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 & 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 was 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 focused 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 was 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 explored 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 of the future ATM system. One of the key elements of UTOPIAs research was the integration of both airborne and ground-based systems and a heterogeneous user (aircraft) population. In particular, UTOPIA focused two important areas: 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 and first results were already presented [1, 2].

I. Introduction

During the course of the project, essential scientific and operational fundamentals were comprehensively investigated and prototypical implementations were realized to provide a functional proof of concept. This includes the review and gap analysis of the concepts foreseen by SESAR to be implemented by 2015/2020, 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 was specified during the course of the project. In this context *extended* means a 500+ NM increased TMA with considerably larger look ahead times of up to three hours to the scheduled time of arrival of an aircraft at the airport. The terminal operations were considered in UTOPIA in terms of inbound sequencing. Since the sources of system uncertainties are heterogeneous [cf. 3], a qualified classification method was required. Therefore, the sources of uncertainties were identified and categorized into different classes. Finally, the specific synchronization parameters were determined by evaluating their statistical significance. The most common areas of uncertainties were related to the: **a)** environmental 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 were appropriate modeled. Since a synchronized trajectory was 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 anticipated 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 used a virtual ATM demonstration environment with interacting agents (system entities with the capability of autonomous acting and decision making [cf. 4, 5]), where agents acted in an extended terminal maneuvering area around Frankfurt Airport (EDDF) to implement the proposed concept of operations. The derived capabilities of the agents systematically allowed the implementation of stochastic characteristics of input parameters within the simulation environment. Herein, a crucial component was the modeling of

This work is co-financed by EUROCONTROL acting on behalf of the SESAR Joint Undertaking (the SJU) and the EUROPEAN UNION as part of Work Package E in the SESAR Programme. Opinions expressed in this work reflect the authors' views only and EUROCONTROL and/or the SJU shall not be considered liable for them or for any use that may be made of the information contained herein.

atmospheric conditions and weather patterns, which were considered to be the main impact factor for uncertain flight intents. To handle this, the TUDD approach of a corridor of uncertainty was used within the UTOPIA project [6].

The UTOPIA demonstration environment is a TCP/IP networked simulation environment combining an enhanced arrival management (based on Barco's 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 was extended to act as an agent in the simulation environment and showed a possible implementation of the required data-link procedures for the 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) served as the middleware component for the required information exchange between the several independent UTOPIA systems and enabled the fully automated execution of the simulation runs. The DCP architecture is outlined in fig. 2. The DCP ensured an appropriate synchronization between the demonstrator components and efficiently managed the message distribution including filtering to avoid unnecessary network traffic. Each demonstrator client system had its own IO thread that optionally contained specific translators/importers to interpret the standardized messages regarding the native command language of the respective demonstrator client.

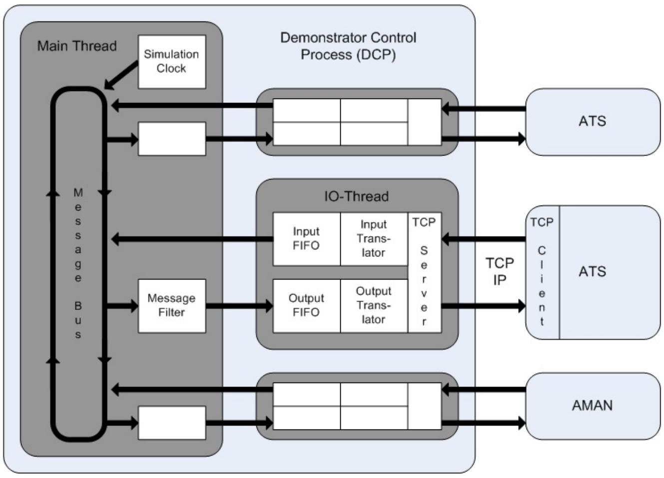

Figure 2: UTOPIA system architecture

Since the interaction between the UTOPIA systems was realized through the DCP using TCP/IP technology, the ATS were integrated in the demonstrator architecture without being at one physical location. The exchange of dynamic data was 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 are transferred by 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).

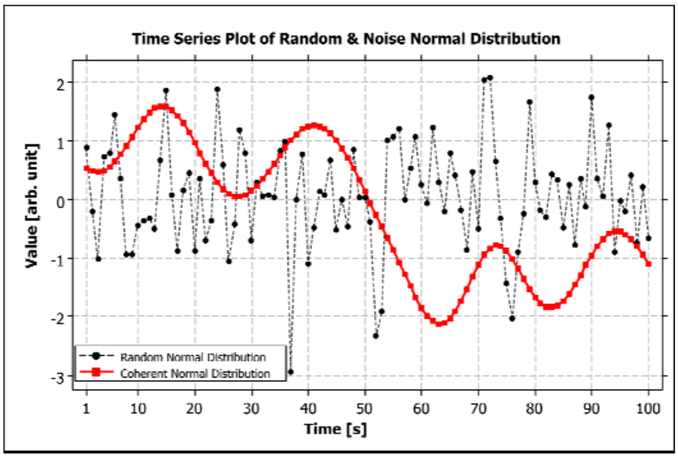

Figure 3: Random noise vs. coherent noise characteristic

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).

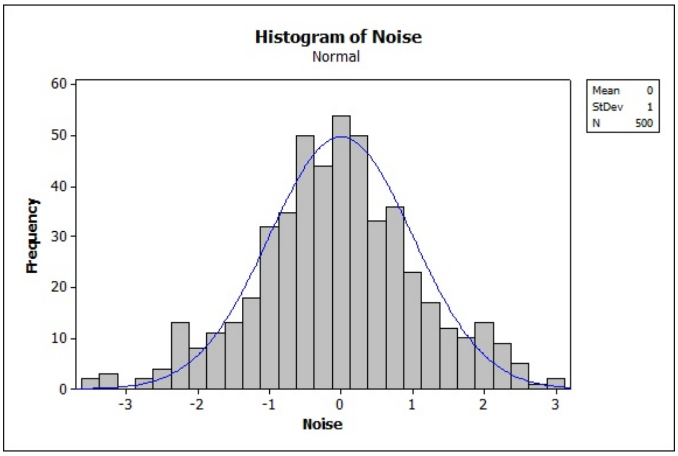

Figure 4: Perlin noise (1D) applied to a standard Normal distribution

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).

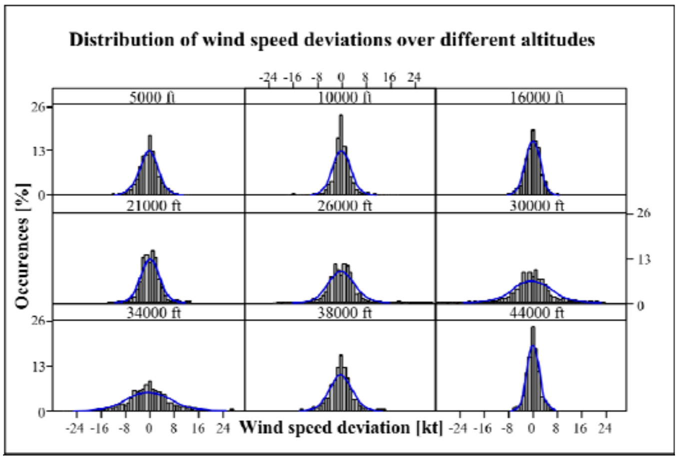

Figure 5: Wind field data from simulated flights through the eTMA of Frankfurt Airport

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.

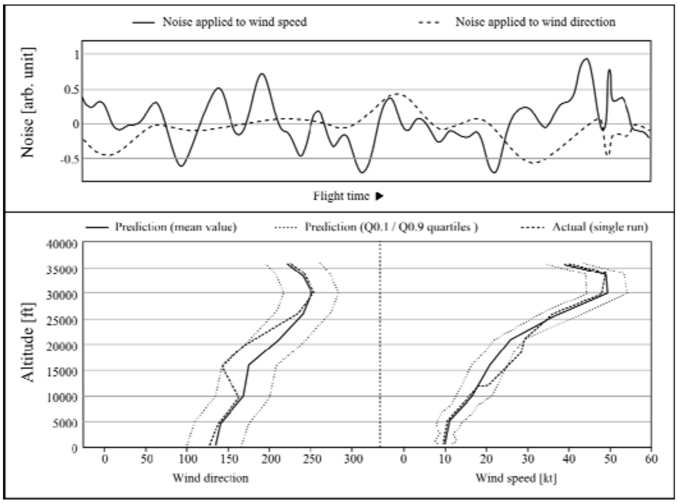

Figure 6: Application of derived stochastic wind field

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).

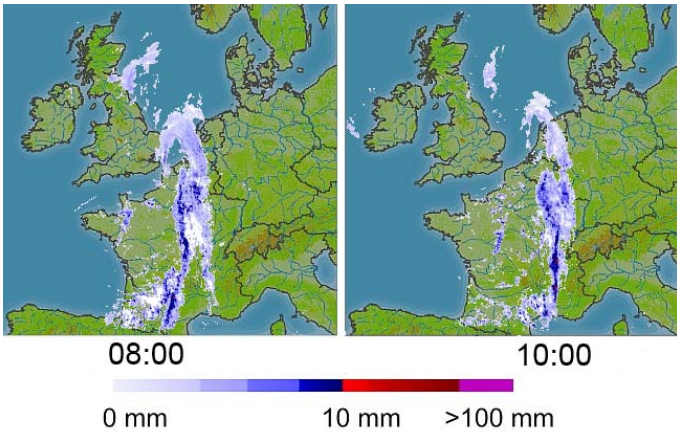

Figure 7: Progress of precipitation radar observations over central Europe (recorded November 1st, 2011)

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. 8 demonstrates the radius of the cell, which must be flown around without any safety clearance (to be added) of four dedicated altitudes.

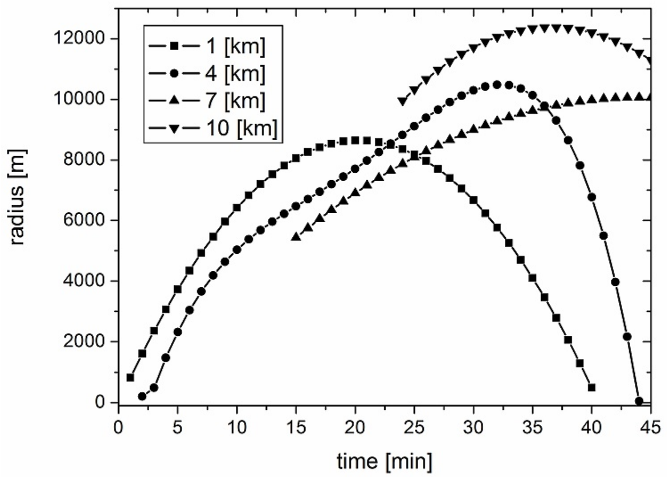

Figure 8: Development of the radius of the thunderstorm cell in four different altitudes

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.

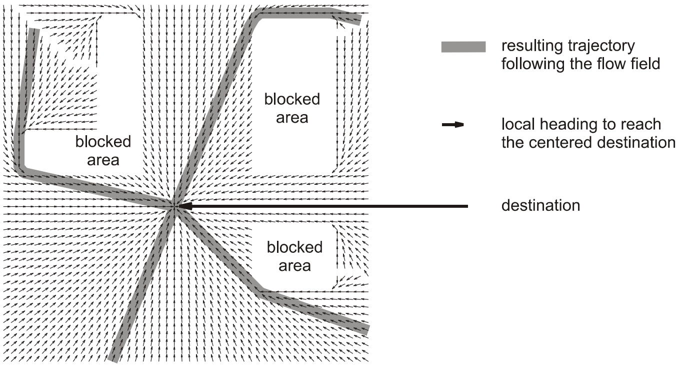

Figure 9: Local flow field heading to centered destination

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 the process is running, reduce trajectory length by executing the next 4 steps 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.

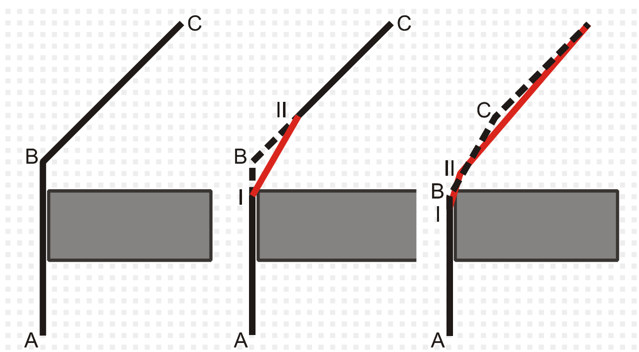

Figure 10: Cut off algorithm for generation of shortest paths on regular grid

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).

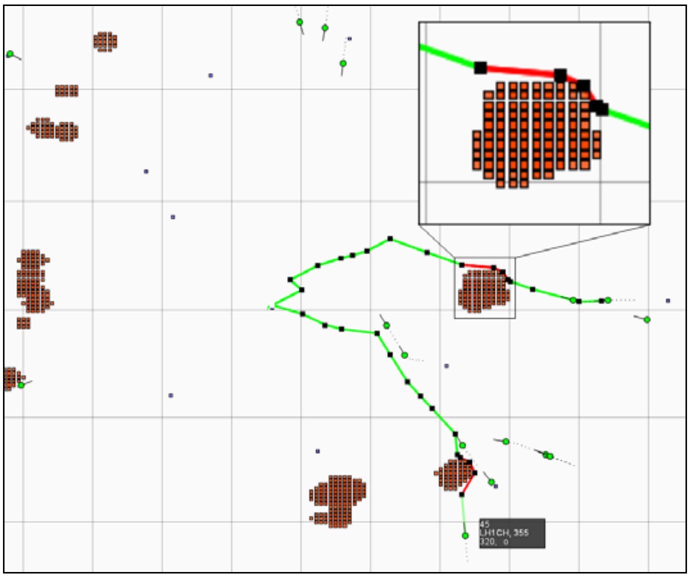

Figure 11: Application of rerouting algorithm

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).

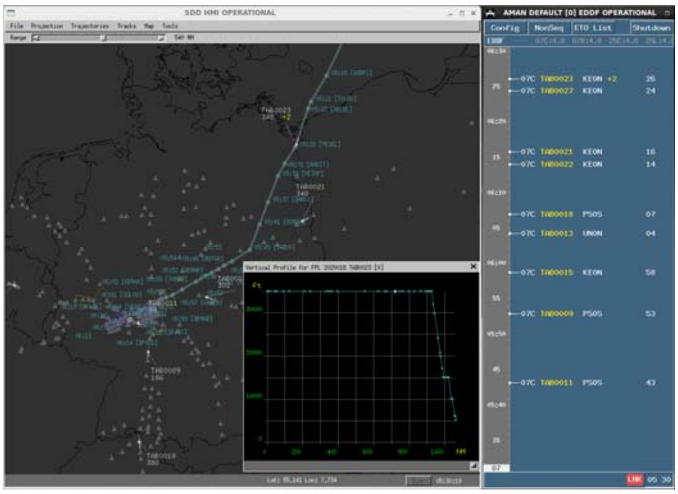

Figure 12: Arrival management system

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).

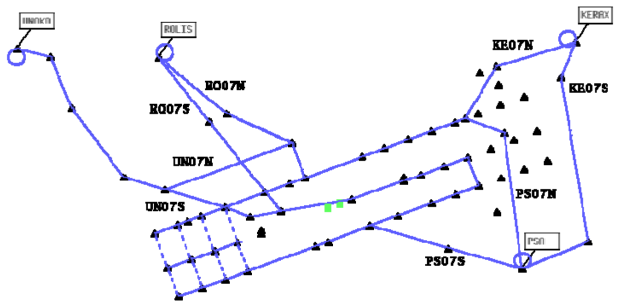

Figure 13: EDDF RNAV 07 approach transitions.

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 (controlled 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).

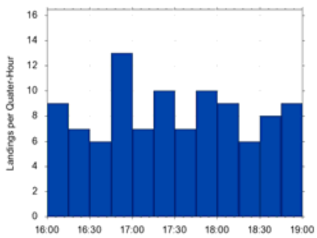

Figure 14: Without advice.

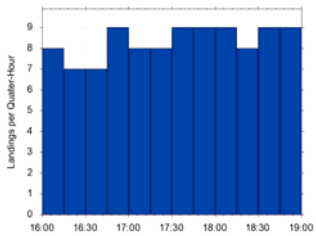

Figure 15: Holdings and vectoring.

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

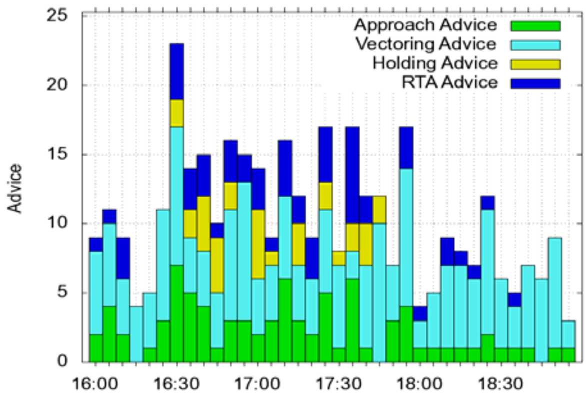

Figure 16: Advice statistics with 50% RTA capable flights.

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.

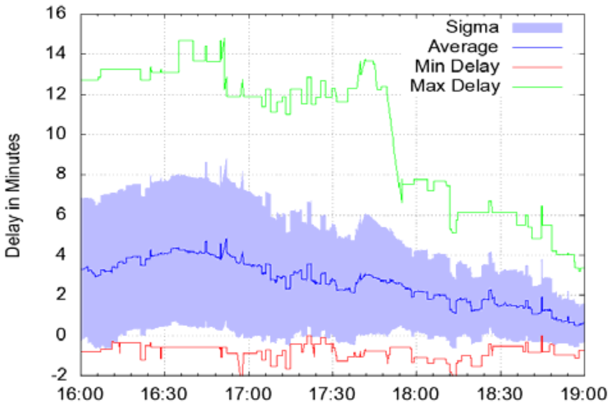

Figure 17: Afternoon AMAN sequence delays.

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.

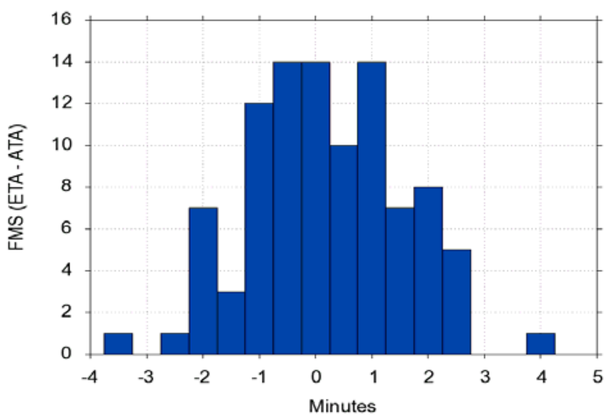

Figure 18: Wind fluctuation induced FMS arrival prediction uncertainty.

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.

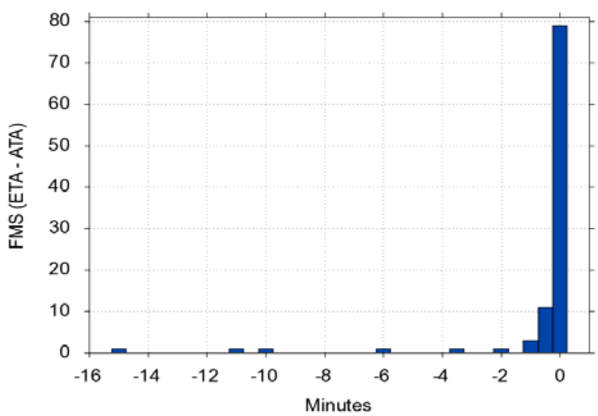

Figure 19: FMS arrival prediction in bad weather.

V. SUMMARY

UTOPIA (*Universal Trajectory Synchronization for Highly Predictable Arrivals Enabled by Full Automation*) aimed at integrating new types of airspace users and the consequences arising from the continuous increase in delegating capacity and safety critical traffic management functions to automated systems. The solution proposed in UTOPIA was articulated in three innovative areas: 1) Study **uncertainty sources** and their propagation including the potential of system disruptions by introducing multi-dimensional aircraft trajectories to allow consistent data handling. 2) Advanced **trajectory management** algorithms and ground **synchronization** functions acting as decision support to both systems and users. 3) Use of **formal language** for trajectory data transmission and trajectory synchronization protocols for heterogeneous systems and users in an automated environment.

The UTOPIA demonstrator environment pointed 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 allowed a comprehensive study of future traffic characteristics. The AMAN managed different kind of traffic scenarios, where a heterogonous mix of traffic was controlled by different ATS (TABATS, FACT, and an A320 simulator). Besides the proven functionality of the distributed simulation network, the capability to include independent air traffic simulators with different capabilities is a solid basis for reliable evaluation of future concepts of operations. In the context of the SESAR long-term and innovative research the UTOPIA project delivered crucial findings for handling inevitable uncertainties predicting the aircraft trajectory. The key findings from the UTOPIA project are summarized regarding their impact to major research topics.

Economy: By increasing the portion of airspace users ready for synchronization, receiving a required time of arrival (RTA) when entering the extended 3 hour horizon TMA, a reduction of fuel consumption of up to 9% could be measured.

Transmission: The required communication bandwidth nearly doubled for the RTA advisory scenarios compared to non-RTA scenarios.

Capacity: Increasing the share of light unmanned aerial systems (UAS) up to 50% caused a drop of runway capacity of down to -7%, mainly caused by extended wake vortex separation requirements. UAS flights were simulated by the BADA model of a Cessna 550 aircraft.

Uncertainty: The consideration of uncertainties in wind prediction within trajectory management decreased the planning stability of the arrival management (AMAN). The simulated uncertainties caused an increase of arrival sequence exchanges up to 200%.

Synchronization: Flight path changes due to bad weather cells were simulated within the UTOPIA demonstrator framework. Aircraft performing re-routings notified the AMAN of the flight path changes, effectively implementing an air-ground synchronization functions. With these air-ground notifications flights were re-scheduled in an earlier stage and thus avoided detrimental re-sequencings.

Aircraft Intent Data Transmission: Aircraft intent and trajectory information was made available to the ground-based arrival management function by using formal language to enhance the ground side trajectory prediction. This function also allows the AMAN to quickly adapt to speed changes of flights which follow CTA/RTA instructions, leading to a planning stability increase of up to 40%.

Vectoring Optimization: After having left or passed the holding fixes the aircraft receive a final vectoring advice by the arrival manager. This advice is optimized using feedback from the aircraft FMS. As a result 95% of the flights touched down with less than 5 seconds deviation from the arrival time scheduled by the AMAN.

Technically, the developed UTOPIA demonstrator proved being a robust test environment to study highly automated air traffic management concepts with emphasis but not limited to arrival management functions, uncertainty source modelling, and heterogeneous traffic configuration analyses. The state of the art operational procedures like holdings and path stretching were extended by studying CTA/RTA approaches.

The effect of relevant sources for uncertainty together with appropriate air-ground synchronization mechanisms could be evaluated in various traffic mix and configuration scenarios against today's ATC concept of traffic operations. We could show that the dynamic exchange of air-ground data significantly improves the performance of the automated arrival management function especially when considering realistic uncertain atmospheric/weather conditions.

References

[1] M. Schultz, H. Fricke, M. Kaiser, T. Kunze, J.L. Leonés, M. Wimmer, P. Kappertz, "UTOPIA - Universal Trajectory Synchronization for Highly Predictable Arrivals Enabled by Full Automation", SESAR Innovation Days, Toulouse, France, 2011

[2] M. Schultz, H. Fricke, T. Kunze, J. Mund, J.L. Leonés, M. Wimmer, P. Kappertz, "Uncertainty Handling and Trajectory Synchronization for the Automated Arrival Management", SESAR Innovation Days, Braunschweig, Germany, 2012

[3] Pabst, T., T. Kunze, M. Schultz, and H. Fricke, Modeling external disturbances for aircraft in flight to build reliable 4D trajectories", International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS), Neapel, 2013

[4] M. Kaiser, J. Rosenow, H. Fricke, and M. Schultz, Tradeoff between optimum altitude and contrail layer to ensure maximum ecological en-route performance using the Enhanced Trajectory Prediction Model (ETPM), ATACCS, London, 2012

[5] M. Kaiser, M. Schultz, and H. Fricke, Automated 4D Descent Path Optimization using the Enhanced Trajectory Prediction Model (ETPM), (ICRAT), Berkeley, 2012

[6] M. Kaiser, M. Schultz und H. Fricke, Enhanced Jet Performance Model for High Precision 4D Flight Path Prediction, ATACCS, Barcelona, 2011

[7] López Leones, J., "Definition of an aircraft intent description language for air traffic management applications", PhD thesis, University of Glasgow, 2008

[8] Karamouzas, I. and M.H. Overmars, "Adding variation to path planning", in Comp. Anim. Virtual Worlds, 19, pp. 283–293

[9] K. Perlin, "An image synthesizer", in Proc. of SIGGRAPH'85, pp 287–296, New York, 1985

[10] K. Perlin, "Improving noise", in Proc. of SIGGRAPH'02, pp 681f, 2002

[11] S. Gustavson , Java implementation, "SimplexNoise.java", 2012, source: http://webstaff.itn.liu.se/~stegu/simplexnoise/SimplexNoise.java

[12] S. Gustavson, "Simplex noise demystified", 2005, http://webstaff.itn.liu.se/~stegu/simplexnoise/simplexnoise.pdf

[13] NOMADS Data Request, NOAA National Operational Model Archive & Distribution System, http://nomads.ncdc.noaa.gov/

[14] NCEP WMO GRIB2 Documentation, Version 11.0.0, http://www.nco.ncep.noaa.gov/pmb/docs/grib2/grib2_doc.shtml

[15] Meteox, http://www.meteox.de/hist.aspx

[16] M. Schultz, T. Kretz, and H. Fricke, "Solving the Direction Field for Discrete Agent Motion", in S. Bandini et al. (ed.) Cellular Automata - ACRI 2010, Proceedings. Volume 6350, Lecture Notes in Computer Science, pp 489-495, Springer, 2010