User
BDT	Business Development Trajectory
BT	Business Trajectory
CD&R	Conflict Detection and Resolution
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CTA	Controlled Time of Arrival
CTO	Controlled Time Over
DCB	Demand and Capacity Balancing
DMAN	Departure Manager
EC	European Comission
ETA	Estimated Time of Arrival

FAB	Functional Airspace Block
FMS	Flight Management System
FPFS	First Planned, First Served
FPL	Flight Plan
KPA	Key Performance Areas
NM	Network Manager
NOP	Network Operations Plan
RBT	Reference Business Trajectory
SBT	Shared Business Trajectory
SES	Single European Sky
SESAR	Single European Sky ATM Research
SMAN	Surface Manager
SWIM	System Wide Information Management
TMR	Trajectory Management Requirements
TTA	Target Time of Arrival
UDPP	User Driven Priorisation Process