2

Implications for Decision Making

D7.2

OptiFrame

Grant:	**699275**
Call:	**SESAR 2020 Exploratory Research: First Call for Research Projects**
Topic:	**Trajectory Based Operations (ER-09-2015)**
Consortium coordinator:	**Lancaster University**
Edition date:	**28 February 2018**
Edition:	**[00.00.02]**

Authoring & Approval

Authors of the document

Name/Beneficiary	Position/Title	Date
G. Murgese		28/02/2018
K. G. Zografos		25/02/2018
G. Lulli		27/02/2018

Reviewers internal to the project

Name/Beneficiary	Position/Title	Date

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

Name/Beneficiary	Position/Title	Date
K.G. Zografos (ULANC)		28/02/2018
L. De Giovanni (CFR)		28/02/2018
G. Murgese (EUROCONTROL)		28/02/2018
R. Verbeeck (NLR)		28/02/2018

Rejected By - Representatives of beneficiaries involved in the project

Name/Beneficiary	Position/Title	Date

Document History

Edition	Date	Status	Author	Justification
00.00.01	19/02/2018	Interim draft report	G. Lulli K.G Zografos	Interim version for the Closing Meeting
00.00.02	28/02/2018	Final version submitted	G. Lulli, K.G Zografos G. Murgese	

OptiFrame

AN OPTIMIZATION FRAMEWORK FOR TRAJECTORY BASED OPERATIONS

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 699275 under European Union's Horizon 2020 research and innovation programme.

Abstract

This document aims at summarizing the work conducted in WP7 of the project OptiFrame "Implications for Decision Makers and Dissemination of results". In particular, the objective of this document is to present the results of Task 7.3 - Implications for Decision Makers - and to report the findings and the feedback received during the completion of Task 7.4 – Organization of the Final Workshop –.

In terms of results, we show the capabilities of OptiFrame to provide information at three different levels of aggregation, i.e., network, individual airline, and individual flight. This enriched information allows to analyse the trade-off among the objectives of all stakeholders and without excluding a priori any efficient solution. These results were presented at a workshop to relevant stakeholders in order to receive feedback regarding the capability of the OptiFrame approach to address decision making issues associated with the generation of 4D trajectories within the context of Trajectory Based Operations (TBO). A number of suggestions and possible improvements were provided by the workshop participants, but more important the potential input of OptiFrame to SESAR IR Project PJ07 and PJ09 was identified:

- Initial assessment tool for newly defined preferences and UDPP prioritisation methods in order to reduce the impact of network constraints and DCB measures.
- What-if functionalities tool to allow AUs to analyse the performance impact of their planning activities and support network collaborative processes.
- Initial assessment tool for showing the benefits of the Multiple Constraint Reconciliation concept (impact of conflicting measures on the network performance).

Table of Contents

List of Figures

List of acronyms

4DT	Four Dimensional Trajectory
ACC	Area Control Centre
AFISO	Aerodrome Flight Information Service Officer
A-ICWP	Advanced Integrated Controller Working Position
AMAN	Arrival Management
AMC	Airspace Military Cell
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider
AOC	Airline Operations Control Centre
AOP	Airport Operations Plan
APO	Airport Operations
APOC	Airport Operations Centre
ASBU	Aviation System Block Upgrade
ASP	ATM Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Control Organisation
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Service
AU	Airspace Users
BPBS	Best Performing Best Served
BTV	Brake to Vacate
CASA	Computer Assisted Slot Allocation
CCS	Capacity Constrained Situation

CDA	Continuous Descent Approach
CDM	Collaborative Decision Making
CFR	Consorzio Futuro in Ricerca (Consortium Future in Research)
CNS	Communication, Navigation & Surveillance
DCB	Demand Capacity Balancing
DMAN	Departure Management
FAB	Functional Airspace Block
FIR	Flight Information Region
FCFS	First Come First Served
FIXM	Flight Information eXchange Model
FOC	Flight Operations Centre
FPL	Flight Plan
GATMOC	Global Air Traffic Management Operational Concept
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
HSPT	Hotspot
ICAO	International Civil Aviation organization
KPA	Key Performance Areas
LAQ	Local Air Quality
LVP	Low-Visibility Procedures
NAS	National Airspace
NLR	NationaalLuchtenRuimtevaartlaboratorium (Netherlands Aerospace Centre)
NM	(European) Network Manager
NMOC	Network Manager Operations Centre
NOP	Network Operations Plan
PBS	Priority By Schedule
RBT	Reference Business Trajectory
R&D	Research & Development
RMT	Reference Mission Trajectory
RNAV	Radio Navigation
RNP	Required Navigation Performance
SB/MT	Shared Business/Mission Trajectories
SBT	Shared Business Trajectory

SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
STA	Scheduled Time of Arrival
STAR	Standard Instrument Arrival
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
UDPP	User Driven Prioritisation Processes
UPR	User Preferred Routing
WOC	Wing Operations Centre

Introduction

1.1 OptiFrame project

The OptiFrame project is part of the exploratory research in the SESAR Joint Undertaking, which has received funding under grant agreement No 699275 under European Union's Horizon 2020 research and innovation programme.

The main objective of the research project is the application of principles of mathematical modelling and optimization to optimally configure and assess the performance of the Trajectory Based Operations (TBO) concept. The core activity and focus of this research project is the development of a framework, consisting of mathematical models and optimization algorithms for pre-tactical operations (planning phase).

The OptiFrame project is organized in the following work packages (WPs):

- WP1 Project Management;
- WP2 State-of-the-art and Stakeholder Expectations;
- WP3 Data Management;
- WP4 Modelling of TBO;
- WP5 Development and Implementation of Solution Algorithms (exact and heuristic);
- WP6 Validation of the OptiFrame approach in normal and disturbance cases;
- WP7 Implications for Decision Makers and Dissemination of results;
- WP8 Ethics.

1.2 Scope of Document

The document is aimed at summarizing the work conducted in WP7 "Implications for Decision Makers and Dissemination of results". The work in WP7 has been structured in four different tasks:

- Task 7.1: Setting up of the project website
- Task 7.2: Dissemination of results
- Task 7.3: Implications for Decision Makers
- Task 7.4: Organization of a Workshop

The objective of this document is to present the results of Task 7.3 and to report the findings and the feedback received during the completion of Task 7.4.

In this deliverable, we summarize the findings of the Project and provide answers or suggestions to some of the open questions about the TBO concept. We also report what has emerged during the Workshop held in Brussels, at EUROCONTOL Headquarters, on the 14th of February 2018.

1.3 Structure of the document

This document is organized as follows. The first chapter summarizes the OptiFrame approach to the solution of the ATFM problem, in particular it shows how the individual steps of the modelling and solving processes are interlocked and gives a high-level idea of the details of each step, together with the relevant references to more detailed documents. Chapter 2, "The nature of OptiFrame solutions", explains the results obtained from the OptiFrame framework and their meaning. In particular, we show how the choice of a multi-objective approach is able to provide the Decision Maker with extensive information that are not provided by a single-objective optimization model. Analysis of the results is made at three different levels: at the overall system level, at the AUs level and at the single flight level. Chapter 3 shows preliminary results on the impact that the incorporation of AU priority schemes has on the system performance. Chapter 4 presents the implications for the Decision Maker and Chapter 5 summarizes the recommendations for future research.

1 The OptiFrame approach

1.1 The TBO concept

As a response to the dramatic growth in air travel witnessed in the last two decades, the European Commission adopted the Single European Sky (SES) framework as a **legislative framework for European aviation.** While the ATM system migrates towards this concept vision, some significant changes have been identified as described in the Global ATM Operational Concept [4]. One such change, TBO is described as follows [4]: "*Air traffic management (ATM) considers the trajectory of a manned or unmanned vehicle during all phases of flight and manages the interaction of that trajectory with other trajectories or hazards to achieve the optimum system outcome, with minimal deviation from the user-requested flight trajectory, whenever possible.*"

TBO represents a shift from present operations towards the use of a shared trajectory, collaboratively developed as the basis for decision-making across the ATM System Participants. Thus, TBO provides an opportunity to shift operations towards greater predictability with flight-impacting decisions being coordinated across concept components. The main differences with today's operations involve:

1. **Sharing** of trajectory information eventually leading to a common view of the trajectory.
2. **Managing** trajectory information using Collaborative Decision Making (CDM).
3. The trajectory that is shared and managed, the Agreed Trajectory, is used as **reference for the flight** by providing a common intent to be achieved during the execution of the flight.

The TBO concept is expected to benefit the ATM system in many aspects through its impact on a number of Key Performance Areas (KPAs), such as cost-effectiveness, predictability, fuel consumption, etc. Moreover, the management of trajectory and the exchange of information between AUs and the ATM system will improve conflict management and facilitate the use of preferred trajectories for each flight. Therefore, it is important to further explore how the TBO concept can be further developed and applied as part of the European ATM masterplan. In response to this need the OptiFrame project was set-off to develop mathematical models and solution algorithms in order to investigate how 4D trajectories can be developed within the framework of the TBO concept.

1.2 The OptiFrame Approach

In order to ensure that the OptiFrame mathematical model is aligned with the requirements of the TBO concept, as well as with the expectations of the ATM stakeholders, we developed an integrated methodological approach depicted in Figure 1. The first step in this approach was the development of the stakeholders' requirements. As part of the development of the requirements, we conducted a thorough literature review, wherein we reviewed documents related to the description of the TBO concept and its implementation steps. In addition, we reviewed the scientific literature related to mathematical models and algorithms addressing planning up to pre-tactical ATFM decisions as well as mathematical models and algorithmic developments from other industries, such as telecommunications and energy market, which face similar types of problems. The major findings of the literature review can be found in Deliverable D7 [2]. These findings provided the required input for identifying a preliminary set of objectives and constraints that can be potentially included in the OptiFrame mathematical model. The identified objectives, and constraints were further discussed and refined at the first OptiFrame workshop.

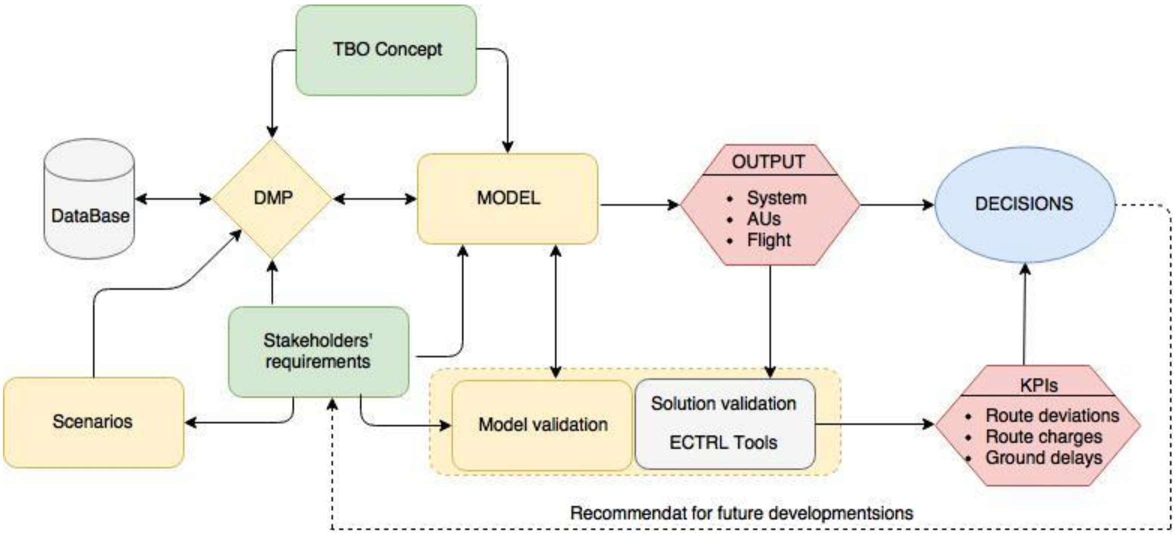


Figure 1: The OptiFrame approach

The scope of this workshop was to elicit the views of the ATM stakeholders about:

i) their preferences and priorities regarding the optimization of 4D flight trajectories within the TBO concept;
ii) the Key Performance Areas (KPAs) and Key Performance Indicators (KPIs) for assessing the performance of the OptiFrame model, and
iii) the scenarios that should be used in order to validate the OptiFrame model.

The findings of the literature review were also presented to the stakeholders to obtain their views on the relevant objectives functions and constraints that can be added to or removed from the modelling considerations. The outcome of this consultation enabled us to develop the OptiFrame mathematical model. It also provided guidance as to how the preferences and priorities of the Airspace Users (AUs) could be integrated in the optimization model. The findings of this consultation process are summarized in D7 [2].

Another essential element of the OptiFrame approach is the representation of the ATM network instances, which should be used for the operationalization of the proposed mathematical model, and for the development of the model validation scenarios. A Data Management Platform (DMP) was developed in order to extract the relevant data from DDR and to properly represent the resulting network in order to be used by the mathematical model. Details regarding the development of the DMP can be found in D8 [12]. Based on the identified scenarios and the network data input the OptiFrame model was validated. The outputs of the OptiFrame mathematical models were used as inputs to the following Eurocontrol Tools (NEST, BADA, RSO) in order to assess the performance of the OptiFrame outputs in terms of the identified Key Performance Indicators. The validation process results and recommendations are summarized in D14 [13]. The validated OptiFrame model was used to analyse the nominal and disturbance scenarios in order to demonstrate its capabilities for supporting 4D trajectory decisions within the framework of the OptiFrame concept. The results of the validation along with the analysis of the implications of the OptiFrame approach for decision making were presented in the second OptiFrame workshop in order to receive feedback from the ATM stakeholders and identify directions for future research. In what follows we provide a brief description of the key elements of the OptiFrame approach. Stakeholders' requirements

With the deployment of the TBO concept, AUs expect to be given more flexibility to better manage their own flights and meet their internal business models. Indeed, the network manager sees every flight as equal, while for the airlines each flight is unique. Since even a small change to some flights may have a bigger economic impact for the airlines. Therefore, AUs expect their preferences and priorities to be taken into consideration in the decision-making process.

a) Preferences

The notion of preference is yet to have a common consensus among the ATM stakeholders. However, the consultation with the European ATM stakeholders [3] suggested that preferences expressed during the planning phase can refer to any mechanism to absorb delays at the tactical level of ATM. This means that AUs could express their preferences in relation to the deviation from the users' preferred 4D-trajectories in terms of delay, flight altitude and lateral deviation (re-routing). In order to accommodate these preferences, the OptiFrame mathematical model will consider three objective functions to be optimized.

b) Priorities

In Deliverable D9 [5], we discussed two prioritisation mechanisms as proposed by the SESAR 2020 Industrial Research activity UDPP in PJ07-02 [4], namely:

i) the Fleet Delay Apportionment (FDA), where AUs assign priority values to their flights and the system apportions delays to flights proportionally to these priority values; and

ii) the Selective Flight Protection (SFP), where an AU can take action if more than one of their flights is affected by a capacity constrained situation by 'suspending' some flights to 'protect' the other(s) from being delayed.

This SESAR 2020 Industrial Research activity [1, 7, 9] has since then evolved to replace the FDA mechanism with the Fleet Delay Re-ordering mechanism (FDR) [8]. It has also proposed a third prioritisation mechanism called Margins of Manoeuvres. The OptiFrame mathematical model has the capability to incorporate all the three prioritization mechanisms i.e. FDR, SFP and Margins of Manoeuvres.

1.3 Database

The data used for testing the OptiFrame model and solution algorithms were extracted from the DDR2 [10, 11] data repository and represent trajectories that were flown. In WP3 of the OptiFrame project, a Data Management Platform (DMP) was developed in order to extract the information needed. The full description of this platform is given in the deliverable D8 [12]. Part of the data needed for testing the model was not available from the database. These missing data have been generated taking into account factors that could possibly have an impact on them. The test instances consider the flights flown on October 3rd 2016 between four major European airports, namely London Heathrow (EGLL), Frankfurt (EDDF), Paris Charles De Gaulle (LFPG) and Amsterdam Schiphol (EHAM). All the details of the data sample are described in Deliverable D11 [13].

1.4 The OptiFrame mathematical model

The OptiFrame mathematical model is a 4D-trajectory based model which aims at optimising the efficiency of the ATM system under the TBO concept by assigning 4D-trajectories to flights based on the AUs' preferences and priorities, and the constraints of the ATM system. Particular to this model is that, not only it considers the 4D-trajectories of aircraft, but it also incorporates the preferences and priorities of the ATM stakeholders. Hence, the proposed trajectories align with the requirements of the TBO general concept. Furthermore, the mathematical model is formulated as a multi-objective optimization problem, which is able to identify the existing trade-offs between the needs and objectives (preferences) of the ATM stakeholders. Therefore, it has the potential of facilitating the negotiation and acceptability of trajectories between the stakeholders. Indeed, the model considers the preferred 4D-trajectory of all the flights in the planning phase and outputs the set of all the non-dominated optimal solutions that can be implemented by the network manager. A solution is called non-dominated or efficient if there is no any other solution outperforming it in terms of all objectives, i.e., minimization of delay, minimization of the deviation from the preferred trajectory, and minimization of the route charges. Each of these non-dominated (efficient) solutions consists of pre-departure 4D-trajectories to be shared or negotiated with other stakeholders and subsequently managed throughout the flight. We consider the following three objectives for minimization:

i) Minimization of the total time deviation (delay) from the AUs' preferred trajectories. For each flight, the delay considered is the difference between the actual departure time of the flight and its scheduled time of departure (STD) i.e. the delay at departure.

ii) Minimization of the cost of deviation from the users preferred 3D-routes (lateral and vertical deviation). This correlates to the cost of fuel burnt when a flight uses a particular 3D-route.

iii) Minimization of the airspace navigation service (ANS) charges. These costs are incurred when a flight travels through the charging zones defined by the states in the ECAC area.

1.5 Model validation and disturbance scenarios

The objective of the validation phase (WP6 of the OptiFrame project) is to ensure that the proposed mathematical model is aligned with the requirements of the TBO concept and the expectations of the stakeholders and that the proposed solution methods can cope with the computational requirements of the problem and that the generated trajectories are aligned with trajectories generated by other tools, e.g., NEST. The OptiFrame validation involved qualitative and quantitative approaches, and the OptiFrame model was validated under nominal and disturbance scenarios.

The qualitative validation of the OptiFrame model under nominal and disturbance scenarios demonstrated that the OptiFrame model is:

a) compliant (generated solutions comply with all applicable constraints of the ATM system) and performant (able to generate solutions within a reasonable computation time);

b) able to consider the balance between the interests of the airspace users (e.g. flexibility) and those of the network manager (e.g. predictability, trajectory conformance);

c) able to cope not only with current-day traffic but also with predicted future traffic (scalability);

d) resilient to the above-mentioned disturbances, able to incorporate stakeholders' preferences and priorities.

The quantitative assessment is done on the basis of an analysis using the EUROCONTROL NEST tool (Network Strategy Tool), Base of Aircraft Data (BADA) 4 aircraft performance model, and the EUROCONTROL Route per State Overflown (RSO) distance tool. The quantitative assessment is limited to the 'exact' implementation of the OptiFrame framework. The 'heuristic' OptiFrame algorithm is only analysed in respect to its scalability. However, in deliverable D5.2 (aka D11) there is evidence of the capability of the heuristic algorithm to solve instances of the OptiFrame with a good level of accuracy. Indeed, the efficient solutions computed by the heuristic algorithms are not "too far" from those computed by the exact method.

The OptiFrame model incorporates the objectives, priorities, and preferences of the ATM stakeholders, along with operational and system constraints in order to generate 4D trajectories. The main conclusions and findings are that OptiFrame is able to adhere to the capacity of sectors and airports using both departure delays and track alterations. The OptiFrame models generate solutions that give the stakeholders the freedom to change the focus from departure delay to trajectory deviation in a gradual way. Depending on the disturbances found within the network the focus can be shifted.

There are also some lessons learned regarding the OptiFrame approach. It was found that in the exact solutions of the OptiFrame model considerable amounts of flight level changes were applied to come to a feasible result. In a practical setting this amount of vertical changes is neither probable nor desirable. This behaviour can – maybe - be attributed to the parameters of the cost coefficients that were used in running the OptiFrame model. These coefficients express the relative emphasis placed on vertical and lateral deviations. Further calibration of these coefficients should be considered to improve the found behaviour. Furthermore, it should be considered that sector capacity is linked to the assumption that flights will plan for usage of the strategically separated routes within a sector. It is therefore recommended that the trajectory deviations proposed in the solutions by the OptiFrame model should comply with these strategically separated route structures.

The heuristic implementation is scalable to larger problem sizes within a limited computational time frame, although a full ECAC-wide scenario has not been tested yet. The largest scenario tested within the project contained 2000 flights between 10 airports and generated solutions within a reasonable calculation time. As expected was the 'exact' OptiFrame model not scalable to practical problem sizes.

The current implementation of the OptiFrame model considers the minimization of the departure delay as one of the objective functions upon recommendation from the first stakeholder workshop. An alternative approach is to consider the minimisation of the arrival delay as an objective function. This could result in a reduction of the variability of the arrival punctuality.

For the test instances under consideration, it was observed that the optimization of the route charges objective did not lead to a significant reduction of the resulting route charges. This behaviour may be due to the structure of the airspace analysed where there was a limited number of different charging zones involved. The effect of the optimization of the route charges objective can be better demonstrated by using scenarios with larger airspaces and more variation in terms of charging zones along the routes.

It is worth noting that the results of the OptiFrame validation were presented to the ATM stakeholders at the second OptiFrame workshop and the feedback received at the workshop has been incorporated in the last section of this deliverable.

2 The nature of OptiFrame solutions

The OptiFrame model has been formulated as a multi-objective mathematical program. We are hence considering three different objective functions to be simultaneously minimized, in line with the goal of giving to the Stakeholders the possibility of choosing the solution to be implemented from a pool of all the possible solutions. In fact, once the objectives of delay, flight efficiency and route charges have been identified, we could use two different approaches to solve the ATFM problem: we could either assign a weight to each objective according to a pre-decided level of importance and combine them in a single objective function, or we could consider all three objectives in three different functions. The first option leads to a single optimal solution in which the weighted sum of the objectives is minimized, while the second option returns a set of optimal solutions, in which the trade-off between the single objectives are highlighted. See Figure 2, where each blue circle represents an optimal solution.

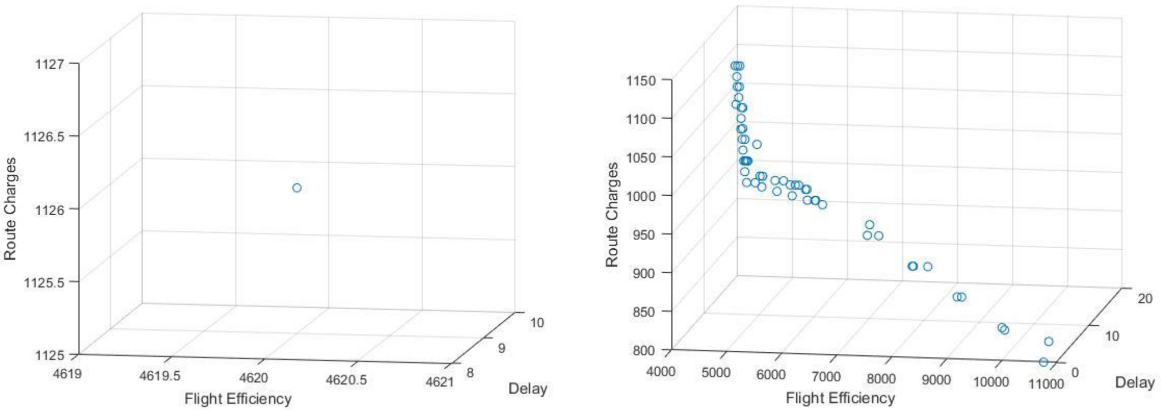


Figure 2 Single objective function vs three-objective functions optimization

The OptiFrame approach follows this second option, so that Stakeholders acquire a better understanding on what are the advantages and drawbacks of giving more importance to one objective function instead of another, before making the actual decision. The solutions that belong to the final set are the *non-dominated solutions*, which are those solutions that are not outperformed by any other solution in terms of all the objectives.

Each solution represented by a blue circle in Figure 2 identifies the values achieved by each single objective value at an aggregate level. In fact, analysis on the full set of solutions only gives an idea of the system's behaviour. Deeper analysis can be performed at the AUs level, in order to assess what is the impact of implementing a particular solution from each airline point of view. Still more in details, analysis can be performed to see the impact of different solutions on a single flight (see Figure 3).

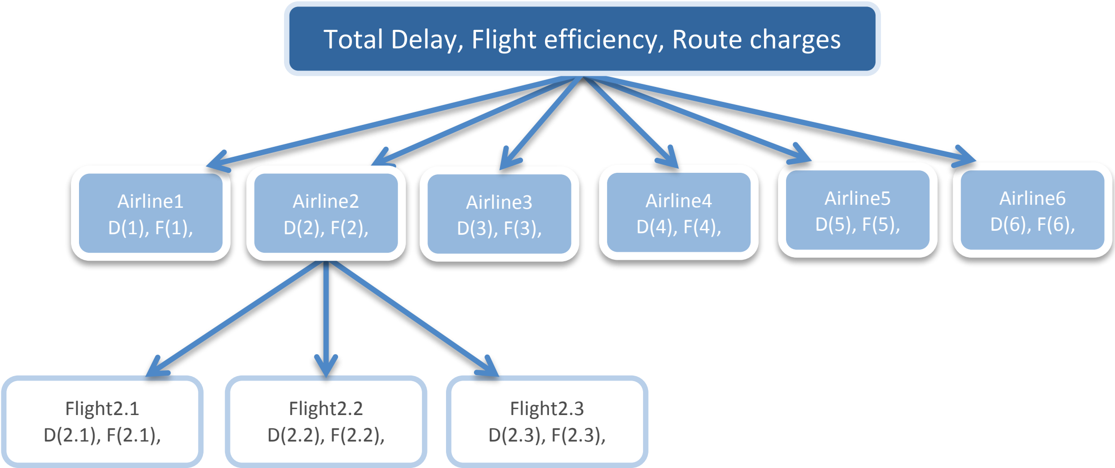


Figure 4: OptiFrame provides results at three different levels of aggregation Network, Individual Airline, Individual Trajectory)

In this Section we present an analysis at these different stages of the solutions obtained from applying the OptiFrame approach to a real data instance. In particular, the instance considered involves all flights between Frankfurt and London Heathrow operated on the 3rd October, 2016 between 9:00am and 3:00pm. The instance hence features a set of 10 flights between two airports and the underlying network includes 21 sector, 269 waypoints and 672 arcs. These data have been obtained from the DDR2 database as detailed in [12].

The computation returned 56 non-dominated solutions.

2.1 Value path analysis

To highlight the existing trade-offs between the objective functions, we represent the set of (computed) solutions with the support of value-path graphs. These graphs show for each objective function the relative gap between the value achieved by the considered solution and the minimum optimal value – across all the solutions -. This means that the relative gap of delay in a given non-dominated solution is computed as the ratio

$$\frac{\text{delay value of this solution} - \text{smallest delay from all the solutions}}{\text{largest delay from all the solutions} - \text{smallest delay from all the solutions}} \times 100.$$

Similar calculations are done for the other two objective functions. In our test case, the three objective functions achieve values belonging to the following intervals:

- Delay: between 0 and 11 time periods,
- Flight efficiency: between 4620 and 10764,
- Route charges: between 800 and 1126.

Each vertical line in Figure 4 represents the percentage gap of one of the three objectives and each non-dominated solution is represented by a coloured line that crosses each vertical line at the corresponding percentage gap value.

From this figure we can easily see that there is a significant trade-off between the three objectives optimal values. As shown in Figure 5, where we highlighted particular solutions, the solutions in which one of the objectives reaches the best possible value are the ones with poor performance in at least one of the other objectives. In particular, we notice that the solution with minimum possible delay achieve also the minimum value for route charges, while the deviation from the preferred routes is at its maximum. On the other side, when deviation is at its minimum, the route charges are at the maximum and the value of total delay is high as well.

The simultaneous minimization of delay and route charges is a feature of this specific instance and hence it should not be considered as a recurrent fact.

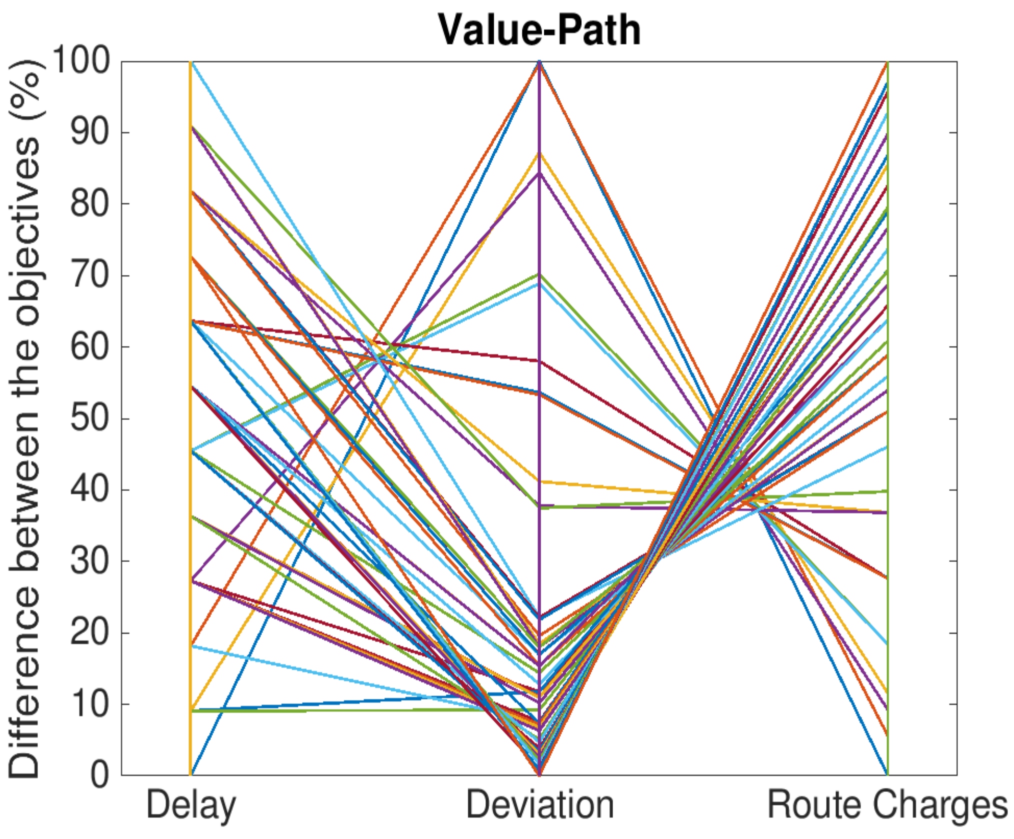


Figure 3 Value-path graph of solutions

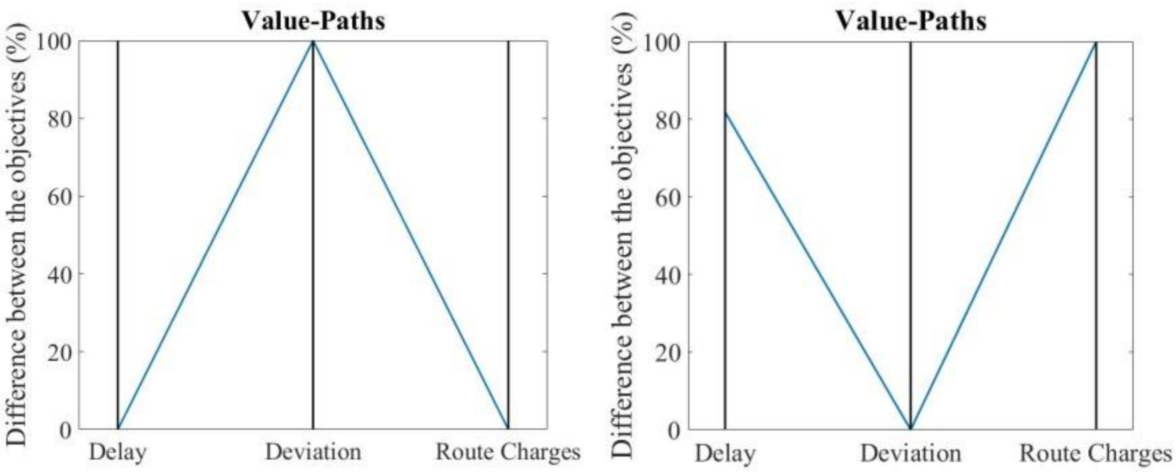


Figure 4 Solutions that achieve minimum values in one objective

2.2 AUs level analysis

The analysis of value-path graphs provides information at a system level highlighting the trade-off involved with the three objectives, but it does not provide information for any specific airspace user. However, OptiFrame has the capability to analyse the impact of each solution on each single airspace user (airline). Information that is recorded by aggregating the contribution of each flight (of the airline) in all the objectives values

In Figures 6, 7 and 8, we show the trade-off of three objectives for each airline – in this small numerical example, which considers the air traffic between London Heathrow and Frankfurt, there are only two airlines - for three specific efficient solutions. More specifically, Figure 6 displays the trade-off for the minimum delay solution. For this solution, although each of the two airlines shares 50% share of total delay, the actually total delay is zero. Figure 7 displays the trade-off for the solution with minimum deviation. In this solution, Airline 2 incurs in a higher percentage of total delay and with respect to the minimum delay solution a slightly increased percentage in route charges. We do not separately present results for minimizing the total route charges, at it is the same solution that minimizes the total delay. We present instead in Figure 8 results on a randomly picked instance, in which we can see that Airline 2 greatly reduces its share in the total delay. From the results we can conclude that each solution has different implications in terms of objective functions for each airline. This analysis can provide AUs with information on which subset of solutions should be preferred from their point of view, but it will be further discussed in Section 4, there is the need of identify a mechanism to facilitate the identification of the best compromise solution

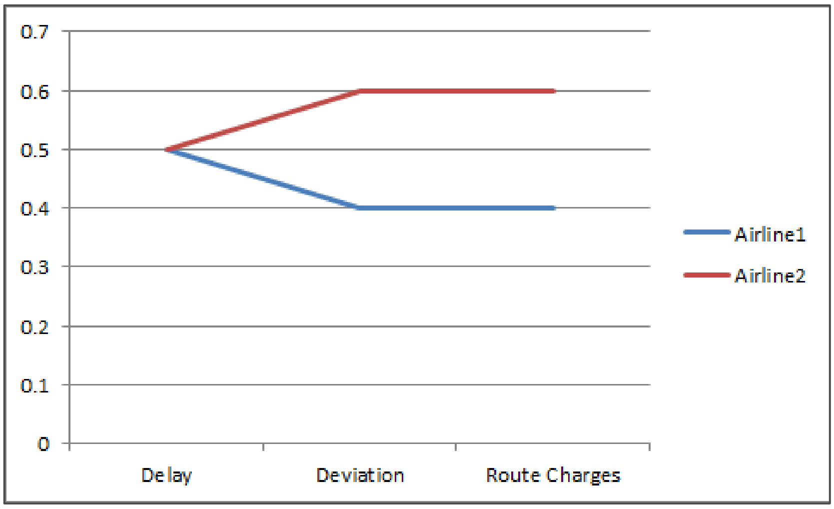


Figure 5 Solution with minimum total delay

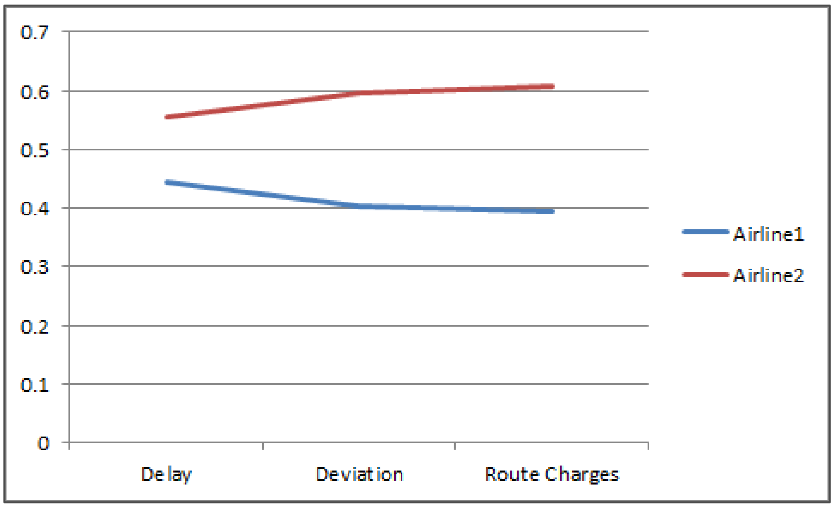


Figure 6 Solution with minimum value of deviation

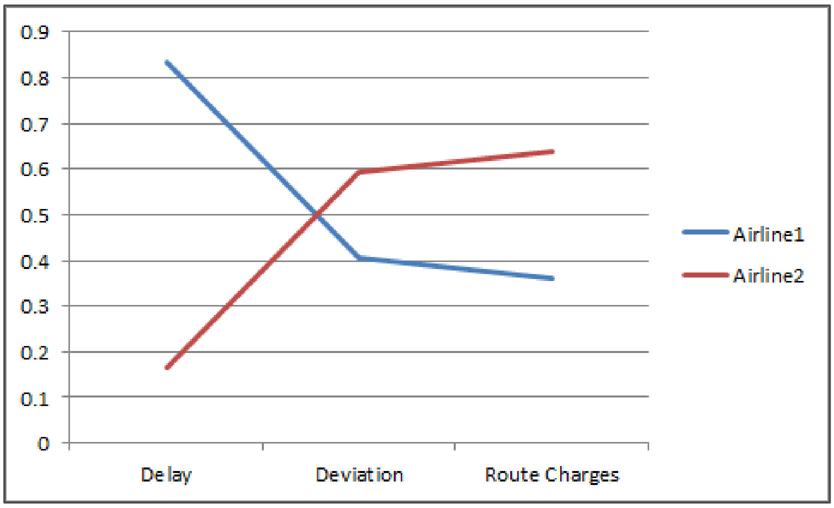


Figure 7: Random solution

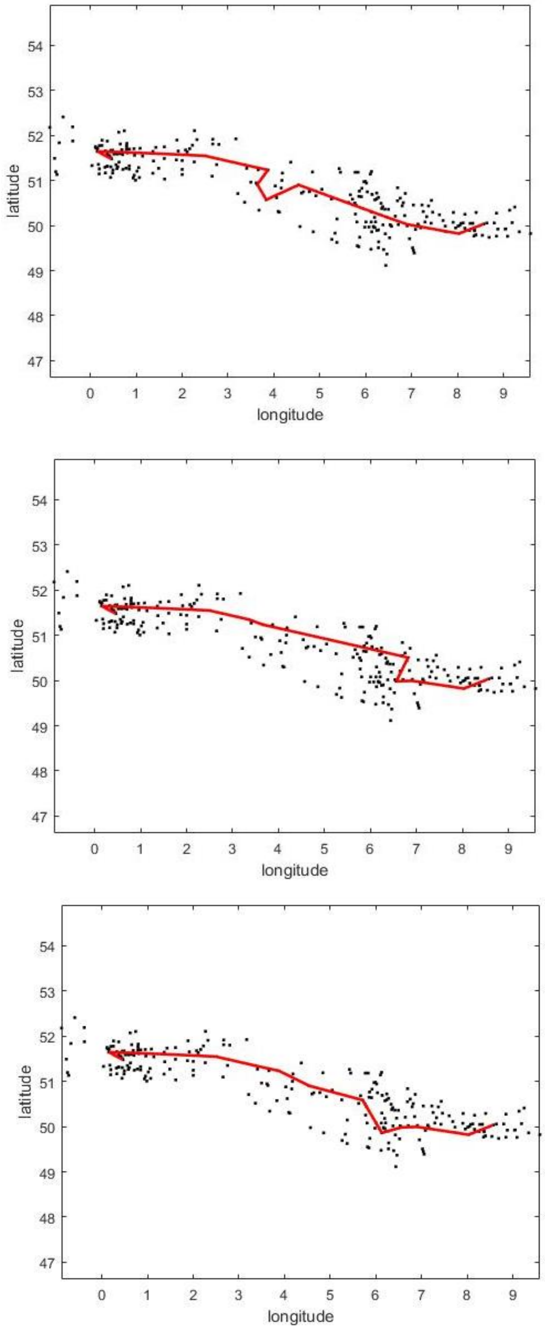


Figure 8 Alternative trajectories for flight from Frankfurt to London Heathrow

2.3 Individual flight analysis

OptiFrame has the capability to provide detailed information at the flight level. Indeed, for each efficient solutions, OptiFrame can show the 4D trajectory and for each flight.

As an example, we here show a flight of Airline 1 flying from Frankfurt to London Heathrow scheduled to take off at 12:25. We collect all the different trajectories flown by this flight in the 56 non-dominated solutions. In Figure 8(a) we can see how a congested sector in the middle of the route forces the flight to be rerouted. This trajectory appears in only 5 out of the 56 non-dominated (efficient) solutions. This solution is perhaps not very realistic from the operational point of view, especially because it requires quite sharp route heading changes. This can be due either to the representation of the network structure, to cost parameter not fine-tuned or both. In 19 solutions the proposed trajectory is the one shown in Figure 8(b), while in the remaining 32 solutions the trajectory is shown in Figure 8(c).

3 Implications for decision making

In previous sections of this deliverable, we showed the type of information that can be provided by OptiFrame. Once again, it is important to highlight the capability of OptiFrame to analyse alternative decisions (solutions) at different level of aggregation, i.e., system level, AUs level and individual flight level to facilitate the decision-making process and a wider participation of all the stakeholders involved.

The intended use of the OptiFrame framework was for the following purposes:

1. as a "simulator" to address some of the issues and questions arising for the exploitation and deployment of the TBO concept in the planning phase, to fully understand the benefits and limitations of the TBO approach;
2. to investigate the optimal balance between different contrasting KPIs relevant for the TBO concept;
3. as an engine for the preliminary identification, on a daily basis, of promising ATM interventions on a continental scale in Europe (ECAC-wide area).

The capabilities of OptiFrame to investigate the optimal balance between different contrasting KPIs relevant for the TBO concept and to detect ATM intervention have been already described in Section 2 of this deliverable.

In this section, we focus on the use of OptiFrame for "what if" analysis. Indeed, the framework can be used to analyse - at different level of granularity - scenarios such as capacity reduction and surge of demand, policy changes, e.g., different route charges and priorities schemes, as well as the implications of any of these situations on Airspace Users operations.

In what follow, we present the following analysis: the impact of different disturbance scenarios and a preliminary analysis of two of the most recent schemes for UDPP.

3.1 Scenario analysis

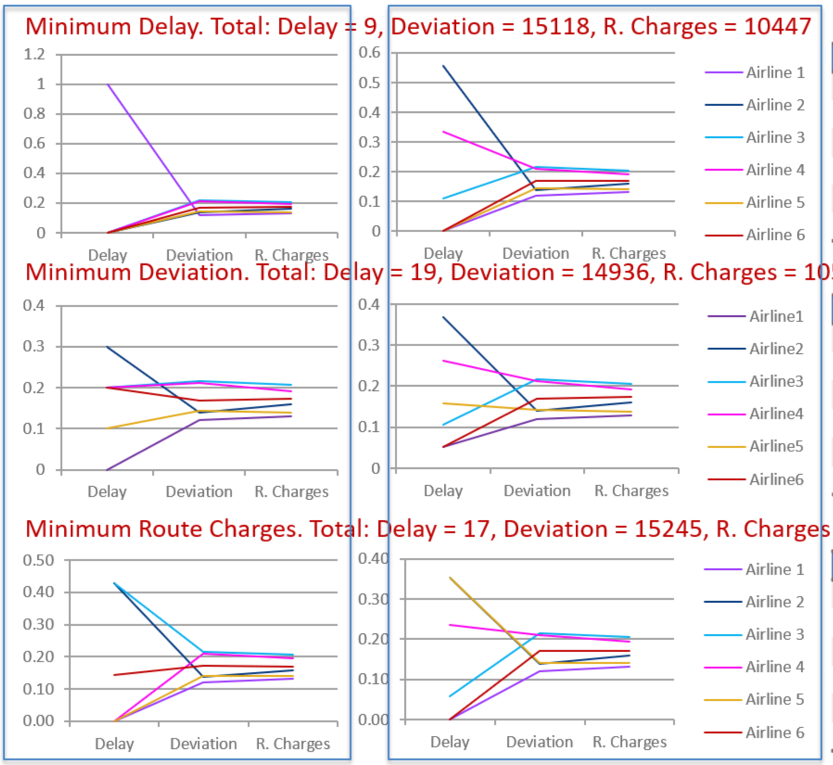
In the following subsection, we analyse the effect of the disturbance scenarios identified in deliverable D13 [ref. 2]. More specifically, we analyse the effect of the realization the scenarios on the set of efficient solutions. The scenarios are: airspace restrictions, airport restrictions and airport closure.

The analysis is carried out by comparing three specific solutions, i.e., the ones that minimize each individual objective, both in the nominal and the disturbance scenario. As a nominal scenario -i.e., the scenario in which no disturbance occurs -, we consider the instance composed all flights operating between Frankfurt, London Heathrow, Paris Charles de Gaulle and Amsterdam Schiphol on the 3rd of October 2016 between 9:00z and 15:00z.

3.1.1 Airport closure

This scenario will involve the closure of one airport (Paris Charles De Gaulle) for one hour due to external circumstances. As a result, aircraft need to be redirected to other airports in the vicinity or delayed.

Under TBO, the 4D trajectories of flights to the closed airports need to be adapted to allow for a diversion to other airports. The impact of these mitigating measures on relevant KPIs will be assessed.



	Delay		Deviation		RouteCharges	
Airline 1	2	0	1805	1808	1387	1389
Airline 2	0	5	2088	2110	1676	1666
Airline 3	0	1	3257	3281	2114	2138
Airline 4	0	3	3176	3189	1984	1996
Airline 5	0	0	2155	2185	1439	1478
Airline 6	0	0	2548	2545	1792	1780

	Delay		Deviation		RouteCharges	
Airline 1	0	1	1795	1795	1369	1369
Airline 2	3	7	2077	2077	1698	1698
Airline 3	2	2	3237	3237	2189	2189
Airline 4	2	5	3167	3167	2032	2032
Airline 5	1	3	2136	2136	1464	1464
Airline 6	2	1	2524	2524	1838	1838

	Delay		Deviation		RouteCharges	
Airline 1	0	0	1837	1839	1335	1337
Airline 2	3	6	2115	2127	1619	1620
Airline 3	3	1	3302	3289	2090	2094
Airline 4	0	4	3224	3221	1973	1974
Airline 5	0	6	2167	2166	1421	1433
Airline 6	1	0	2632	2603	1733	1740

Figure 9: Airport closure

Figure 12 displays the statistics of both the nominal and the disturbance scenario. More specially, the histograms on the left-hand side display the trade-off involved with the three objectives for the nominal scenario. For the sake of clarity, the top histogram refers to the solution that minimizes the total (system) delay; the one in the middle refers to the solution that minimizes deviation (or flight efficiency); finally, the one at the bottom plots the trade-off for the solution that minimizes the route charges. The information is aggregated per airline – the ones operating within pairs of cities considered in the instance -. Moreover, all the histograms are scaled, meaning that the *y-axis* reports the percentage of the total of the objective. As an example, airline 1 absorbs all the delay for the minimum delay solution.

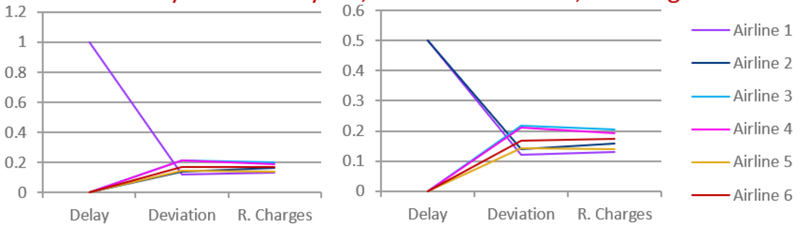
The histograms in the middle display the trade-off for the disturbance scenarios. Finally, the table summarizes the absolute values per each airline, objective and both the scenarios (nominal in grey colour and disturbance scenario in red colour).

As expected, the airport closure has a negative impact on the efficiency of the system. However, at least for the tested instance, the degradation of the objective functions is limited.

3.1.2 Airport restriction

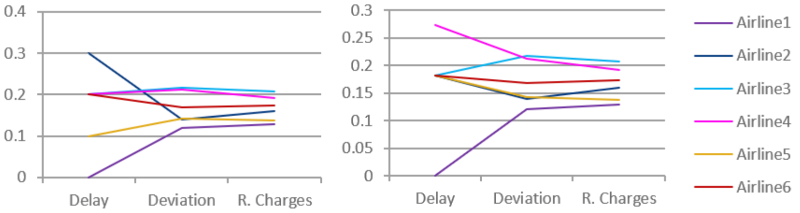
In this scenario, airport capacity restriction for instance due to adverse weather conditions. Mitigation may modify a number of inbound flight trajectories to rebalance the arrival demand. Similarly to the case of airport closure, the airport restriction has a negative impact on the efficiency of the system. However, at least for the tested instance, the degradation of the objective functions is limited. It is also important to observe that to mitigate the negative effect of airport capacity restriction there is a redistribution of delays, deviations and route charges across the airlines.

Minimum Delay. Total: Delay = 2, Deviation = 15078, R. Charges = 10355



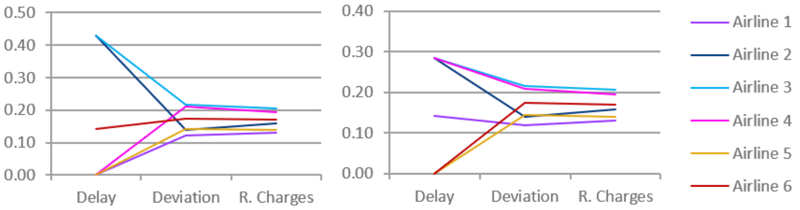
	Delay		Deviation		RouteCharges	
Airline 1	2	1	1805	1821	1387	1361
Airline 2	0	1	2088	2095	1676	1640
Airline 3	0	0	3257	3278	2114	2122
Airline 4	0	0	3176	3179	1984	1977
Airline 5	0	0	2155	2162	1439	1455
Airline 6	0	0	2548	2543	1792	1800

Minimum Deviation. Total: Delay = 11, Deviation = 14936, R. Charges = 10590



	Delay		Deviation		RouteCharges	
Airline 1	0	0	1795	1795	1369	1369
Airline 2	3	2	2077	2077	1698	1698
Airline 3	2	2	3237	3237	2189	2189
Airline 4	2	3	3167	3167	2032	2032
Airline 5	1	2	2136	2136	1464	1464
Airline 6	2	2	2524	2524	1838	1838

Minimum Route Charges. Total: Delay = 7, Deviation = 15243, R. Charges = 10173



	Delay		Deviation		RouteCharges	
Airline 1	0	1	1837	1819	1335	1337
Airline 2	3	2	2115	2127	1619	1620
Airline 3	3	2	3302	3290	2090	2103
Airline 4	0	2	3224	3179	1973	1977
Airline 5	0	0	2167	2185	1421	1420
Airline 6	1	0	2632	2643	1733	1716

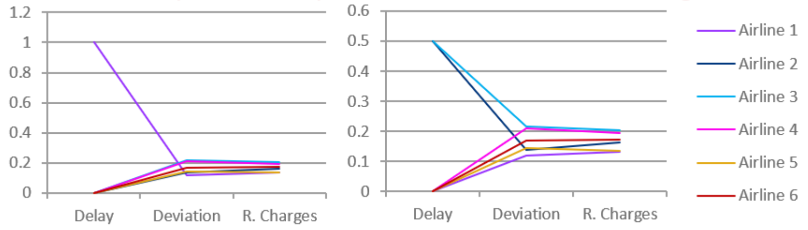
Figure 10: Airport restriction

3.1.3 Sector restriction

This scenario involves unforeseen limitations/availability of airspace impacting several flights. Certain parts of the airspace are not always available or are limited in the acceptable level of traffic. As these periods are often not known well in advance, the planning system needs to be robust against these unforeseen circumstances.

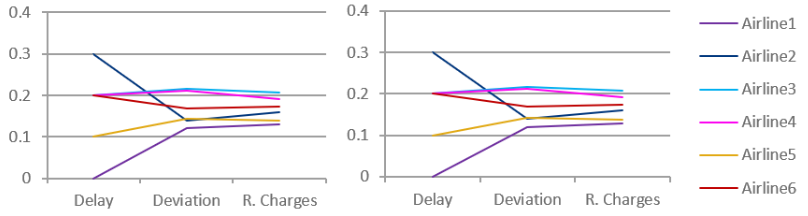
Similarly to the cases described above, the airport restriction has a negative impact on the efficiency of the system. However, at least for the tested instance, the degradation of the objective functions is almost negligible. This is due to the larger number of options to mitigate the negative of the disturbance scenario. Indeed, in the case of sector restrictions two levers are available, i.e., ground delays and rerouting (i.e., horizontal deviations).

Minimum Delay. Total: Delay = 2, Deviation = 150293 R. Charges = 10457



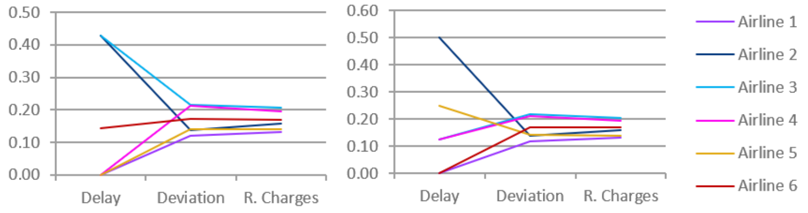
	Delay		Deviation		RouteCharges	
Airline 1	2	0	1805	1812	1387	1378
Airline 2	0	1	2088	2080	1676	1692
Airline 3	0	1	3257	3250	2114	2144
Airline 4	0	0	3176	3173	1984	2024
Airline 5	0	0	2155	2156	1439	1425
Airline 6	0	0	2548	2552	1792	1794

Minimum Deviation. Total: Delay = 10, Deviation = 14936, R. Charges = 10590



	Delay		Deviation		RouteCharges	
Airline 1	0	0	1795	1795	1369	1369
Airline 2	3	3	2077	2077	1698	1698
Airline 3	2	2	3237	3237	2189	2189
Airline 4	2	2	3167	3167	2032	2032
Airline 5	1	1	2136	2136	1464	1464
Airline 6	2	2	2524	2524	1838	1838

Minimum Route Charges. Total: Delay = 8, Deviation = 15278, R. Charges = 10170



	Delay		Deviation		RouteCharges	
Airline 1	0	0	1837	1819	1335	1337
Airline 2	3	4	2115	2130	1619	1614
Airline 3	3	1	3302	3318	2090	2089
Airline 4	0	1	3224	3221	1973	1974
Airline 5	0	2	2167	2196	1421	1416
Airline 6	1	0	2632	2594	1733	1740

Figure 11: Sector restriction

3.2 Analysis of the UDPP schemes

One of the key aspects of the OptiFrame approach to the ATFM problem is the ability of its model to incorporate priorities. This can be made by means of a pre-processing phase that modifies the input data according to the priorities input. Afterwards, the instance is solved using the OptiFrame framework.

In this Chapter we present preliminary results on the effect that the application of priority schemes has on the system performance. In particular, we focus on the FDR and Margins of manoeuvres schemes. In order to be effective, priorities have been applied to a realistic instance that represents the air traffic between four major European airports, namely London Heathrow, Frankfurt, Paris Charles De Gaulle and Amsterdam Schiphol, on the 3rd October 2016. The instance has 186 flights and has been built on the basis of the real data extracted from the DDR2 database [12]. The comparison is made on the basis of the solutions obtained from the OptiFrame heuristic algorithm.

3.2.1 Application of FDR priority scheme

We applied the FDR priority scheme to an airline that incurred in a delay at one of the airports in some of the efficient solutions. We suppose that, given the probability of the flight to be delayed, the airline decides to give to it a higher priority and hence its departure time is swapped with the departure time of a subsequent flight of the same airline. Total delays are computed taking into account the original departure times.

Figure 10 shows in red the optimal Pareto Frontier obtained using the exact method on the instance without priorities, in blue the efficient solutions found by the heuristic algorithm and in yellow the efficient solutions found under the priority scheme. As it can be easily seen, the introduction of the priority scheme in this case study instance does not disrupt the performance of the algorithm and the quality of the found solutions. Even though the solutions with and without the priority scheme are different, their quality is comparable.

Notice that this priority scheme is unlikely to produce infeasible solutions if the original schedule allows a feasible one, as even after the reordering the flights may be displaced in time as much as it is necessary to comply with the capacity constraints.

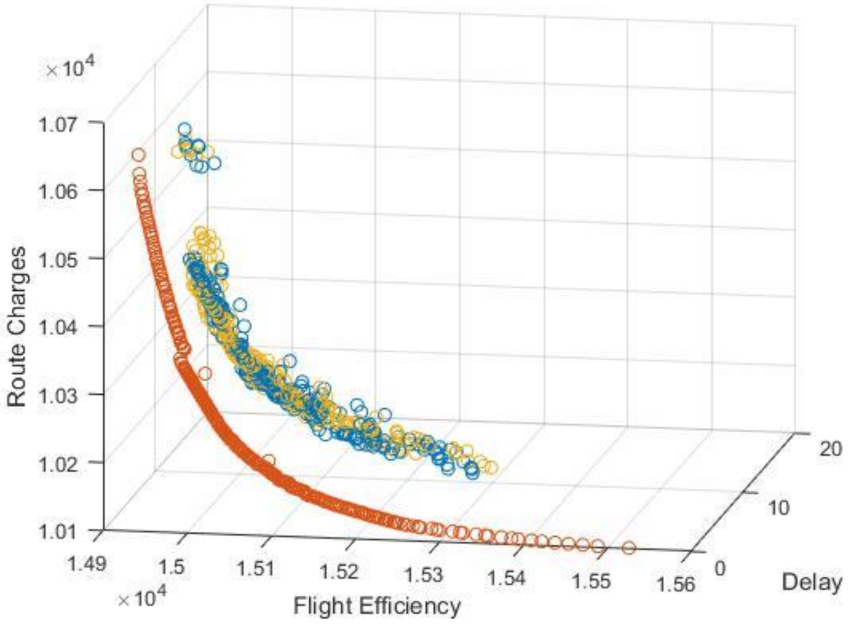


Figure 12 FDR priority scheme

3.2.2 Application of Margins of manoeuvres scheme

In order to apply the Margins priority scheme, we select for each airline a pair of flights to be prioritized by means of reducing the feasible time window for departure. In this way, we force the flight to follow the time-not-before and time-not-after rules set by the scheme.

In Figure 11 we show the performance of the heuristic algorithm under this priority scheme. As for the previous figure, the yellow dots represent the new solutions while the blue ones represent the efficient solutions without the application of the priority scheme. Also in this case we can notice that the performance of the algorithm is not disrupted, even though there is a slight increase of the objective functions values, in particular in the region with higher deviation and route charges. This is a reasonable assumption, as the introduction of margins forces the solution to decrease the delay for the selected flights, which are more likely to be rerouted in order to be assigned to a feasible trajectory. We also notice that an extensive implementation of margins may result in an infeasible solution, in particular when the underlying network is not highly connected. In fact, by forcing a large number of flights to depart almost on time we need a great availability of possible reroutes to ensure all capacity constraints are satisfied.

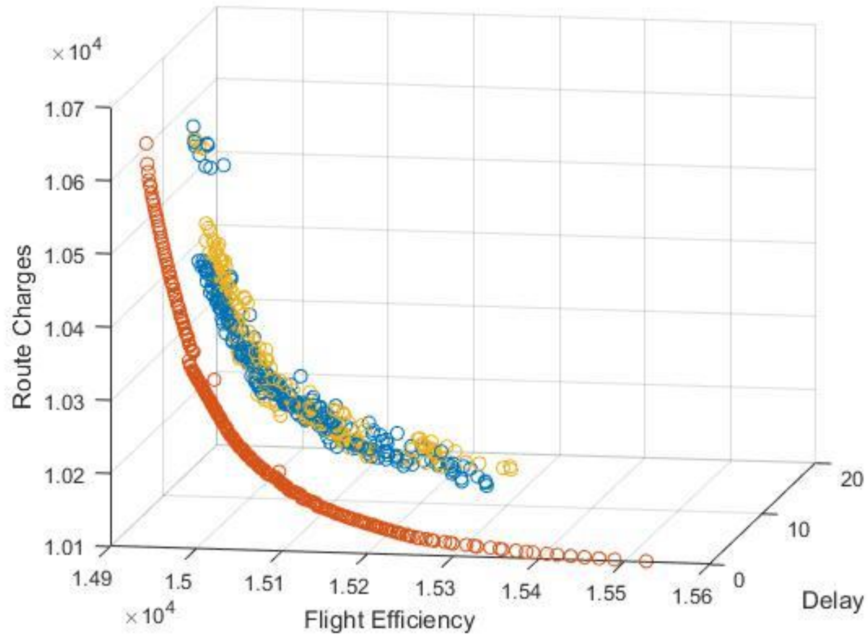


Figure 13 Margins priority scheme

3.3 OptiFrame for Collaborative Decision Making

The distinctive characteristic of the OptiFrame approach is the development of multi-objective models that: i) consider simultaneously the three objectives , i.e. delay, flight efficiency, and route charges, that reflect the preferences of the ATM stakeholders, and ii) provide to the decision makers information regarding the trade-offs between the three objectives. As it has been already discussed in Section 2, all solutions that belong to the efficient frontier are “equally good” in the sense that there is no any other solution that outperforms them in terms of all three objectives. However, the final decision regarding how the ATM will operate requires the selection of one solution (among all the available efficient solutions) that will be the solution that will be implemented. This decision regarding the selection of the point (solution) of the efficient frontier that the network will operate is a very central and crucial issue regarding the implementation of the TBO concept. The criticality and importance of this decision stems from the fact that each point (solution) of the efficient frontier may impact differently the different stakeholders, i.e. network manager and airspace users. Furthermore, different stakeholders may assign different importance to the different objectives expressing their preferences. For instance, some Airspace Users (airlines) may be more sensitive to delays, while others may be more sensitive to flight efficiency or route charges. Therefore, the selection of the solution that will be implemented must be the outcome of a Collaborative Decision Making process which will lead to the definition and selection of the “best compromise solution”, i.e. this will be the solution that will be acceptable by all stakeholders. The development of a commonly agreed solution is a tedious process and its outcome it is not easy to be achieved.

In general, there are two approaches that can be used in order to reach a commonly agreed decision among multiple stakeholders in the presence of multiple and sometimes conflicting objectives, namely the bottom-up and the top down approaches. The bottom-up approach currently adopted and implemented in OptiFrame, does not require the priori articulation of the preferences by each stakeholder. According to the bottom-up approach the entire efficient frontier is generated and based on the information provided by all solutions to the stakeholders, the stakeholders are called to express their preferences that will lead to the selection of the "best compromise solution (see Figure 14, below).

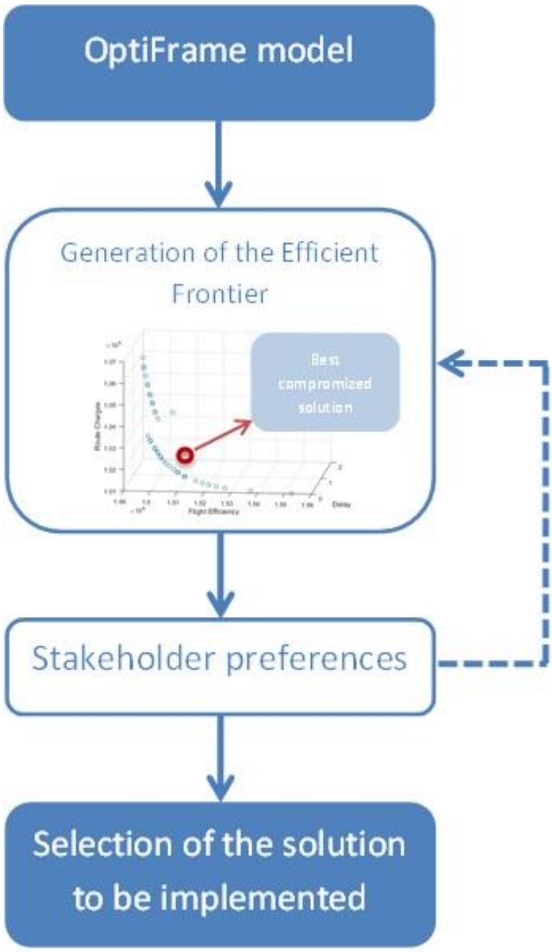


Figure 14: The bottom-up Approach

In the case of the top-down approach, the stakeholders are called to priori articulate their preferences, e.g to indicate if it is more preferable for them to delay or to re-route each flight, these preferences then are used as an input to the solution of the multi-objective problem (see Figure xxx). In the case of the top-down approach, the solution of the multi-objective problem provides the commonly agreed solution.

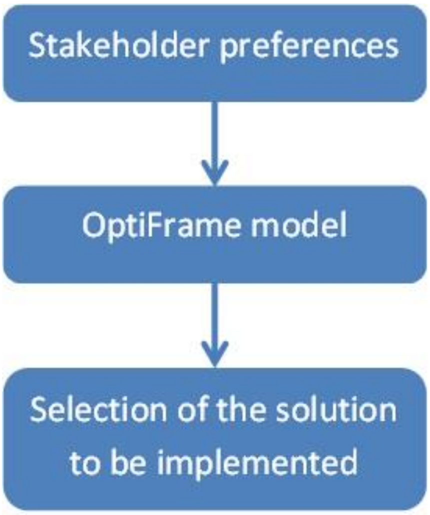


Figure 15: The top-down approach

The major advantage of the bottom-up approach is that it provides much more information about the trade-off among the objectives of all stakeholders and that it does not exclude priori some efficient solutions. The disadvantage of the bottom-up approach is that it may create an information overload that it will make it difficult for the decision makers to mentally process it and reach a commonly agreed decisions. The advantage of the top-down approach is that it may produce easier the commonly agreed solution, however its disadvantage is the exclusion of some efficient solutions.

The preceding discussion suggests that further research is needed in order to decide: i) if the OptiFrame approach should also consider the top-down alternative and ii) how consensus about the selection of the efficient solution that should be implemented can be achieved.

4 Stakeholders' Feedback and Directions for Future Research

The findings of the OptiFrame approach were presented at a workshop to relevant stakeholders in order to receive feedback regarding the capability of the OptiFrame approach to address decision making issues associated with the generation of 4D trajectories within the context of Trajectory Based Operations (TBO). The workshop was held on February 14, 2018 at the EUROCONTROL Headquarters in Brussels. The workshop was attended by representative of Eurocontrol NM and PRU, Air Navigation Service Providers, Airlines, international experts in the area of Air Traffic Flow Management, and by a representative of the COPTRA project.

The workshop started at 10:00 am and it was concluded at 15:15, the agenda of the meeting is provided in the appendix. The workshop context and objectives were communicated to the perspective participants in the invitation letter, along with the relevant workshop participation consent forms as required by the established Project Ethics Procedures described in D18. Electronic copies of all presentations were provided to all participants before their arrival, while hard copies were made available to them at the workshop.

The workshop was divided into two parts. Each part included presentations that were followed by questions and dedicated discussion time was allocated at the end of each Workshop Part. Discussion issues/questions were also identified as part of the presentations in order to provide a semi-structured framework for the discussion and the provision of the feedback. A wrap-up session was also included at the end of Part B, to summarize the major findings of the workshop and to provide future research directions.

The first part of the workshop (Part A) involved presentations related to the: i) overall OptiFrame Approach, ii) methodology used to develop the OptiFrame Models including the organization of the first stakeholders' workshop, iii) TBO 4D decision making requirements, iv) incorporation of stakeholders priorities and preferences into the OptiFrame models, v) OptiFrame models and proposed solution approaches, vi) the data needed to operationalize and validate the OptiFrame model, and vii) the use of the OptiFrame for decision making at three different aggregation levels, namely, system level, airline level, and individual flight level. The second part of the workshop (Part B) was focussed on the presentation of the: i) validation methodology, ii) qualitative assessment of the OptiFrame approach, and iii) quantitative assessment of the OptiFrame approach.

Following the Question and Answer (Q&A) and discussion sessions, and the expression of views of the workshop participants the following suggestions regarding the implications of OptiFrame for decision making and directions for future research were identified: 1) Specification of the nature and intended use of the OptiFrame approach; 2) alignment of the OptiFrame approach with stakeholders' preferences and priorities; 3) avoidance of frequent altitude changes; 4) input of the OptiFrame approach to SESAR 2020 Projects PJ07 and PJ09; 5) filtering of desirable OptiFrame solutions; 6) facilitating the selection of the best compromise (acceptable) solution; 7) issues associated with the complexity of the network and computational speed; 8) assessment of the impact of alternative prioritization mechanisms on system performance; and 9) maturity assessment and input to subsequent research stages. In what follows we briefly summarize the identified issues.

4.1 Specification and intended use of the OptiFrame Approach

The OptiFrame approach is intended to provide decision support and facilitate collaborative decision making at a "planning" (e.g. six hours in advance) decision making level. The OptiFrame approach should be understood as a service function or in other words as an engine to detect ATFM interventions. The OptiFrame approach can be used by the Network Manager Function in cooperation with all Airspace Users (operational data sharing) in order to find "mutually acceptable solutions" that will reflect as close as possible the users' preferred trajectories. It is through this process that the TBO objective of providing flexibility to airspace users and ensuring punctuality of the flights is achieved.

4.2 Alignment of the OptiFrame Approach with stakeholders' preferences and priorities

The OptiFrame approach has incorporated into the proposed model the stakeholders expectations (elicited at the first OptiFrame workshop and in subsequent interactions). In terms of the preferences the three objectives that have been incorporated reflect the minimization of the horizontal and vertical deviation from the user preferred trajectories, the minimization of departure delays, and the minimization of the route charges. Given the fact that the conversion of all these objectives into a single monetary value is very difficult, and that the air space users do not want to reveal their cost structure and other commercially sensitive proprietary information, the choice was made to use a multi-objective formulation in order to approximate the utility function of the airspace users. The difficulty for the conversion of the delay and route deviations (in terms of time and space) into monetary values stem from the fact that there is a multitude of factors affecting the dynamic relationship between delay, distance, and monetary costs. Furthermore, it should be recognized that the conversion of delays and flight efficiency values into single monetary value can not be based on the same conversion factors for all airlines. This is due to the fact that airlines operate under different business models. Therefore, the consideration of the same conversion factors may raise fairness and equity issues.

On the question of the inclusion of the route charges as an explicit objective of the OptiFrame model, the answer provided by the AUs was definitely yes. Regarding the issue of including arrival versus departure delays, it was recognized that the consideration of arrival delays may be appropriate and desirable. However, it was also argued that the current frame of mind in the industry is closer associated to departure delays and as such the use of departure delays was considered appropriate. The future adoption of the arrival delay is technically possible and can be easily accommodated by the OptiFrame model, however its practical implementation will require a cultural shift in the industry. In terms of the incorporated priorities, the use of the UDPP mechanisms contributes to the alignment of the OptiFrame approach with the broader ATFM developments taking place within the SESAR 2020 framework.

4.3 Avoidance of frequent vertical changes and horizontal changes within the same sector

The validation outcome of the OptiFrame approach identified that the model produces frequent changes of flight levels, which are not desirable from an actual operational and safety point of view. This means that a systematic process needs to be introduced in order to streamline the vertical profile of the proposed trajectories. This streamlining can be achieved through a combination of actions including introduction of additional constraints limiting the frequency of vertical changes, and/or further calibration of the of the OptiFrame model parameters that establish the relative importance between planar and vertical trajectory changes.

Furthermore, it was observed that in the instances tested the model had generated lateral deviations within the same sector. This outcome may be attributed to the fact that the tested instances were rather constrained in terms of the horizontal connectivity of the sectors involved. Therefore, the limited options offered to the model for horizontal deviation outside a given sector may have led to this type of behaviour. This issue can be resolved by adding extra constraints in the pre-processing of the data that will not create networks that will provide lateral deviation links within the same sector.

It was recommended that future research efforts in TBO should consider the implementation of these streamlining mechanisms.

4.4 OptiFrame input to S2020 IR projects PJ07 (OAUO) and PJ09 (Advanced DCB)

PJ07 - The project Optimized Airspace Users Operations (OAUO) aims at defining and validating improved Airspace Users processes and tools related to their interaction with the ATM Network Operations in SESAR 2020. The current ATM environment based on static flight plans is evolving through SESAR towards Trajectory Based Operations (TBO) in order to improve Airports and ATM Network performance.

PJ09 - The project Advanced Demand and Capacity Balancing (Advanced DCB) aims at evolving the existing DCB process to a powerful distributed network management function which takes full advantage from the SESAR Layered Collaborative Planning, Trajectory Management principles and SWIM Technology to improve the effectiveness of ATM resource planning and the network performance of the ATM system in Europe.

The OptiFrame approach showed that, although for a limited set of Airports and flights, it was possible to integrate AU's defined preferences and priorities in order to assess the impact on the AUs and on the Network in terms of some specific Performance Indicators. Based on the current work performed in PJ07 (both Solution 1 and Solution 2) and in PJ09 (Solution 3), OptiFrame could be used by these Projects as:

- Initial assessment tool for newly defined preferences and UDPP prioritisation methods in order to reduce the impact of network constraints and DCB measures
- What-if functionalities tool to allow AUs to analyse the performance impact of their planning activities and support network collaborative processes
- Initial assessment tool for showing the benefits of the Multiple Constraint Reconciliation concept (impact of conflicting measures on the network performance)

4.5 Filtering of OptiFrame Solutions

The OptiFrame approach generates a wide spectrum of alternative efficient solutions. For realistic problem instances, representing large networks, the number of available solutions might be such that it will be difficult to compare and understand the trade-offs involved between the three objectives (i.e. departure delay, total deviation, route charges). Therefore, there is a need to introduce a filtering mechanism that will systematically reduce the number of alternative solutions to a subset that can be understood by the decision makers. One criterion that was proposed was to establish a threshold value of delay below which the decision maker is not sensitive to the value of delay. For instance, airspace users may indicate that all solutions with delay values less than 15 minutes should be discarded. This means that the decision makers are not interested to assess the trade-off between the delay and the other two objectives when the delay value is relatively small, and that it is only above this threshold value that they would like to see how much they have to sacrifice in departure delay in order to gain something in one or both of the other two objectives. Following the same reasoning, similar filters can be established for all three objectives. These filters can be applied progressively until the set of alternatives has been reduced to a manageable number. For instance, one can indicate that all solutions that deviate from the absolute optimum of each objective by less than 10% and by more than 90% should be excluded from further consideration. It should be stressed here that, although only a sub-set of the generated solutions will be considered, it is useful to generate all efficient solutions in order to have a more accurate picture of the trade-offs present at a given instance. It was suggested that the development and implementation of filtering mechanisms for reducing the number of efficient alternatives should be incorporated in future research activities.

4.6 Facilitating the identification of the best compromise solution

Even though the number of alternative solutions after the application of some sort of filtering will be significantly reduced, there still a need to come up with a single commonly agreed best compromise solution which will be the solution that will be finally implemented. Therefore, there is a need to establish a systematic mechanism for selecting the best compromise solution among all efficient solutions. This selection should be the outcome of a collaborative decision-making process that will entail the collaboration and eventually convergence of all stakeholders to a commonly agreed solution. Different methods have been proposed in the literature for ranking alternative solutions of a multi-objective, multi stakeholder problem like the one under consideration. Among the proposed methods, the Analytical Hierarchy Process (AHP) has been used in solving Air Traffic Management problems. Zografos and Giannouli (2001) used AHP in order to rank alternative ATM systems in Europe, while Zografos and Tsanos (2009) used this method for ranking alternative separation minima involving multiple objectives and multiple stakeholders. Therefore, it is suggested to use a multi-criteria Decision Making (MCDM) making methodology, like AHP, to post-process the results of the OptiFrame approach. Alternatively, the OptiFrame model can be also used in a top-down approach where the preferences of the various stakeholders will be expressed a-priori and in this sense they will constitute an input to the solution of the OptiFrame model. These developments are recommended to be further investigated as part of future research activities.

4.7 Network complexity and computational performance

As it has been presented in previous OptiFrame Deliverables, the ATM network is evolving dynamically over time in terms of its underlying structure and topology. This means that in different points in time the Network over which the optimization problem is solved is changing significantly, e.g. Airspace structures are changing dynamically. Moreover, the Fee Route Airspace availability is increasing. A trade-off exists between the level of granularity of the representation of the ECAC area, and the size of the resulting optimization problem. A very detailed Network description may result to problem sizes that will not be possible to be solved in reasonable computational time. The OptiFrame experience has demonstrated that the proposed heuristic algorithms can be used to solve large problem instances, which need to be improved before attempting to solve problems resulting from the detailed representation of the whole ECAC airspace. Therefore, future research should try to address issues step by step, associating the level of detail of the Network representation and the computational performance of the heuristic algorithms. The final objective, in order to fully assess the OptiFrame approach, should be the application of OptiFrame to an ECAC wide scenario to be compared to current Network Operations (dealing with ~35000 flights per day).

4.8 Assessment of the impact of alternative prioritization mechanisms on system performance

The OptiFrame approach provides the capability to test alternative prioritization mechanisms and evaluate their impact on the overall system performance. This is a very useful feature of the OptiFrame as it can simulate alternative prioritization mechanisms, quantify potential impacts, and provide evidence based guidance for policy making. Within the framework of the OptiFrame two alternative prioritization mechanisms were tested, namely the Flight Delay Re-ordering (FDR) and the Margins schemes. For both cases the results are rather encouraging and suggest that the use of these mechanisms does not degrade the overall ATM system performance measured in terms of departure delay, route deviation, and route charges. However, further testing with larger ATM networks is suggested in order to provide conclusive evidence supporting this claim.

4.9 Comparison of the OptiFrame Approach with CASA

An important aspect of the validation, further development, and implementation of the OptiFrame approach is its comparison with the currently used tool CASA. The current state of the validation of the OptiFrame approach approximates its comparison with CASA through the use of the OptiFrame solution that minimizes delay as the baseline for comparing the other efficient solutions. Although, the existing level of validation provides some early evidence of the capabilities of the OptiFrame approach more rigorous comparison of the two approaches is needed in order to further advance the development and implementation of the OptiFrame approach.

4.10 Maturity assessment and input to subsequent research stages

The OptiFrame project is an exploratory research project and as such it lies in the first stage of the maturity assessment scale, i.e., from maturity level 0 to maturity level 1. However, the OptiFrame project has demonstrated and provided early evidence of the proof of the TBO concept. The mathematical models developed and implemented by the OptiFrame project have successfully incorporated the preferences and priorities of the ATM stakeholders. The proposed heuristic algorithm can solve in reasonable time problems of significant size in reasonable time. However, more work is needed to scale this algorithm to solve problems for networks representing the ECAC airspace. The validation of the OptiFrame concept under nominal and increased demand scenarios has demonstrated the generation of meaningful 4D trajectories and has assessed the performance of the developed trajectories in terms of the identified Key Performance Indicators. The outcomes of the OptiFrame project were also presented to key stakeholders who provided useful feedback regarding the potential of the OptiFrame to further support the development of the TBO concept. In order for the OptiFrame to become a tool for the development of the TBO concept the following directions for further research were recommended:

- Further calibration of the model and potential inclusion of additional constraints limiting the number of altitude changes and the horizontal deviation within the same sector.

- Further development and improvement of the computational performance of the proposed algorithms.
- Refinement of the process leading to the representation of the ATM network over which the OptiFrame is used.
- Development of a post-processing engine that will automate the analysis of the alternative efficient solutions generated by the OptiFrame model and will provide Decision Support for reaching a consensus regarding the OptiFrame solution that should be implemented.
- Comparison of the OptiFrame approach with the CASA tool.

5 References

1. UDPP SESAR 1, Step 2, concept in brief: VP730 Demo, Laurent Guichard, Oct 2016.
2. The OptiFrame Consortium (2016), Technical report reviewing the state-of-the-art on ATFM. Deliverable D7. SESAR exploratory Research. www.lancaster.ac.uk/lums/central/current-projects/optiframe/. Accessed July 11, 2017.
3. The OptiFrame Consortium (2016), Report of the OptiFRAME workshop: the stakeholders views. October 5, 2016, Brussels. Available upon request. http://www.lancaster.ac.uk/lums/central/current-projects/optiframe/. Accessed July 11, 2017.
4. International Civil Aviation Organization-ICAO (2005), Global air traffic management operational concept. First edition-2005. https://www.icao.int/Meetings/anconf12/Document%20Archive/9854_cons_en[1].pdf. Accessed July 13, 2017.
5. OptiFrame Consortium, Mathematical models for TBO. Deliverable D9, December 2016.
6. UDPP SESAR 1, Step 2, concept in brief: VP730 Demo, Laurent Guichard, Oct 2016.
7. SESAR, D07 UDPP Step 2 V1, Project 07.06.04, Ed. 00.02.02, January 2014.
8. Laurent Guichard, UDPP Concept. Project 07.2 UDPP, June 2017.
9. N. Pilon, S. Ruiz, A. Bujor, A. Cook & L. Castelli (2016), Improved flexibility and equity for airspace users during demand-capacity imbalance. *In D. Schaefer (Editor) Proceedings of the SESAR Innovation Days (2016) EUROCONTROL. ISSN 0770-1268.*
10. EUROCONTROL, DDR2 Reference manual, 2.0.1., October 2014
11. EUROCONTROL, DDR2 Web Portal, http://www.eurocontrol.int/articles/ddr2-web-portal, last time accessed February 2017
12. OptiFrame Consortium, Routines for data extraction and for the generation of ATFM algorithm input data. Deliverable D8, February 2017.
13. OptiFrame Consortium, OptiFrame computational framework. Deliverable D11, October 2017.
14. OptiFrame Consortium, Detailed assessment of the OptiFrame computational framework for normal and disturbance cases. Deliverable D14, February 2018.
15. Zografos, K.G. and I.M. Giannouli (2001). Development and Application of Methodological Framework for Evaluating the Cost-Effectiveness of an Air Traffic Management System for

Europe, Transportation Research Record: Journal of the Transportation Research Board, Vol. 1744, pp. 52-64.

16. Zografos, K.G. and C.S. Tsanos (2009), "Developing and applying a methodology for assessing the implementation potential of reduced separation minima", Proceedings of the 88th Transportation Research Board Annual Meeting, Washington D.C., U.S.A., 11-15 January 2009.

Appendix A Second Workshop Agenda

OptiFrame Workshop
NEPTUNE room, Eurocontrol HQ
Brussels - February 14th, 2017

AGENDA

09:45 - 10:00	Registration
10:00 - 10:15	Welcome and remarks from the Project Officer
10:15 – 10:45	OptiFrame framework
10:45 – 11:05	OptiFrame data management
11:05 – 11:30	Coffee break
11:30 – 12:00	OptiFrame for TBO decision support
12:00 – 12:30	Discussion – part A
12:30 – 13:45	Lunch
13:45 - 14:15	OptiFrame validation and assessment
14:15 - 14:45	Discussion – part B
14:45 - 15:00	Closing remarks