Modelling and Evaluation of Automated Arrival Management Considering Air Traffic Demands

M. Schultz, H. Fricke, T.Kunze, T. Gerbothe
Technische Universität Dresden
Dresden, Germany

C. Grabow, J. De Prins
Boeing Research and Technology Europe
Madrid, Spain

M. Wimmer, P. Kappertz
Barco Orthogon GmbH
Bremen, Germany

***Foreword*—This paper describes the major results of the UTOPIA project. UTOPIA is part of the SESAR Work Package E program, which is addressing long-term and innovative research for the Single European Sky. One of the greatest challenges that the future ATM system will need to face in the next decades is the integration of new airspace users and the continuous increase in delegating capacity and safety critical traffic management functions to automated systems. The accommodation of these new airspace users, which will have to coexist with conventional users, a widely reorganized airspace and the increased level of automation will necessarily need a paradigm shift with regard to the trajectory management functions. The objective of the UTOPIA project is to provide a better understanding of essential trajectory management functions to efficiently manage heterogeneous traffic considering the increasing presence of autonomous ATM systems. In particular, UTOPIA focusses on data models, synchronization requirements and algorithms needed to ensure the safe management of merging traffic in an extended terminal maneuvering area, executed by an autonomous arrival management function acting as separator. The converging flows of traffic that will be studied comprise heterogeneous airborne systems, in particular, advanced and legacy flight management systems, representing airspace users with different synchronization capabilities.**

Keywords-heterogenous traffic, arrival management, formal languages, disruption, uncertainty, trajectory synchronization, multi-dimensional trajectory

The UTOPIA consortium consists of three members, namely Technische Universität Dresden (TUDD), Boeing Research and Technology Europe (BRTE), and Barco Orthogon GmbH (Barco), and is led by TUDD. The UTOPIA consortium will explore several innovative aspects considered in the Work Package E research area Towards Higher Levels of Automation in ATM. This theme fosters the research in those areas and technologies that will increase the levels of automation, up to and including full automation, of the future ATM system. One of the key elements, as indicated in the WP-E thematic program, will be the integration of both airborne and ground-based systems and a heterogeneous user (aircraft) population, which is the subject matter of UTOPIA. In particular, this project focuses in two areas outlined in this theme: exploring the coexistence of subsystems with different levels of automation in a complex system, as well as algorithms and control paradigms using higher degrees of automation. A detailed structure of the research done within the UTOPIA project [1] and first results [2] are already presented.

I. INTRODUCTION

During the project lifecycle the essential scientific and operational fundamentals have been comprehensively investigated and prototypical implementations have been realized to provide a functional proof of concept. The fundamental research areas contain main aspects of an initiating review and gap analysis, a detailed concept specification, followed by the identification of stochastic parameters, the development of a stochastic model, and finally the design scheme for the virtual environment [2]. UTOPIA's concept of operations in the widened terminal maneuvering area (extended TMA - eTMA) with respect to mixed traffic scenarios has been specified during the course of the project. In this context *extended* means a 500+ NM increased TMA with considerably larger look ahead times referring to the scheduled time of arrival/departure of an aircraft at the airport. The terminal operations are being considered in UTOPIA in terms of inbound and outbound sequencing. Since the sources of system uncertainties are heterogeneous [cf. 3], a qualified classification method is required. Therefore, the sources of uncertainties have been identified and allocated to different classes. Finally, the specific synchronization parameters have been determined considering the significant classes. The most common areas of uncertainties are related to the: **a)** environment vagueness, **b)** operational factors of stochastic behavior and nature, and **c)** aircraft navigation performance and guidance accuracy. To evaluate and mitigate possible (negative) impacts on the data synchronization (by means of identical "data picture" of the ATM system status), propagation aspects are efficiently modeled. Since a synchronized trajectory is defined as a shared and timely aligned view of at least two stakeholders onto the flight status and the flight intent, UTOPIA's view on the future ATM System anticipates heterogeneous air and ground-based stakeholders in an automated environment and their required interactions to exchange trajectory information (input and predicted data) [2].

The UTOPIA project uses a virtual ATM demonstrator environment with interacting agents (system entities with the capability of autonomous acting and decision making [cf. 4, 5]), where the agent act in an extended terminal maneuvering area around Frankfurt Airport (EDDF) to implement the

UTOPIA is co-financed by EUROCONTROL on behalf of the SESAR Joint Undertaking in the context of SESAR Work Package E

proposed concept of operations. The derived capabilities of the agents systematically allow implementing the stochastic characteristics of input parameter within the simulation environment. Herein, a crucial component is the modeling of atmospheric conditions and weather patterns, which are considered to be the main impact factor for uncertain flight intents. To handle this, the TUDD approach of a corridor of uncertainty is used within the UTOPIA project [6].

The UTOPIA demonstration environment is a TCP/IP networked simulation environment combining the Barco arrival manager (AMAN) as a ground-based trajectory management tool and two air traffic simulators (ATS), *Future ATM Concept Test bench* (FACT from BRTE) and *Testbench for Agent Based Air Traffic Simulation* (TABATS from TUDD) [2]. Additionally, the Airbus A320 fixed based simulator (depicted in fig. 1) available at TU Dresden has been extended to act as agent in the simulation environment and show a possible implementation of the required data-link procedures for automated arrival management functions.

Figure 1: Airbus A320 fixed base simulator at TU Dresden serving as independent agent in the UTOPIA simulation

A Demonstrator Control Process (DCP) serves as the middleware for the required information exchange between the several independent UTOPIA systems, to run the simulation exercises fully automated. The DCP architecture is outlined in the fig. 2. The DCP ensures a timely synchronization between the components and manages the message distribution including filtering to avoid unnecessary network traffic. Each demonstrator client system has its own IO thread that optionally contains translators to interpret the exchanged messages into the native command language of the respective client.

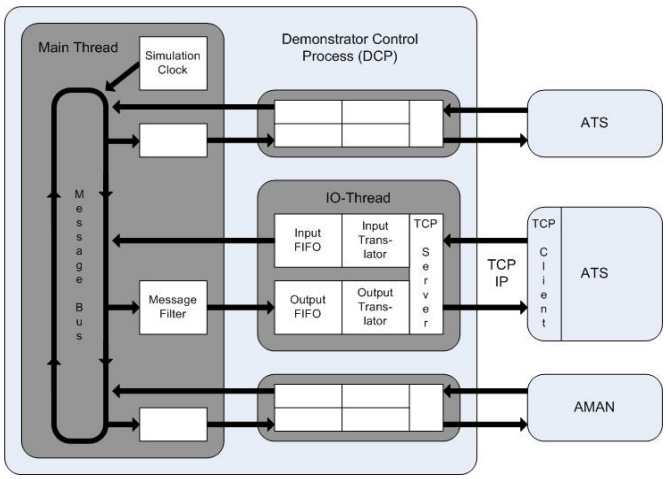

Figure 2: UTOPIA system architecture

Since the interaction between the UTOPIA systems is realized through the DCP using TCP/IP technology, the ATS can be integrated without being at one physical location. The exchanged dynamic data is defined in an unambiguous way using XML formatted messages with respective schemata. While some data required messages specifically designed for the UTOPIA context, trajectory data can be transferred using existing language definitions such as Flight/Aircraft Intent Description Language (FIDL/AIDL) [7].

II. METHODOLOGY

The methodology section emphasizes three relevant research topics of UTOPIA: the common implementation of the identified stochastic input parameters for wind using noise functions, the implementation of weather scenarios and their impact of the aircraft trajectory, and the performance measurement.

A. Stochastic Input – Coherent Noise Function

During the UTOPIA project we identified several input sources which possess a stochastic behavior by nature. To cover this realistic behavior in our models, we transferred the observations from the input data into a frequency analysis (data classification) and derived reliable stochastic density functions. In the context of the simulation of stochastic behavior the aggregation of several simulation runs have to ensure that the fundamental statistics will be met. The previously used standard method was used to generate random numbers during the single simulation run based on the underlying statistics, ignoring the prior generated numbers (no history of progress). But applying this method for trajectory generation results in unrealistic patterns, e.g. it is possible that wind direction my change directly from the defined minimum to the maximum. In fact, this behavior is correct from the statistical point of view, but does not reflect the real behavior. Rather coherent wind fluctuations are expected within a certain area around a given

location and within a certain time period. It is expected that heavy changes of input values are accompanied by relaxation effects, leading to adjusted gradient changes (damping effects, see fig. 3).

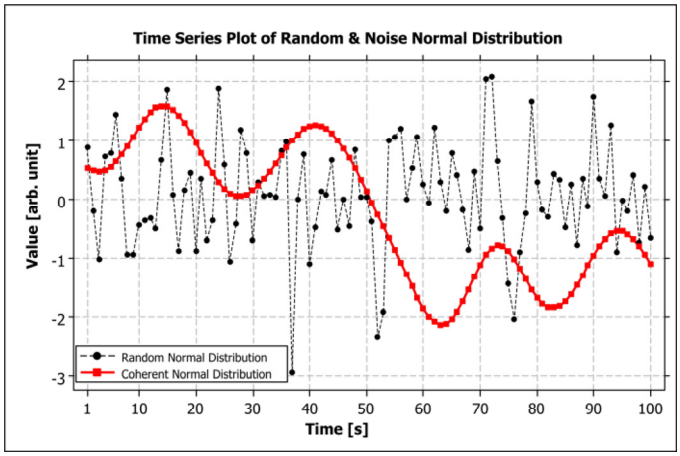

Figure 3: Random noise vs. coherent noise characteristic

In this context, coherent noise functions provide a valid technique to include the gradient of the parameter changes ensuring a random bias with a smooth transition [8]. A pseudorandom noise function was introduced and improved by Perlin [9, 10]. The simplex noise implementation [11] was used for the creation of aircraft trajectories, which ensures an appropriate computational complexity, an advanced isotropic characteristic, an assured continuous gradient, and a 4D path generation [12]. We calibrated the random bias of the coherent noise to return a standard Normal distributed behavior (see fig. 4).

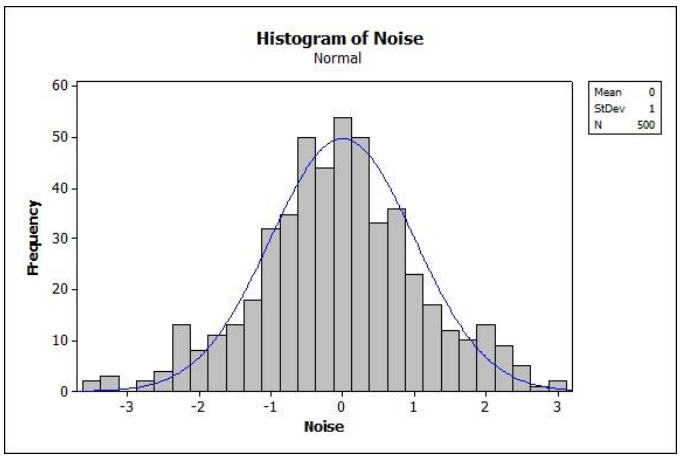

Figure 4: Perlin noise (1D) applied to a standard Normal distribution

In order to obtain realistic wind fluctuations, the configuration parameters of the Normal distributed noise function are parameterized using the wind statistics of the Frankfurt Airport environment. For this purpose, the wind field data are taken from NOMADS database [13]. The data is available in GRIB format [14] and provide an appropriate resolution of measurement points (resolution 0.5 degrees). To derive a reliable wind statistic, 160 synthetic flights were generated and systematically directed through the Frankfurt airspace. Finally, the wind measurements are statistically fitted with a Normal distribution per altitude band (parameters are mean value and standard deviation, see fig. 5).

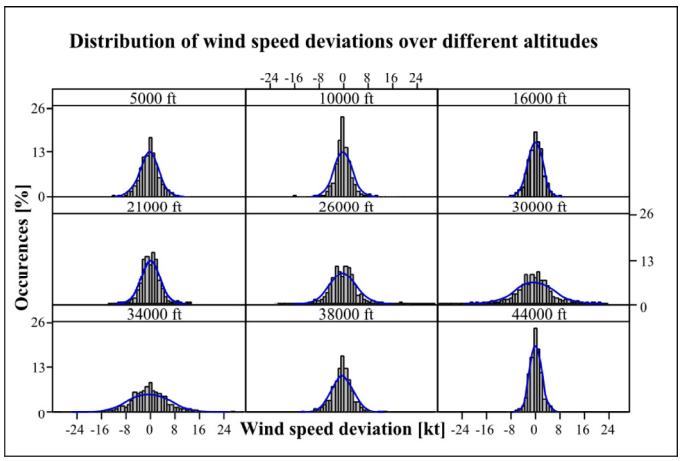

Figure 5: Wind field data from simulated flights through the eTMA of Frankfurt Airport

One wind profile is initialized per simulation run and used for the trajectory prediction process of the AMAN and the modeled flight management systems by the ATS. The actual atmosphere experienced by the aircraft is a dynamic 4D wind field that depends on time and location (altitude, latitude, and longitude). In the following fig. 6 the noise characteristics are shown for one example flight to EDDF.

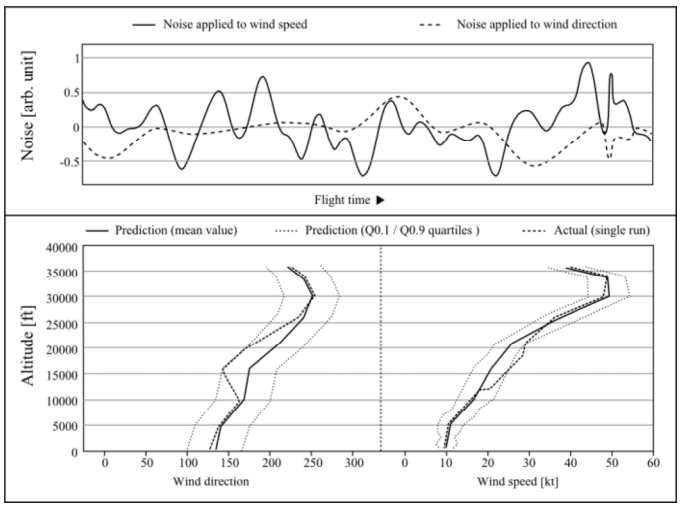

Figure 6: Application of derived stochastic wind field

B. *Adverse Weather Conditions*

In line with SESAR Concept of Operations the UTOPIA consortia identified the atmospheric conditions as one dominant contributor to uncertainty in trajectory prediction and synchronization. The evaluation of common European weather impacts led to the elaboration of few, but major phenomena. Based on these findings, the weather evolution inside the eTMA will be an important shape parameter of the UTOPIA

scenarios, beside the mandatory airspace/ aircraft/ procedure variations. To reflect the real weather conditions at Frankfurt Airport (including the surrounding eTMA), reliable data sources from the national/international weather service were analyzed. To derive significant weather phenomena, precipitation radar information was taken as a primary input. As shown in Figure 6, the precipitation radar data are a reliable indicator for the location and motion of the weather phenomena. The precipitation radar information is typically updated every 15 minutes. Due to the fact that only significant weather phenomena are focused for the scenario building process within the UTOPIA project, historical weather events were identified and the corresponding radar information (grid of 512x512 data points representing the area of central Europe [15]) with a dimension of approx. 2000x2000 km leading to a resolution of approx. 4 km per data point (see fig. 7).

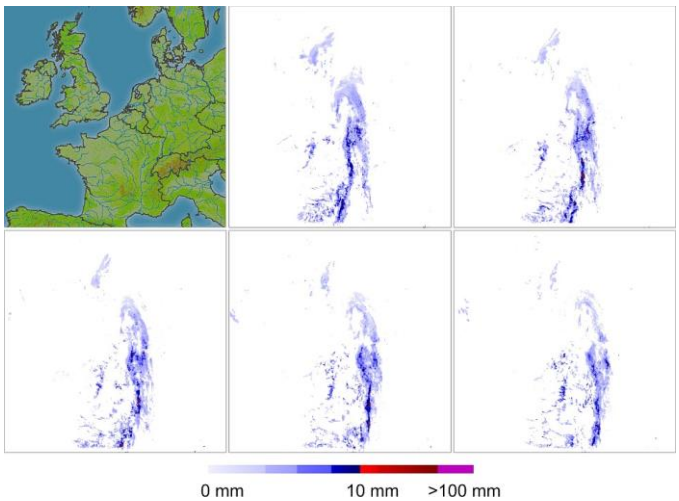

Figure 7: Progress of precipitation radar observations over central Europe (01.11.2011, 8:00 – 12:00, from top left to right bottom)

The severity of the flight conditions is directly linked to the proposed scale for mm precipitation [15]. This scale ranges from light blue (*marginal* conditions, < 0.2 mm/h) up to purple (*extreme* conditions, > 150 mm/h). Herein the precipitation is deduced from the measure of the radar reflectivity in a decibel (dBZ) range. *Heavy* (> 10 mm/h), *very heavy* (> 30 mm/h) and *extreme* conditions are frequently accompanied by strong convections, lightning strikes, and thunderstorms. Thunderstorm cells should thus not be travelled, because of threats coming from heavy vertical winds (downburst), wind shear or electrical fields inside the cells. Furthermore, those cells should never be passed below, as large turbulences due to vertical winds and the wind shear should be expected. Flying above the cells is a safe procedure during the growing stage, but only with large safety clearance (around 1000 ft per 10 kt upwind), because of the fast vertical growth and requires sufficient flight performance. Typical thunderstorms reach upwind speeds up to 38kt. Furthermore, after 15 min lifetime, passing above the cell tends to become impossible, because the cloud may exceed maximum operating altitude of the aircraft. Thunderstorms should be flown around horizontally with a minimum distance of 20 NM.

Thunderstorm cells are modeled according to the typical evolution of such a cell. They develop in a labile stratified atmosphere with a large relative humidity. Over a typical lifetime of 45 min the spatial and temporal resolution of the model is 1 km and one minute, respectively. The development of thunderstorm cells comprises three phases: cumulus, mature, and dissipating stage.

Often, thunderstorm cells occur nearly simultaneously. They are arranged according to the geostrophic wind and move in this wind direction. Typically, they do not share the same development stage which leads to a much longer lifetime of the thunderstorm. Further, the geostrophic wind causes a shear of the cells themselves and of the arrangement of the cells. In UTOPIA the weather model provides the evolution of the radius of the thunderstorm cell in the dedicated atmospheric layer. This model is simplified (piled layers) as aircraft are assumed to bypass and detour the thunder cell horizontally. Fig. 7 demonstrates the radius of the cell, which must be flown around without any safety clearance (to be added) of four dedicated altitudes.

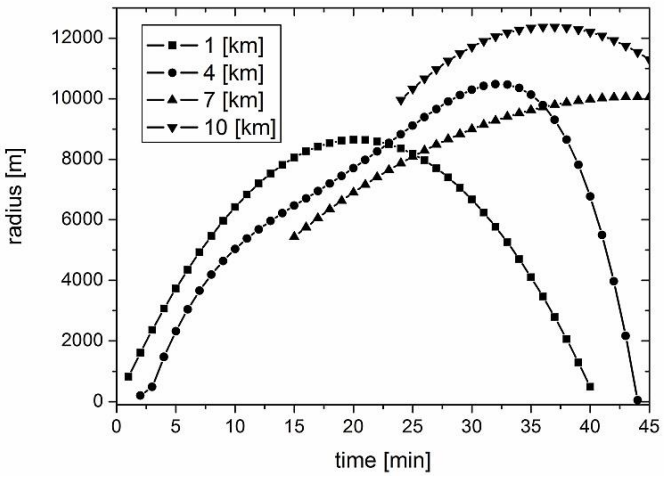

Figure 8: Development of the radius of the thunderstorm cell in four different altitudes

Based on this simplified weather model and the previous weather data screening the movement of thunder cells in the area of Frankfurt eTMA was combined to (adverse) weather scenarios. Herein each grid point of the radar with at least a *heavy* rain conditions was taken as the originating point of one thunderstorm cell.

To horizontally reroute the aircraft around a generated thunderstorm cell, the underlying regular grid structure with a size of the grid cell of 4x4 km is used. The proposed algorithm [16] is already developed for an environment, which is based on a regular grid. Finally, the algorithm provides a flow field (2D normalized motion vector), which contains the heading to the defined destination from any point of the grid considering all grid cells blocked by adverse weather conditions (solving a single-source shortest path problem). An example is shown at the following fig. 9.

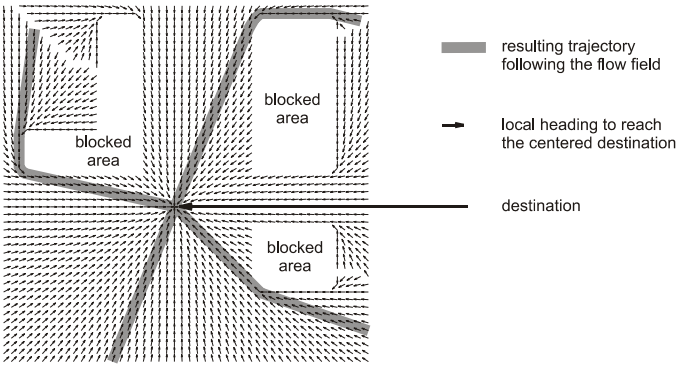

Figure 9: Local flow field heading to centered destination

If the corresponding distances are large against the size of the thunderstorm areas, the algorithm points out some deficiencies, which immanently arise from microscopic focus of the calculation process (local heading) and macroscopic view of the resulting trajectory. These deficiencies are caused by two effects, so in some cases the algorithm does not a) detect small obstacles or b) extend trajectories (see fig. 10).

To ensure the calculation of reliable detours (trajectory with the shortest path), two additional steps are introduced. First, if the algorithm does not detect small weather cells (visibility testing between connected way points), the trajectory is split up into temporal segments (half distance between waypoint and weather cell) until the resulting trajectory is free of obstacles. Second, an iterating cut off process minimizes the trajectory length replacing distant or redundant way points. The cut off process runs as follows: while cut off process, reduce trajectory length, do for each set of sequentially connected way points A, B, C:

- insert temporal way point I between A and B and II between B and C (including A, B, C),
- change position of I and II until the distance between A – I – II – C reaches a minimum,
- remove B if B != I or B !=II,
- insert I if I != A or I != B, insert II if II != B or II != C.

The progress of the cut off algorithm is shown at the following fig. 10.

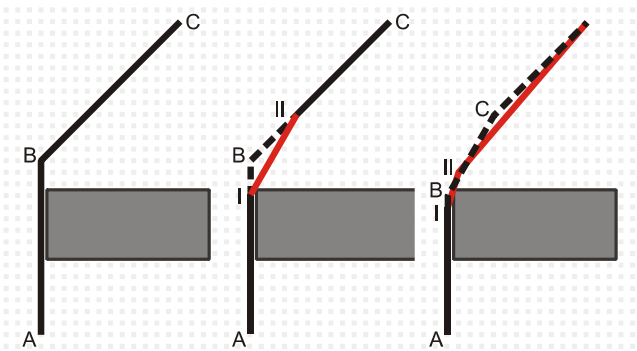

Figure 10: Cut off algorithm for generation of shortest paths on regular grid

The application of rerouting algorithm to the aircraft trajectories to avoid adverse weather conditions (yellow cells) is shown at fig. 11 (running inside the TABATS client).

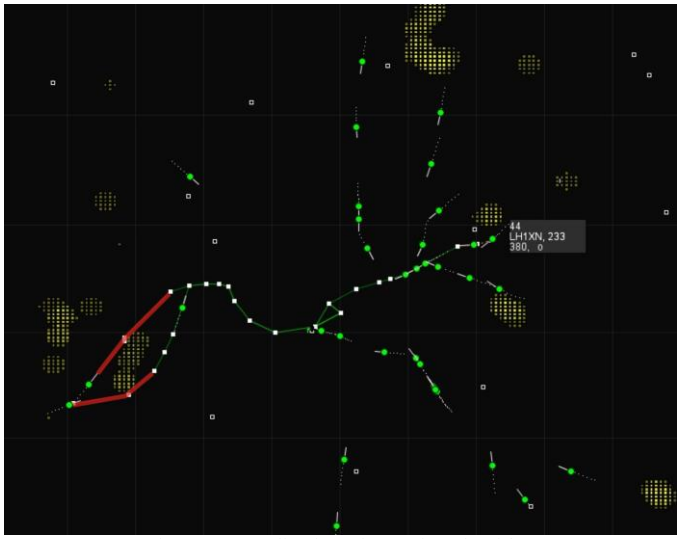

Figure 11: Application of rerouting algorithm

III. Scenario Setup and Performance Metrics

This section describes the UTOPIA demonstrator airspace and traffic setup and gives an overview over the arrival manager advice and the metrics which were used to analyze the performance of the automated arrival management system (fig. 12).

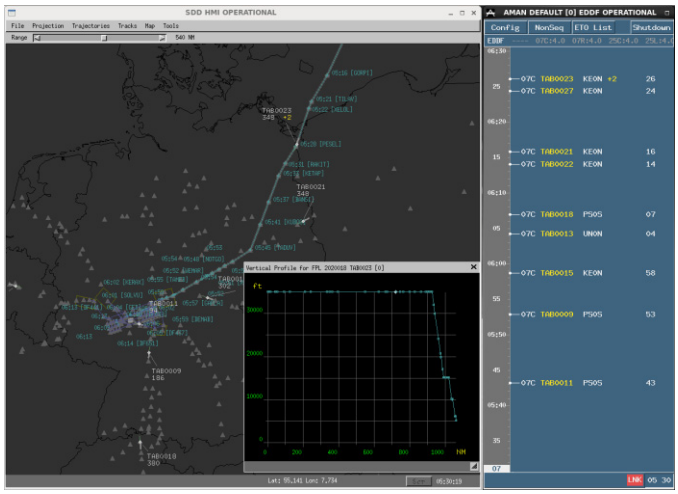

Figure 12: Arrival management system

A. Airspace

The UTOPIA project uses the eTMA of the Frankfurt/Main airport in its previous three runway setup to conduct its simulations with a planning horizon of up to three hours. The EDDF simulations use a subset of the RNAV Z approaches to the 07C runway including the variable 'trombone' path stretching patterns. Fig. 13 shows the RNAV 07 approach transition including the used holding patterns (circles) and the approach trombone variants (dashed lines).

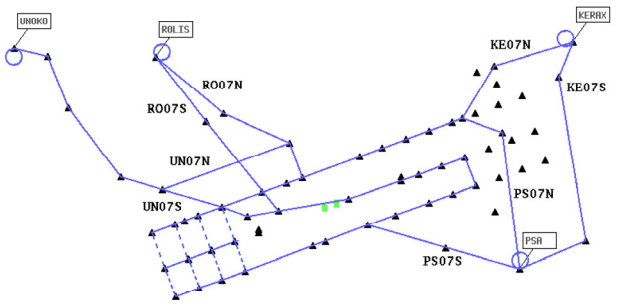

Figure 13: EDDF RNAV 07 approach transitions.

B. *Traffic Variations*

The simulated traffic is generated based on a sample of one day of European traffic supplied by Eurocontrol's Network Operations Division. The EDDF inbound traffic is modified to vary major input parameters, e.g. the flight density, distribution of the wake turbulence categories (WTC), or RTA capability rate of aircraft. Each resulting flight is then mapped to one of the aircraft types which can be simulated by the FACT or TABATS air traffic simulators. The following three major traffic variations are implemented: **1)** Two WTC variations consider the early morning arrivals between 4am and 7am and the afternoon traffic between 4pm and 7pm. The morning is dominated by heavy Trans-Atlantic flights while the afternoon features mostly medium Inter-European flights. **2)** The traffic density has been adjusted with respect to the European traffic data to generate a realistic density with an average aircraft delay of more than 10 minutes in the morning and about 5 minutes in the afternoon. This takes into account the chosen approach separation of 4nm for the 07C runway resulting in a maximal runway capacity of 35 landings per hour. **3)** Different amounts of traffic caused by unmanned aerial systems (UAS), which are simulated with comparable aircraft (represented by a model of a Cessna 550 aircraft).

C. *Arrival Management Advice*

The arrival manager creates different advice for the simulated aircraft to organize the approach traffic. If at a certain point in time the inbound traffic density exceeds the runway capacity a sub-set of the flights has to be delayed or accelerated. Close to the airport delay can be absorbed by flying holding procedures, using longer approach trombones and by modifying the approach transition in a more fine grained fashion (vectoring). In early stages a flight can be accelerated or slowed down by CTA (calculated time of arrival) or RTA advice. The simulations were executed with different amount of flights being able to implement CTA/RTA advices.

D. *Performance Metrics*

The section summarizes the most important metrics extracted from the simulated traffic which are used to judge the quality of the automated arrival management process. These metric values can be split into two categories. External metrics reflect values relevant for passengers, airports and airlines. Internal metrics inspect inner parameters of the arrival management process, the air ground communication etc. First, a summary of the external metrics:

- The *fuel consumption* is of course import for the airlines and shall be minimized as far as possible.
- The *average flight time* or respectively the *average flight delay* are relevant for all participants of the flight and arrival process.
- The *runway throughput* is import for the airport and shall be as close as possible to its theoretical maximum if the air space is congested.

From the internal arrival management system viewpoint some of important metrics are:

- *Sequence stability* and *planning time stability* reflect how often position changes in the arrival sequence occur and how stable a scheduled arrival time during the last flight period is. The sequence stability also affects controller work load.
- The *delay distribution* is defined by all flight delays in the current arrival sequence. The arrival manager tries to distribute delays to the flights as equally as possible among other optimization goals.
- *CTA/RTA accuracy* measures how precise aircraft can execute the advice. In this context it is important that RTA advice can be updated in flight.
- The arrival manager *advice frequency* contributes to the air ground communication bandwidth which is a limited resource.

IV. Simulation Results

This section discusses some of the important results derived from the UTOPIA demonstrator simulations. The simulations cover three areas summarized as follows: The **baseline simulations** investigate and verify the functionality of the automated arrival management system as set up by the UTOPIA demonstrator. The **uncertainty related simulations** cover wind prediction uncertainties, airport take off time prediction uncertainties and disruptions due to bad weather flight path re-routings as presented in the previous section. **Air ground synchronization experiments** consider two types of mechanisms which exchange information between aircraft and the ground side to optimize the arrival management.

A. *Baseline Simulations*

Within the context of basic simulator setup two aspects are of importance and interest. First, the basic management using holding and vectoring advice is verified. Second, the impact of an increasing number of CTA/RTA capable aircraft on the metric values is presented. The figures below show how the landing rates without aircraft advice (fig. 14) and after active arrival management via holding and vectoring advice (fig. 15).

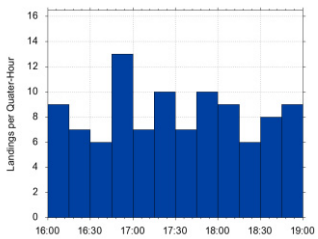

Figure 14: Without advice.

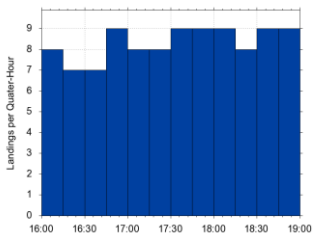

Figure 15: Holdings and vectoring.

It can be seen how the arrival flow is normalized to the expected maximal amount of 8-9 landings per quarter hour. Fig. 16 gives an overview of the issued advice during the afternoon with 50% CTA/RTA capable flights. Each flight entering the radar horizon receives an approach advice assigning standard terminal arrival route (STAR) and runway. Flight deceleration for delay absorption is first advised using CTA/RTA advice. Holdings are assigned to flights with more than 8 minutes remaining delay in the proximity of the holding fixes. Final flight delay is absorbed by trombone path stretching using vectoring advice

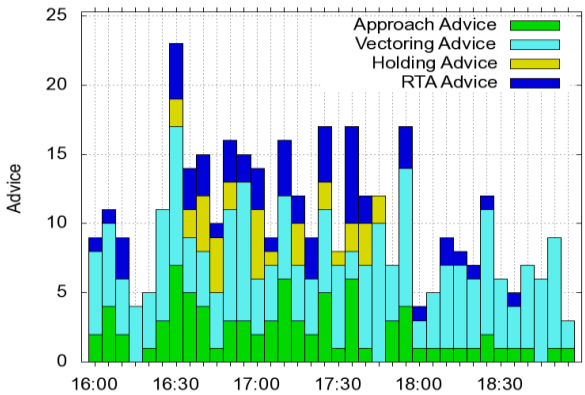

Figure 16: Advice statistics with 50% RTA capable flights.

The fig. 17 depicts the time development of the average planned delays for the flights in the arrival sequence. Comparing fig. 16 and fig. 17 shows how the decreasing delay towards the evening leads to less issued holding advice.

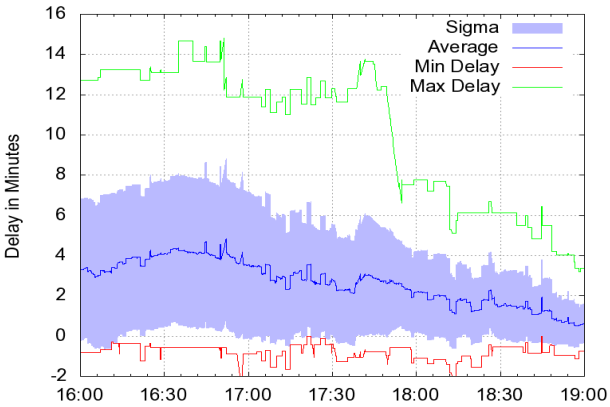

Figure 17: Afternoon AMAN sequence delays.

The following tab. I contains the dependency of external metrics on the amount of RTA capable flights for the morning scenario. Each value is averaged over all flights landed during the simulation evaluation time. The amount of RTA advice is calculated for the RTA capable flights respectively. The fuel consumption shows a clear decrease with the increase of RTA capable flights. This is an expected benefit of the utilization of RTA advice. An interesting effect in this specific UTOPIA setup is that the fuel consumption benefits saturate at about 50% CTA/RTA capable traffic. With higher amounts the runway capacity decreases and the delays increase. The results with high RTA flight fractions possibly contain simulation artifacts due to the high computational overhead of the RTA optimizations. Further simulations could analyze in more detail the different possibilities to setup and vary the parameters which handle the CTA/RTA advice issuing logic.

TABLE I. RTA CAPABILITY ANALYSIS

RTA Capability	**0%**	**25%**	**50%**	**75%**	**100%**
Fuel Consumption [t]	9.4	9.2	8.6	8.5	8.6
RTA Advice	0	3.32	4.0	4.3	4.7
Holding Advice	0.9	0.8	0.7	0.7	0.7
Landings	105	101	102	101	98
Delay [min]	13	14	14	18	20

B. Weather Prediction Uncertainty

Another set of simulations investigate the uncertainty introduced to trajectory prediction and arrival planning due to the differences between predicted and actual wind fields. Both the aircraft flight management systems (FMS) and the arrival manager use the predicted weather wind field to predict the flight trajectories. During the simulations the simulated aircraft experience wind field fluctuations according to the model presented in this document.

Fig. 18 shows the uncertainty the wind fluctuations introduce within the estimated arrival time calculated by the FMS trajectory prediction.

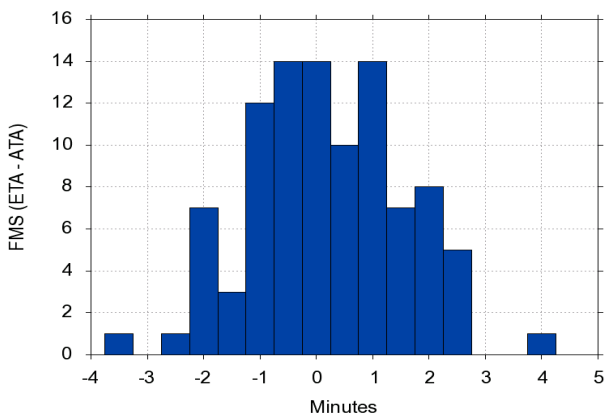

Figure 18: Wind fluctuation induced FMS arrival prediction uncertainty.

Without this uncertainty contribution the simulators maintain a prediction error less than half a minute. This setup uses the morning traffic sample with about two hours average flight time and a homogenous predicted wind field with an intensity of 50 knots from the east. Using this weather prediction uncertainty model the negative impact of growing trajectory prediction uncertainties on the arrival management process can be shown. The arrival manager planning stability decreases and strong wind fields even drop the landing rates below the nominal runway capacity.

C. Bad Weather Disruptions

The bad weather disruption (BWD) scenarios simulate areas with adverse weather conditions moving through the arrival managed airspace. These thunderstorm cells force a number of aircraft to take alternative routes which deviate from the originally planned flight paths. The BWD events introduce a respective uncertainty into the arrival management process as at some time they force aircraft to re-plan to alternative routes.

The final fig. 19 shows the impact of bad weather cell induced re-routings on the initial flight time planning. Although this example scenario uses a larger bad weather front only a few aircraft are forced to take longer detours. Figure depicts in contrast that wind fluctuations have a more moderate effect but on the other hand affect most of the flights. The negative effect of the flight path changes can be observed in decreased arrival management stability, higher fuel consumption and larger flight delays. Within this simulation context an air-ground synchronization mechanism is investigated. It transmits the flight path adaptations to the arrival manager which uses this information to immediately adapt the arrival sequence. Without this method the ground side guesses the aircraft intent changes based on the radar surveillance data. With this air-ground synchronization the affected flights are re-scheduled in an earlier stage avoiding detrimental re-sequencing.

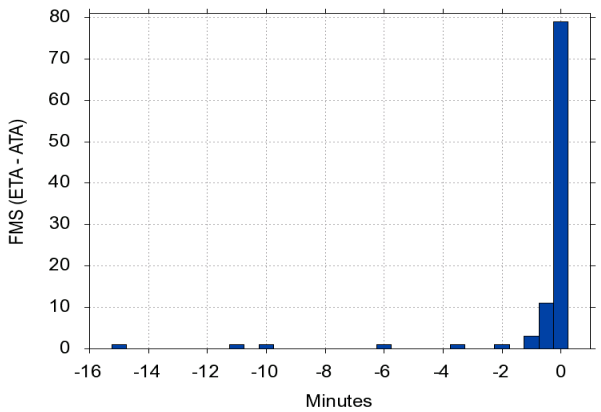

Figure 19: FMS arrival prediction in bad weather.

V. SUMMARY

The UTOPIA demonstrator environment points out the significant influence of stochastic input factors to the aviation systems. In the course of the model generation it becomes apparent that the coherent noise technique is a key element for stochastic applications. The developed environment allows a comprehensive study of future traffic characteristics. The AMAN manages different kind of traffic scenarios, where a heterogonous mix of traffic is controlled by different ATS (TABATS, FACT, and a A320 simulator). Besides the proven functionality of the distributed simulation network, the capability to include independent air traffic simulators with different capabilities is solid basis for reliable evaluation of future concepts of operations. In the context of the SESAR long-term and innovative research the UTOPIA project delivers crucial findings for handling inevitable uncertainties predicting the aircraft trajectory. Therefore, this demonstration environment should now be included at following industrial and academic research activities to ensure a seamless knowledge transfer from UTOPIA and to strengthen the European research community.

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