Uncertainty Handling and Trajectory Synchronization for the Automated Arrival Management

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***Foreword*—This paper describes a project that is part of SESAR Work Package E, which is addressing long-term and innovative research.**

***Abstract*—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, we will focus on the data models, synchronization requirements and algorithms needed to ensure the safe management of merging traffic in an extended TMA, 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 (WP-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 high degrees of automation. A detailed structure of the research done within the UTOPIA project is presented at [1].

I. Introduction

One main objective of the forthcoming development of the ATM Operational Services is to increase the predictability at given reliability levels (confidence intervals in the statistical sense) of the aircraft behavior within the ATM system, by reducing instabilities and system inefficiencies. The aircraft trajectories considered by the ATM systems will be the result of a collaborative planning process. Essentially, these trajectories capture the business objectives of the airspace users taking into account the applicable ATM constraints. To support the future trend of automation all trajectory-related information has to become the main piece of data being shared between all system partners involved. This trajectory-based information has to contain an accurate description on how a specific trajectory is intended to be flown (regarding user preferences like how a specific airline prefers to fly climb, en-route, and descent profiles based on an individual cost function) and how an aircraft is intended to be operated to follow that trajectory within a timeframe (detailed speed, lateral and altitude profiles as well as aircraft configuration e.g. flaps). It is anticipated that humans will not be able to manage such an amount of data, justifying the need for automated systems to assist both the controllers and pilots from the beginning until the automated solution shifts the distribution of human workload towards a supervising function while leaving the decision making process and monitoring to the automated systems.

The air traffic system possesses a non-deterministic nature, where a view on the system within a look-ahead time horizon of up to 2 hours is inherently incomplete. This is mainly caused by the uncertainty of the predicted states of the system (e.g. unknown meteorological conditions, flight delays, airline behavior, or center capacities). The objective of the UTOPIA project is to perform a qualitative and quantitative analysis of the effects of stochastic impact factors on the behavior of a fully automated control environment. Inside the UTOPIA project, detailed strategies will form our concept of operation to achieve dynamic trajectory synchronization between the automated systems and ensure that any future airspace user, with different levels of equipment and automation (e.g. new

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avionics generation versus legacy airborne systems) will benefit from the services and capabilities built in the future ATM system.

Other than existing solutions that are based on ICAO Annex 10 compliant surveillance equipment for tactical decisions (arrival management systems or decision support tools), the UTOPIA stochastic data model deals with a more strategic approach of handling highly flexible, individual aircraft trajectories (nD-trajectory [1]) with known levels of confidence, enabled by the synchronization of trajectory data between air and ground based systems. The synchronized data sets will as such include stochastic variance of certain key parameters to provide decision support systems with a prediction capability at known quality. UTOPIA`s targets consequently outline the next step to the concepts and technologies introduced by SESAR and will finally lead to a fully automated strategic trajectory management of heterogeneous airborne systems. SESAR foresees this change in a timeframe beyond 2025, corresponding to the target timeframe of the UTOPIA concept of operations.

II. PROGRESS OF UTOPIA'S RESEARCH

During the project lifecycle the essential scientific and operational fundamentals are comprehensively investigated and prototypical implementations are 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.

A. *Review and Gap Analysis*

The initial analysis describes the commonly expected situation of the air traffic management network in 2020, which the SESAR Consortium pointed out in the European ATM Masterplan. Insights on trends and technologies which are used to achieve the new ATM concepts using Trajectory Based Operations (TBO) are explicitly highlighted. The goals of the two current ATM modernization programs SESAR and NextGen [2] have been reviewed as well. Also previous research projects (e.g. PHARE [3]), which dealt with TBO, were reviewed, since their progress and results are still highly relevant to the research within the UTOPIA project. Following the operational concept description of both SESAR and NextGen in the relevant areas of aircraft automation, ground automation and trajectory synchronization, the technical requirements for airspace users and ground-based systems to participate accordingly are focused. The review is complemented by a technical evaluation of current research activities in the associated fields of formal models and languages (used for predicting and synchronizing trajectory data), as well as sources of uncertainty which impact the accuracy and reliability of trajectory synchronization. Furthermore, current research activities in the areas of trajectory management and complex system modeling complete the technical review. The review and gap analysis shows that UTOPIA`s goal to develop a comprehensive and robust traffic synchronization concept is still an open, highly relevant research topic that will produce results vitally needed for the future ATM challenges.

B. *Concept Specification for mixed Traffic Operations in the Terminal Area*

UTOPIA's concept of operations (ConOps) in the widened terminal maneuvering area (extended TMA) with respect to mixed traffic scenarios has been specified (various types of aircraft with different capability levels) during the course of the project. In this context *extended* means a 500+ NM increased TMA with considerably larger look ahead times (LAT) referring to the scheduled time of arrival (and departure) of aircraft at the airport for which terminal operations are being considered in terms of inbound and outbound sequencing. The SESAR Milestone Deliverable 3 "The ATM Target Concept" [4] and the European ATM Master Plan as published in [5] were used to summarize the SESAR ConOps and the technological baseline of aircraft operations in the year 2020.

C. *Identification of Stochastic Parameters*

During the last decades of research, it has become evident that trajectory prediction is permanently impacted by uncertainties in the available data sets caused by limited prediction capabilities of the external (sensor) systems. These uncertainties will obviously impact the preferred performance considering the predicted and actual flight trajectories. Since the sources of system uncertainties are heterogeneous, a qualified classification method is required. Therefore, the sources of uncertainties are identified and allocated to different classes. Finally, the specific synchronization parameters are determined considering the significant classes. The most common areas of uncertainties are related to the:

- environment vagueness, e.g. random variations of environmental factors, e.g. wind fields, temperature profiles and humidity, local static and dynamic pressure characteristics
- operational factors of stochastic behavior and nature, e.g. variability with regard to the actual flight crew or flight management system (FMS) actions in a given situation as well as to the times at which those actions are implemented, or mismanagement of the flight crew due to human machine interface operating error.
- aircraft navigation performance (ANP) and guidance accuracy (precision of speed, altitude or direction tracking), e.g. random navigation and guidance errors, such as those captured by the ICAO standards for the required navigation performance (RNP) [cf. 6]

Network effects of these areas induce relevant system interactions, which consequently result in deviations of the planned trajectories in time and space. To evaluate and mitigate possible (negative) impacts on the data synchronization (common and identical "data picture" of the ATM system status), propagation aspects have to be modeled and appropriate control strategies must be developed (e.g. dependency analysis). Current system designs cover merely deterministic input data and derive essential information for the decision support systems, which also disregard the stochastic nature of the operational conditions of the ATM environment.

D. Stochastic Modeling

The corresponding UTOPIA activity covers all required theoretical background for modeling appropriate algorithms to efficiently handle the investigated causes of uncertainties, focusing on the relevant parameters that heavily impact the process needed for ensuring a synchronized view of the aircraft trajectory. Since the uncertainty modeling aims at the impact of varying input parameters in regard to the expected accuracy of the synchronized aircraft trajectory, the uncertainty effects cannot be easily absorbed by a predefined Total System Error (TSE) as proposed within the RNP/RNAV concept. For this reason, the concept of 4D trajectories according to SESAR and NextGen is being extended to an n-dimensional trajectory (nDT) approach combining the information of uncertainties transmitted to the existing ground prediction system. Using this n-dimensional information, the knowledge discrepancy between predicted trajectories (ground manager target) and real-time aircraft tracking (actual aircraft flight path and position) can be handled.

A synchronized trajectory represents a shared and timely aligned view of at least two stakeholders (typically ATM ground system and the flight deck) onto the flight status and the flight intent. To reach this, the physical, mathematical, and operational properties and dependencies have to be explicitly investigated. Therefore the stochastic modeling focuses on the selected stochastic parameters which are captured by todays/future sensor system and their associated implementation into the operational environment. 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 and synchronize the n-dimensional trajectory information between all involved trajectory predictors. Since a trajectory is considered as synchronized if all involved ATM stakeholders share the same collaborative view, a specific threshold has to be defined (corridor of uncertainty - COU) to point out the unsynchronized system status.

It may be noted, that the modeling does not consider pre-flight induced uncertainties such as delays as Take Off Time (calculated TOT vs. actual TOT) discrepancy not being subject of UTOPIA. All aircraft are assumed to already be in-flight, relatively on-time, and physically travelling the extended TMA airspace of a major hub airport.

E. Design Scheme for virtual System Environment and Description of derived Agent Capabilities

The virtual ATM environment and its agents (system entities with the capability of autonomous acting and decision making, see fig. 1) in an extended terminal maneuvering area around a major hub airport have been designed for the upcoming UTOPIA demonstrator phase. The description of agents and their derived capabilities pave the way to systematically incorporate the stochastic characteristics of input parameter within the simulation environment as identified in the previous research activities.

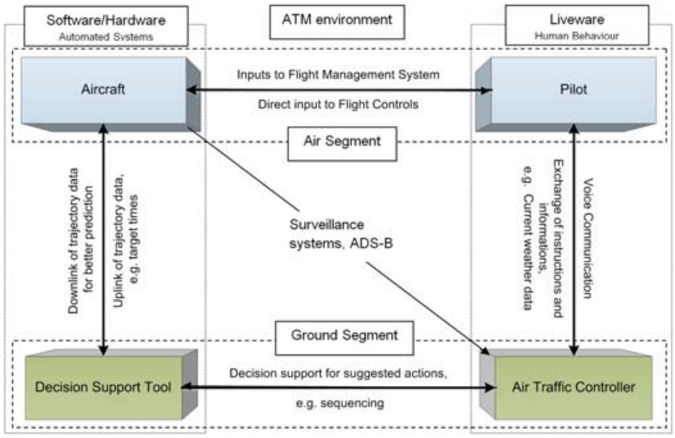

Figure 1: Simplified interaction between agents

A crucial design 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. Finally, a mandatory set of messages for inter-agent data exchange is derived, which will be further extended along the project progress incorporating the Aircraft Intent Description Language (AIDL) and related uncertainty information within the context of using formal languages.

III. SIMULATION ENVIRONMENT

The proposed trajectory synchronization concepts will be validated with simulation experiments by means of a demonstrator that models the interaction of different airborne agents and an autonomous arrival management system. The architecture and components of this simulation environment are described below. Implementation of the derived model fundamentals is an ongoing task in the project schedule.

A. System Layout/Architecture, Components

The UTOPIA Demonstrator 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) and *TU Dresden Agent Based Air Traffic Simulator* (TABATS), developed by BRTE and TUDD respectively. A Demonstrator Control Process (DCP) serves as the middleware for the required information exchange between the several UTOPIA systems, to run the simulation exercises fully automated. The DCP architecture is outlined in 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 language of the respective client.

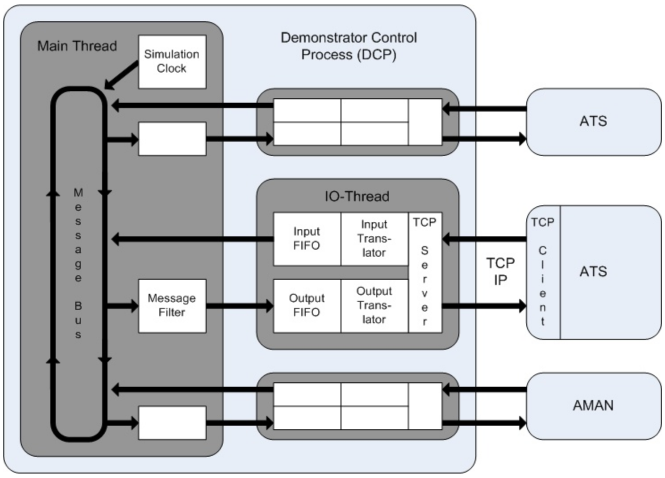

Figure 2: UTOPIA system architecture

1) Barco-Orthogon, Arrival Manager AMAN

The Barco arrival manager [7] uses flight plans, surveillance data and an airport configuration to calculate and optimize the aircraft arrival sequence of an airport. In its operationally used version the AMAN generates e.g. holding recommendations, speed advice, runway selections etc. to realize the optimal arrival sequence and schedule. In today's operations such advice has to be executed by the responsible controllers. The AMAN can take into account operational parameters like runway approach directions, runway closures, departure slots, aircraft emergencies, preferred runways for cargo aircraft etc. It is capable to handle these parameters and their changes in a time dependent manner. In the automated environment of the UTOPIA demonstrator the AMAN no longer serves as an advisory tool for the controllers, but directly issues instructions to the simulated traffic.

2) Boeing Research and Technology Europe, FACT

The Future ATM Concept Test bench (FACT) is an air traffic simulation environment developed by BRTE for conducting ATM performance assessments in the extended terminal area and prototyping innovative ATM concepts or technologies [8]. A three degree-of-freedom point-mass, kinetic trajectory computation engine (TCI) generates the flown trajectories covering the full aircraft state vector including forces, fuel consumption and aircraft configurations. Aircraft performance data is supplied by BADA 4 models1, supplemented with BADA 3 models for aircraft types not available in BADA 4.

A detailed model of the General Electric Flight Management System (GE FMS) supplied for the B737 powers the guidance and navigation of all simulated aircraft (see schematic aircraft simulation process of fig. 3). The FMS model serves the guidance reference trajectory prediction (TP) and the actual guidance around the reference. The modeled navigation capabilities include the automated Vertical and Lateral Navigation modes, and the Required Time of Arrival (RTA) function of the GE FMS. During flight execution, feedback loops trigger guidance reference recalculations as required. Deviations from the guidance reference trigger mode changes and corrective actions using automatic throttle activation and spoilers based on specific deviation thresholds. A pseudo pilot model times the required configuration changes of the aircraft. In accordance with legacy FMS capabilities a limited wind profile and temperature offsets can be supplied to the FMS TP from weather (WX) forecast data.

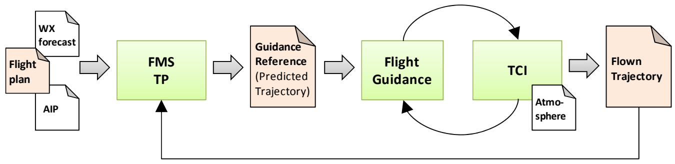

Figure 3: FACT Schematic Simulation Process

3) Technische Universität Dresden, TABATS

The ATM simulation environment developed at TUDD is an agent-based approach for conducting ATM related simulations and assessments. It includes a highly precise aircraft performance model, described in [9], to generate trajectories for the common civil airliner Airbus A320 and the McDonnell Douglas MD-11, which is mainly used as a freighter these days. The model includes the full aircraft state vector along the complete trajectory including aircraft configuration, fuel flow and forces. Additional aircraft models are available through a BADA 3-based performance model.

The Flight Guidance and Flight Management System model is derived from an Airbus A320 Flight Guidance and Control System (FMGCS). The model is used to generate the initial reference trajectory and the actual flight guidance once the aircraft is airborne as pictured in fig. 4.

The model currently includes the vertical navigation guidance, with lateral guidance and Required Time of Arrival functionality in development. Deviations between predicted reference trajectory and actual trajectory execution are triggered through changed atmospheric parameters (e.g. temperature, wind) and ATC advices coming from a controller or decision support tool (DST) like the Barco AMAN used in UTOPIA. The reference trajectory is regularly recalculated as part of the flight execution loop.

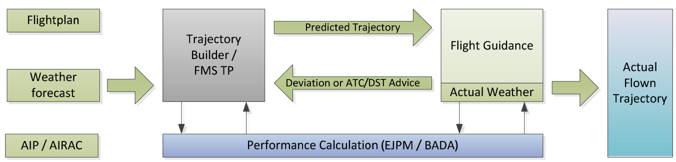

Figure 4: TABATS Schematic Simulation Process

[1] Currently only for Boeing aircraft types.

B. System interaction

Interaction between the UTOPIA systems is realized through the DCP using TCP/IP. Besides administrative messages to synchronize the Demonstrator, the following operational data interaction takes place. The AMAN transmits the advisory instructions to be consumed by the ATSs:

- Advice – event-based messages with new routing, RTA or holding pattern instructions.

The trajectory data shared by the ATSs with the AMAN currently encompasses:

- Track – periodical messages with surveillance information,
- Flight plan – event-based message with flight plan information, and
- nD Trajectory – event-based message as a sequence of 4D waypoints, and optionally additional aircraft state information and/or uncertainty information.

The exchanged dynamic data is defined in an unambiguous way using XML formatted messages with respective schemata. At a later stage the UTOPIA n-dimensional trajectory information exchange will be extended with flight intent and aircraft intent messages.

IV. Scenario Setup

This section contains an overview of the current status of the UTOPIA simulation scenarios and upcoming extensions.

A. Simulation scenario

UTOPIA simulates automatically handled arrival traffic into an extended TMA of the Frankfurt/Main airport. This section contains information about the airspace setup, the used traffic mix and the advices generated by the arrival manager to organize the inbound flights. Furthermore, details about the metrics to analyze the quality of the traffic control in different scenario setups are presented.

1) Airspace

The UTOPIA project has chosen to use the extended TMA of Frankfurt/Main (EDDF) airport for its simulations. It was decided to utilize the 'old' three runway layout of Frankfurt airport which does not include the new northern 07L/25R runway. In the three runway configuration the runways used for landing are 07C/07R and 25C/25L respectively. The proximity of the two parallel approach runways does not allow operating them independently.

The EDDF simulations use the RNAV approaches which include the variable 'trombone' patterns. The resulting approach transitions are a subset of the RNAV Z transitions. Fig. 5 gives an overview of transitions for the ‘07’ direction. The dashed segments show the different trombone variants which can be used for flight delay absorption. Each transition starting way point KERAX, PSA, ROLIS and UNOKO has an associated holding area which is used for further delay absorption.

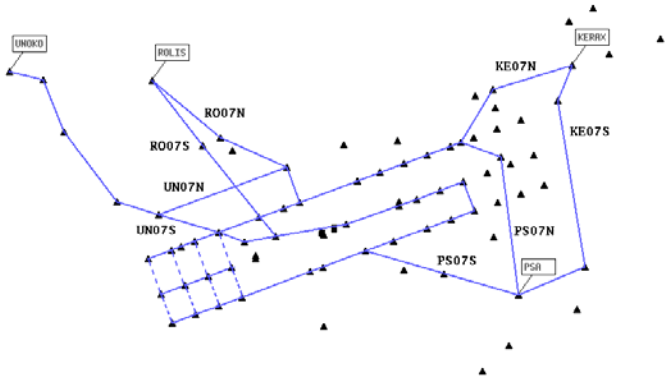

Figure 5: Overview of EDDF RNAV 07 approach transitions

2) Traffic

The basis for the traffic sample currently used is a day of traffic data supplied by the CFMU. The simulation only takes inbound traffic into Frankfurt into account. For each flight the following data is used: call sign, aircraft type, flight plan and initial height and speed at the waypoint at which the aircraft enters the simulation horizon. The simulated operational horizon is initially 60 minutes of flight time before touch down and will be extended to up to three hours.

At the current implementation level the air traffic simulators are able to follow given approach transitions, to fly holding procedures and to execute requested time of arrival (RTA) instructions for given waypoints. The respective approach, holding and RTA advices are generated by the AMAN depending on the simulation scenario configuration. This implies the currently possible traffic mix options:

- Traffic density: Based on the traffic density for a chosen high traffic period from the CFMU data scenarios with 50%, 75%, 100%, 110% and 120% of the reference traffic will be executed.
- RTA capability: The simulations will be performed with the following amounts of aircraft being able to execute CTA/RTA advice: 0%, 25%, 50%, 75% and 100%.
- WTC mix: Based on the CFMU data of light, medium and heavy traffic fractions the weight turbulence categories will e.g. be shifted towards higher amounts of heavy traffic.

Once the transmission of uncertainty data and further trajectory synchronization information (4D trajectories, AIDL/FIDL messages) from air to ground is implemented, the respective capability variants for further simulations will be defined. The same holds for the definition of weather scenarios in the context of respective uncertainty source modeling.

3) AMAN Advice

The arrival manager creates advice of different types to organize the approaching 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 delays 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 an RTA/CTA advice or by influencing the aircraft route in a more detailed fashion e.g. by supplying a different approach route.

In the current simulation setup the arrival manager uses the set of advice types explained below. The advice types are prioritized from top to bottom:

- RTA/CTA advices are currently generated for the aircraft at the approach transition entry fixes with target times which meet the arrival manager scheduling.
- When aircraft passed the transition fixes, remaining delay is absorbed by first using longer approach trombones, and secondly holding procedures.
- Further fine tuning is implemented by advising continuous variants of the otherwise discretely distinguished trombone variants.

4) *Conflict Handling*

Without human controllers in the loop the question arises how flight de-conflicting is performed within the UTOPIA simulations. In its current incarnation the arrival manager solves conflicts solely at the runways. Thus, it relies on the ATCOs to maintain conflict free traffic inside and outside the TMA. As a first means the UTOPIA demonstrator implements a conflict detector to monitor all occurring conflicts. These will be evaluated to analyze the amount and type of conflicts. These results will give hints about the necessary future measures needed for de-conflicting in fully automated ATC environments.

5) *Evaluation Metric*

To analyze the multitude of data generated by the demonstrator simulations an automated evaluation tool has been implemented. It calculates a number of traffic metrics which shall help to understand and quantify the performance of the arrival management system. The following list gives an overview of the metric definitions as well as some hints to understand their meaning. During the course of further UTOPIA activities this metric set will be extended and refined.

- Sequence variability: The arrival order of a set of aircraft for a given runway defines an arrival sequence. Any external parameter change might lead to a possibly better sequence, where 'better' might e.g. mean a smaller sum of all aircraft delays with respect to their independent flight schedules. On the other hand, each sequence change typically implies aircraft advice changes which cause either controller work load or automatic message transmissions between ground and air. In case of automated transmissions this might conflict with the possibly limited communication bandwidth resource.
- Planning time stability: The planning time stability reflects how often the arrival manager has to adapt the planned landing time of aircraft. Deviations between planned and actual landing time can have different reasons. In automated situations the plan execution depends on how well e.g. aircraft can execute RTA/CTA or other advice. Weather effects, short route flights and other disturbances influence the AMAN planning realization. Finally, the planning time stability depends on how well the arrival manager trajectories predict the actual flight behavior.
- Runway throughput: By monitoring the runway throughput it can be verified whether the arrival planning and execution works with sufficient efficiency. The actual throughput can be compared to the theoretical maximum which can be estimated by the given aircraft approach separations.
- Delay distribution: The delay experienced by a flight can be defined as the difference between its actual arrival time and the arrival in the case the aircraft would have flown undisturbed by any other aircraft. In other words, the flight delay is the difference between the real and the ideal arrival time. Flight delays arise if the approach airspace of an airport is congested and the aircraft have to spend time in holding procedures or are delayed by prolonged approach routes.
- RTA accuracy: For an RTA advice given by the arrival manager it is of interest whether the RTA advice is executed correctly by the aircraft. On the other hand, advice might have been generated but could not be implemented by the aircraft. The RTA accuracy metric shall shed light on these problems.
- Advice frequency and bandwidth: Digital messages from the arrival manager to aircraft contain advice, which have to be confirmed by the pilot, thus causing pilot work load. The advice frequency measures this work load. Furthermore, the messages use the limited communication bandwidth, and it is therefore important to monitor the used message bandwidth.

V. IMPLEMENTATION AND SIMULATION RESULTS

This section presents outcomes of a baseline simulation which shall deliver first insights into the results to expect later on. Currently, a set of test and debug simulations are run with the FACT and TABATS air traffic simulators executing the traffic generation while receiving advice from the arrival manager. The aim is to remove remaining problems in Utopia XML communication, to verify the airspace implementation consistency, to check the advice execution like flown holding procedures, etc. For each demonstrator run the metric evaluator calculates the simulation metrics. The test runs are used to finalize the metric evaluator and especially to make sure that the metrics are calculated correctly. Furthermore, the metric evaluator is extended to serve as an investigation tool for the ATS and arrival manager behavior and to perform simulation consistency checks. For each simulation the content of a radar display and the arrival timeline are saved as screen shots about every 10 seconds. These screen shots are concatenated to films that quickly provide an overview of each demonstrator run.

A. Baseline Simulation

The baseline simulation uses the CFMU flight plan data of flights entering a 60 minutes AMAN horizon during 3 hours of simulation time. In this case the arrival manager solely advises approach transitions to the flights. RTA/CTA, holding, trombone or vector advice is not yet issued. The next figure (fig. 6) gives an overview of the flown trajectories. In the center the flown arrival trombones and the 07C approaches are visible.

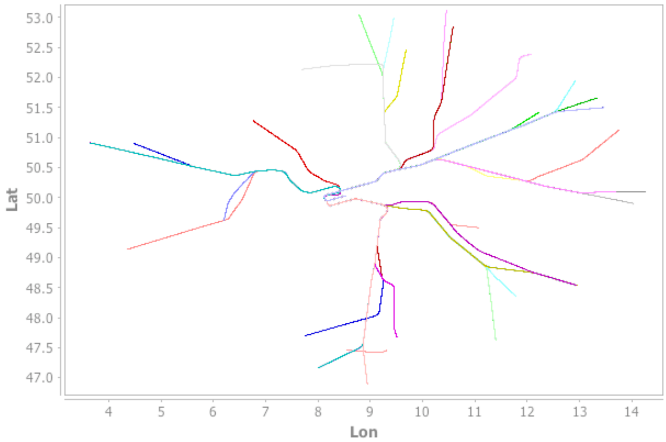

Figure 6: Base line simulation trajectory overview

The next two figures (fig. 7 and 8) display the situation at 4:39 in the test radar HMI and the arrival manager time line.

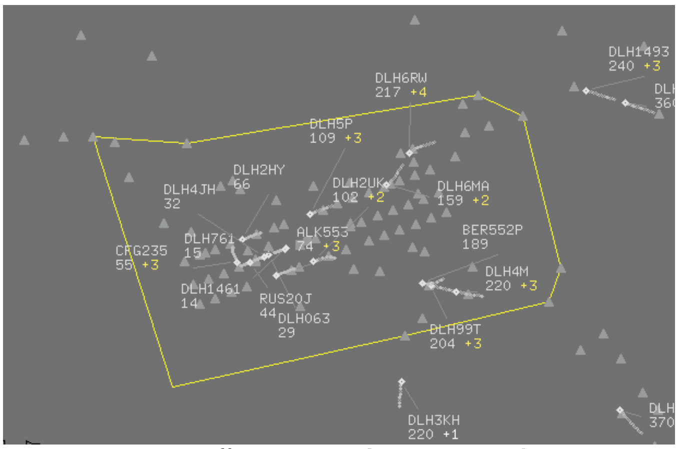

Figure 7: Traffic at 04:39Z in the EDDF approach area

Each radar track label contains the call sign, the flight level and optionally the flight delay. In today's operational installations this flight delay would have to be absorbed by ATCOs advising holdings or respective approach path alterations.

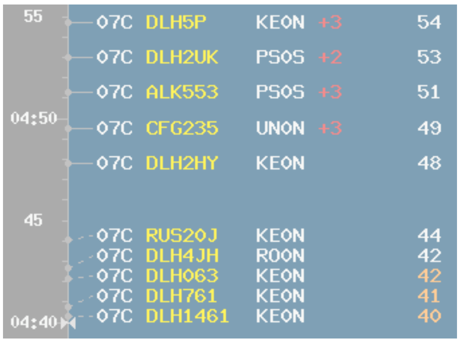

Figure 8: Time line status at 04:39Z

The time line shows the planning time vertically, the bow tie at the bottom marks the current time. Each sequenced flight is displayed with a label line. The label is connected to the time line at its planned arrival time. Each label contains the runway, the call sign, the approach transition, an optional flight delay, a possible holding advice and the approach time minutes. The five lower labels have dashed connectors as their flights have passed the final approach fix. In this case the expected actual landing time is displayed by the connector. The most recent two pairs of flights obviously violate the minimal separation during their final approach phase.

B. Baseline Simulation Metrics

The UTOPIA metric evaluator uses information logged during a simulation to calculate the metrics which shall give insights into the quality of the arrival management process. A few metric results of the baseline simulation are discussed below.

1) Runway Throughput

A metric which can be easily calculated is the runway throughput as shown in the in fig. 9. The peak of converted 60 landings per hour results from the uncontrolled traffic flow violating the minimum separation requirements.

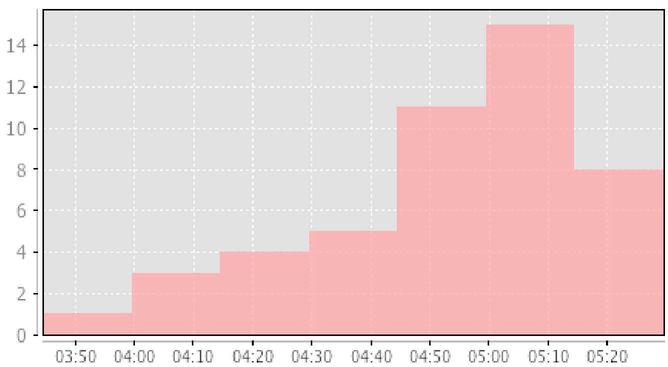

Figure 9: Landings per quarter hour at runway 07C

2) Planning Time Stability

The next metric investigates how the well the initially planned arrival time is actually met by a flight. Fig. 10 shows that all aircraft arrived earlier than calculated in the initial arrival manager schedule. This implies that the trajectories calculated by the arrival manager do not model very well the behavior of the simulated flights. This will be investigated in the upcoming trajectory comparison module of the metric evaluator.

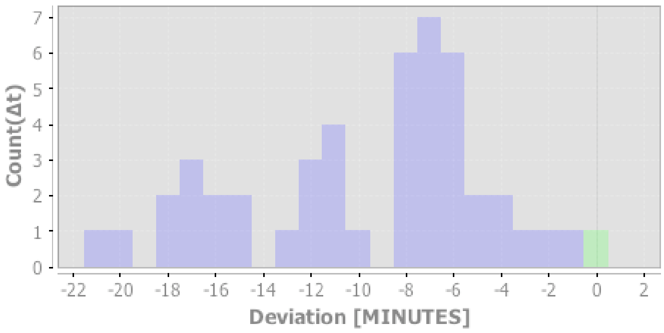

Figure 10: Distribution of actual arrival times minus initially planned arrival time

3) *Sequence Delay Distribution*

The arrival manager always keeps a current arrival sequence which defines the order and scheduling of the aircraft arrivals. In high traffic periods many aircraft will have to absorb delay in holding areas and approach path deviations to meet the planned arrival times.

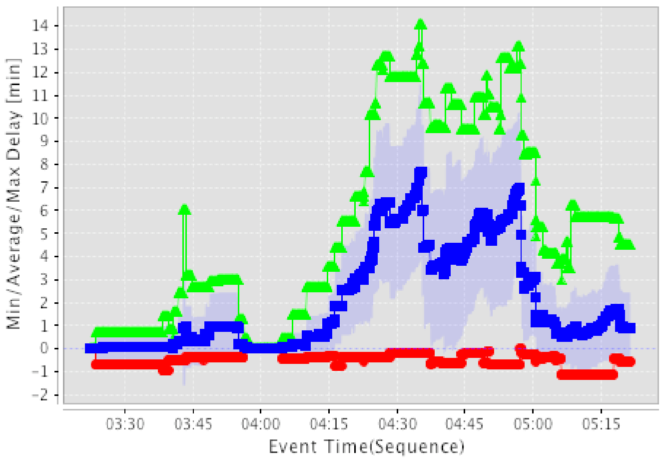

Figure 11: Min/Average/Max delay of planning sequences

Fig. 11 depicts the minimal, average and maximal delay in each planned sequence. Times with high average aircraft delay originate from high arrival traffic density. It is also important that the maximal aircraft delay does not deviate from the average delay too much to avoid unfairness in the treatment of different aircraft types or airlines. The area around the blue average delay marks one standard deviation of the per sequence delay distribution.

VI. Outlook

For the continuation of the project the following next steps, organized in 4 phases, are foreseen for the UTOPIA experiments:

First identify the sources of discrepancy between trajectories predicted by the AMAN and the simulated flights from the baseline simulations presented in fig. 10. No additional sources of uncertainty should be added at this point. Potential candidate causes for trajectory inconsistency are aircraft performance mismatch, flight intent deviations (for example, descent speed schedule), differences between guidance reference generation and AMAN trajectory prediction logic, and fundamental modeling errors. The resulting quality metrics for the baseline arrival management process will conclude *phase I*.

Based on the aforementioned trajectory discrepancy analysis, *phase II* will introduce trajectory synchronization messages between AMAN and the simulated flights and evaluate the gains of various levels of information sharing (nD trajectory data). This includes a dependency analysis on RTA capability. Experiments will be conducted to evaluate the effect of the previously mentioned traffic mixes. Additional metrics like fuel consumption and trajectory synchronization metrics will be defined. The AMAN advisory strategies will be evaluated in light of the occurring conflicts to identify potential improvements as far as feasible.

In a next step, *phase III*, the degree of reality of the scenarios will be enhanced by introducing stochastic uncertainty sources with a main focus on environmental uncertainty. Simultaneously, uncertainty information sharing will be added to the trajectory synchronization process. Again, the various traffic mixes will be considered.

Finally in *phase IV*, the robustness of the proposed concept will be tested with regard to disruptions. A disruption in the UTOPIA framework is defined as an event resulting from a partial or complete loss of synchronization service, related to one or several trajectories. Disruptions could also arise when reaching a maximum bearable level of uncertainty, for example, in case of adverse atmospheric conditions.

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