Arrival Management Decisions by Visualising Uncertainty

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ARRIVAL MANAGEMENT DECISIONS BY VISUALISING UNCERTAINTY

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To balance the flow of inbound aircraft and the capacity at airports, more and more Air Navigation Service Providers use Arrival Management (AMAN) systems. These provide decision support to sequence managers in planning inbound flights to optimize capacity, flight efficiency, and predictability. All AMANs are based on predictions of an aircraft's arrival time. Due to various disturbances the error of these predictions grows larger with the prediction horizon. Air Traffic Controllers will therefore not be able to effectively use the support at a certain horizon due to the lack of confidence in the provided information. This paper proposes and tests an enhancement based on the probability density function of the expected arrival time, allowing controllers to include uncertainty in the decision making process.

Arrival Managers (AMANs) aim to balance the inbound flow of aircraft with the available capacity at the airport. When aircraft are predicted to arrive too close after each other, AMAN provides support in deciding how to influence the 4D trajectory of the aircraft involved. Assuming aircraft fly an optimal trajectory from the operator's perspective, disturbance from this trajectory should be kept to a minimum. For example, a smaller speed increase over a longer flight time is more fuel efficient than a larger speed increase of over a shorter time, while achieving the same difference in time. To improve performance and to support future trajectory-based operations, the planning horizon of AMAN is envisaged to be increased from the current typical 100 NM to 200-500 NM (Barff et al., 2012; Bronsvoort et al., 2011). This planning horizon is currently limited by the ability to get information on the aircraft at a longer horizon, the ability to influence the aircraft further from their destination, and the reliability of the predicted arrival times.

System Wide Information Management will enable continuous sharing of all relevant information concerning a flight between all involved actors (SESAR JU, 2011; JPDO, 2008). Through SWIM, different Air Navigation Service Providers (ANSPs) will also be able to share their requirements on a trajectory (such as an arrival time planned by AMAN) as well as their capabilities to provide for such requirements. While this resolves the first two limitations on the planning horizon, future prediction uncertainty is expected to reduce but unlikely to disappear altogether. As disturbances may influence the trajectory over a longer time and new sources of error may be introduced, a longer horizon will increase the uncertainty in arrival time (Mondoloni, Paglione, & Green, 2002; Mueller, Sorensen, & Couluris, 2002; Hunter 2004).The actual uncertainty may vary due to for example weather, actual traffic, or aircraft navigation capability. However, the uncertainty is transparent to the operator; the effective horizon will be based on general experience and not on the actual accuracy at a given time.

Research has demonstrated the ability to calculate the uncertainty in a particular trajectory (Whysall, 1998; Mueller et al., 2002; Schaefer, Gizdavu, & Nicholls, 2004). It is hoped that, by providing this information to the human operator, a higher benefit from AMAN may be achieved in situations with low uncertainty through better decision making.

This paper consists of three parts. The first two sections describe the development of the visualisation of the information on a common concept for AMAN using the Ecological Interface Design (EID) framework. Secondly, the interaction with such an interface is discussed leading to further definition of the visualisation. The last segment describes the setup, and execution of initial experiments to test the visualisation concept.

Approach

Most current AMAN display interfaces are based on a moving timeline on which the expected or planned arrival times are shown (Hasevoets & Conroy, 2010). This allows a 2D representation of the 4D spacing problem as relevant to the planner (who is not separating the traffic in 3D but rather adjusting the flow to allow for easier separation). However, this display provides limited information on the available capacity, the required spacing, the limits on the accuracy of the arrival time, or an aircraft's capability to meet that time. The lack of such information results in either a need for extensive knowledge and experience of the planner, or is not accounted for leading to lower overall performance.

The EID framework (Vicente & Rasmussen, 1992) helps in developing of the display that presents the content and structure of the working environment using the Abstraction Hierarchy (AH). Subsequently, the form of presentation is developed using the skills, rules, and knowledge taxonomy (Rasmussen, 1983). A display has been designed that explicitly visualizes the uncertainties in arrival times, and how these uncertainties would affect sequencing performance and controller strategies/control actions. Thereby a constraint-based approach, inspired by the EID paradigm, has been adopted.

Visualisation

Current timeline presentations show the Estimated Time of Arrival (ETA), or the planned time of arrival. None of the current operational systems, and very few of research systems, shows the required spacing between two aircraft. No explanation for the lack of this information could be found in literature. This parameter is however the key factor in safety (i.e., minimal amount of spacing) and capacity (i.e., available room for spacing). In the concept display, the required spacing is shown as a blocks, see Figure 1(a). The block indicates the time that the aircraft occupies the available landing capacity. Its surface then represents demand (expressed in seconds). A single aircraft would use a capacity of 1 (i.e., 1 runway) for that amount of time. This provides the separation requirement and runway occupancy but, as Figure 1(a) shows, provides poor indication of a lack of separation when these blocks overlap.

If a single block represents the use of a landing slot (in time), blocks of different aircraft may be added up to indicate instantaneous demand at each moment in time. Any demand higher than the number of available landing slots represents a shortage of capacity; see Figure 1(b). In this form, the equality (during the planning phase) of a predicted loss of spacing and a shortage of capacity is directly evident. Both of these issues require action, and any solution to one problem also resolves the other.

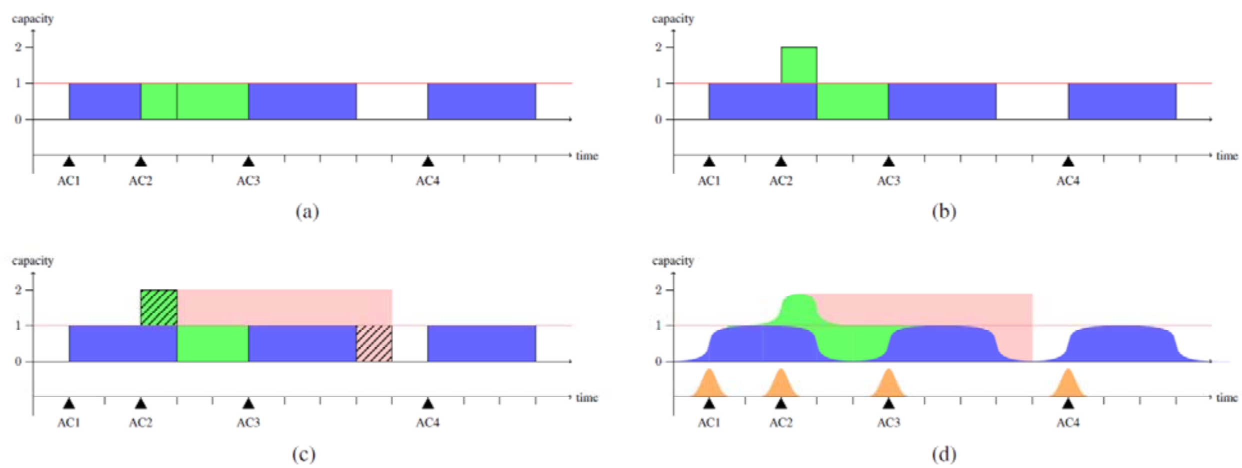


Figure 1: Development stages of the enhanced timeline. The blue area shows the amount of capacity used by the aircraft, the orange shapes show the arrival time PDFs, and the pink area shows the relation between an excess in demand and the earliest time that that excess demand can be resolved.

Arrival Time Uncertainty

Uncertainty information is added by providing the Probability Density Function (PDF) of arrival over time on the timeline; see Figure 1(d). The width of this graph indicates the time at which the aircraft may arrive, the shape indicates the most likely arrival time (the highest point) as well as the likelihood that the aircraft may deviate from that Development stages of the enhanced timeline. The blue area shows the amount of capacity used by the aircraft, the orange shapes show the arrival time PDFs, and the pink area shows the relation between an excess in demand and the earliest time that that excess demand can be resolved.

When the ETA is provided as a PDF, the nature of the occupancy blocks should change as well: When an aircraft is predicted to have a given probability on a given time, it has an equal probability of occupying the separation interval from that time. This results in a Cumulative Density Function (CDF) limited by the separation time (visible in Figure 1(d) as the blue shapes). Effectively, the occupancy block now becomes the expectation value for the occupancy for each aircraft.

Resource Occupancy

As the runway is occupied for a certain amount of time after the aircraft arrives, the instantaneous expectation for runway occupancy due to the expected arrival at this time can be expressed as:

$$O_{P_i(t)}\left[t, t+s\right] = P_i\left(t\right)$$

In which s is the applicable spacing interval. The expectation for the occupancy at a given time then becomes the integral or ---the CDF--- of the arrival time probability for the spacing interval before it:

$$O_i\left(t\right) = \int_{u=t-s}^{t} P_i\left(u\right) du$$

The CDFs for all aircraft can again be added up to calculate the total expected occupancy:

$$O\left(t\right) = \sum_{i=1}^{n} \int_{u=t-s}^{t} P_i\left(u\right) du$$

The summed CDFs provide the expectation value for runway occupancy for all aircraft. When the CDF is equal to the capacity, the runway will be occupied, regardless of which aircraft will be occupying it. Even in situations with very high uncertainty, this indicator can provide support in balancing capacity to demand without yet knowing the exact landing sequence of the aircraft.

Interaction

When the aircraft are indicated at their respective ETAs, the display only provides the current predicted arrival schedule. To support the controller in developing a suitable planning the controller can test potential modifications to the schedule directly on the display. These probes are implemented as a Direct Manipulation Interface (DMI) (Hutchins, Hollan, & Norman, 1985).

The operator is able to directly modify the arrival time of aircraft, and by doing so, see the potential effect of the change on the situation. The system provides real-time update of the arrival time PDF and CDF, therefore showing the complete expected result of the action.

The direct manipulation style of human-computer interaction is particularly useful for probing different solutions as it immediately shows whether a solution is furthering the goals of the user. By highlighting the CDF of the aircraft being probed (in Figure 1(d), the contribution of the selected aircraft is shown as the green area), the user can also explore the contribution of the aircraft to the total capacity problem.

Planning Limits

Not all possible changes in arrival time are available: aircraft have a limited maximum speed, which limits the amount of time before the ETA that aircraft can arrive. Similarly, aircraft have a limited endurance, which limits the maximum delay. Furthermore, either deviation will at some point no longer be efficient for the aircraft operator, and therefore undesirable. In combination with DMI, these limits can easily be visualised as an interval in which the aircraft can be planned.

Occasionally it may be that the required delay for the last aircraft in a series of too closely packed aircraft is not feasible. In such a case either the first aircraft in the sequence have to arrive earlier or extra capacity (runways) needs to be made available. If aircraft can only be planned one at a time, the required delay on the last aircraft can only be determined once all earlier aircraft have been delayed sufficiently.

To assist the planned in deciding on whether to advance aircraft, delay aircraft, or add capacity, the total amount of required delay is shown. Figure 1(c) shows the graphical relation between such an excess in demand, and the earliest time at which it is resolved; as soon as an equal area above the capacity limit is provided as unused area below that limit, the problem is resolved. The planner can now directly see the amount of delay required on the last aircraft of a sequence. Figure 1(c) shows AC3 to be the last aircraft involved. If this delay is too large, the solution has to be found elsewhere. Similarly, any aircraft beyond the area is unaffected by this problem. As the determination of this time to resolution is solely based areas in the graph, Figure 1(d) demonstrates that the same technique can also be used in the uncertainty display.

Experiment

Note that the display described above is has no attributes specific to aviation. The display supports solving a planning problem in which certain actors will use a certain limited resource for a specific amount of time, at a specific time in the future. Therefore, the display might be applicable to other logistic planning problems such as shipping or railways for example.

The lack of specific context also allows testing the display with untrained human subjects rather than operational experts. This display was tested with seven students aged 22 to 28, who, while all having a background in aerospace engineering, have no operational background in Air Traffic Control.

The experiment's objective was to determine the effect of the addition of uncertainty information and the resolution information on the ability to efficiently plan inbound traffic. In the experiment, subjects were provided with four different displays: the block-type display without uncertainty, PDF-based display, and both displays with the indicator on resolution time (Figure 2).

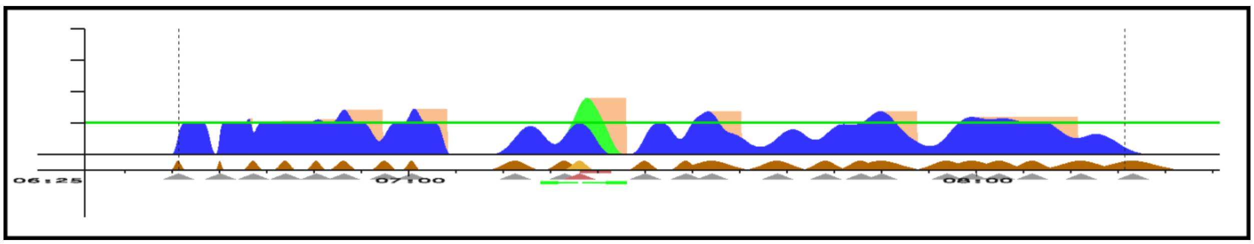


Figure 2: The experiment display in the full configuration. For clarity, the background colour has changed from black to white. The green lines below the aircraft symbol show the control space available for that aircraft.

Subjects were tasked with spacing traffic on a horizon of 2 hours with a minimal separation of 200 seconds between each aircraft. Subjects were asked to monitor and ensure sufficient separation first of all. Secondly, their task was to give instructions as early as possible, and to minimise the number of instructions for each aircraft. Since this would be a very low workload task with limited measuring possibility, traffic was sped up 30 times allowing for 3 hours of traffic to be simulated in runs of 6 minutes.

The scenarios were set up to have an running average spacing over 5 aircraft of 270 seconds at arrival to provide adequate solution space with sufficient aircraft landing to determine performance. Subsequently, a prediction error was superimposed on the actual arrival time. The prediction error was based on a normal distribution with a variable initial standard deviation that reduced to a fixed, small final standard deviation. Aircraft were modelled to fly constant, identical speeds to the runway with an ability to accelerate or decelerate an equal amount.

Each subject completed 8 training runs, followed by 16 measurement runs in which the combination of display and scenario was Latin-squared to eliminate training or fatigue effects. To determine the subjective workload of the planner, an Instantaneous Self-Assessment (ISA) probe appeared on the side of the screen every 30 seconds (Tattersall & Foord, 1996). The simulation system further recorded all changes to the planning and the resulting landing schedule.

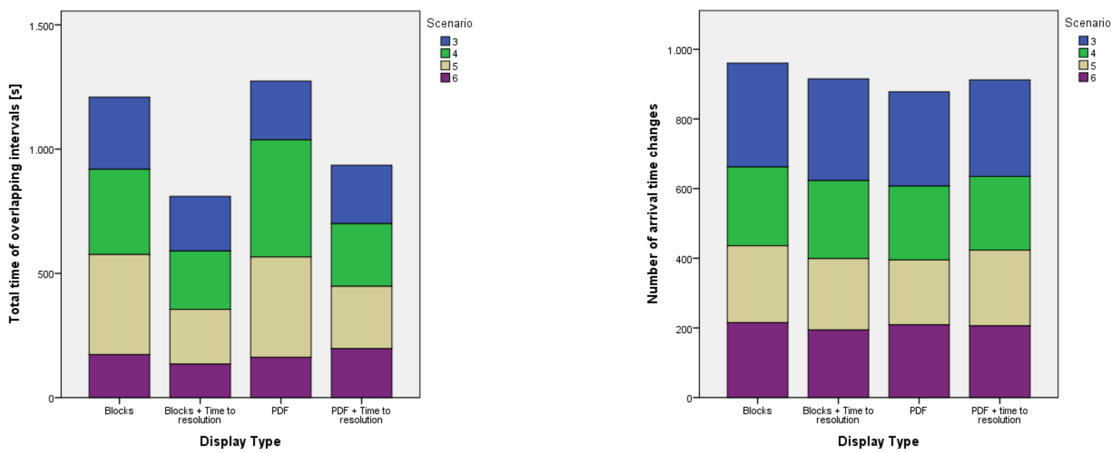
It was hypothesized that the new display would allow for more gradual planning in which the spacing buffer is adjusted to suit the uncertainty of the aircraft involved. This in turn should lead to less occurrences of predicted overlap resulting in fewer corrective actions on spacing and less spacing conflicts at landing.

Results

Initial analysis of the workload rating showed a clear correlation between duration of the experiment and perceived workload, even at the later experimental runs. This coincided with comments from all subjects that they only became comfortable with visualisation of uncertainty at later stages of the experiment. No further trends or effects could be found on the presentation of uncertainty, suggesting that the training stage was too short to effectively use the new visualisation.

Comments from the experiment subjects indicated that the uncertainty display was considered complex. In particular understanding the contribution of the each aircraft to the total CDF was considered unpredictable. This may be due to the morphing shape as uncertainty decreased. In general subjects preferred the blocks as they provided a more direct indication of the amount of buffer between two slots. Subjects did indicate that the size of the uncertainty helped them in estimating the required amount of buffer between two aircraft.

In both displays with the resolution time indication, the number of remaining spacing conflicts, and the total time of overlap was considerably lower than in their baseline counterparts, as shown in Figure 3(a). Figure 2 shows that the indicator could help in highlighting small conflicts by introducing a new colour on the screen. To eliminate the possibility that this indicator acted solely as more recognisable signal of a conflict, Figure 3(b) shows that the lower number of conflicts was reached without an increase in the number of corrections. This result suggests that the display helps in establishing more appropriate spacing between aircraft.



(a) (b)

Figure 3: Effect of the display of time to resolution on prevention of conflicts. Left: the total number of seconds over overlap in landing interval. Right: The number of corrections performed on landed aircraft.

Discussion

The continuation of the learning curve suggest that subjects need more training for a true test of the effect of the display on the planning performance. Further experiments need to be performed. While to CDF may provide a presentation of the occupancy with its relation to uncertainty that is more correct, subjects suggested that the combination of blocks and the PDF may provide a more understandable presentation.

The current approach assumes that aircraft can make an equal adjustment in speed both faster and slower. In reality the available speed change may not be that flexible, and time adjustments may be available through other means (e.g. take-off delay, route adjustment). This would make the available speed envelope much more dependent on individual aircraft. Furthermore, the display did not indicate the cost of speed change, and thus the efficiency of the manoeuvre. A 5 minute delay can be achieved with a very small change in speed (and efficiency) if performed 2 hours before landing, at 30 minutes however, considerable speed changes are required.

The changes in arrival time did not include the cost of a change in schedule to the operator. The cost of a delay depends on the commercial operation of the airline and is therefore unlikely to be equal for each operator or even each flight. The above difference in limitation in available control space and the different cost of adjusting arrival time might need representation in the display to lead to more efficient decisions. As this consists of a number of further constraints on the work domain, the EID framework is expected to be used in this context as well.

The display assumes knowledge on an aircraft's ETA which is available now but might be too uncertain to be of any use. Secondly the display requires information on the uncertainty of the arrival time. The models described used in previous concepts were focussed on the airborne segment of the flight (Whysall, 1998; Mueller et al., 2002; Schaefer, Gizdavu, & Nicholls, 2004). At the horizons considered in this concept, the models will also have to include the predictability of factors on the ground. Therefore, further study will be required to develop appropriate uncertainty models.

Conclusion

This paper demonstrates that it is possible to visualise arrival time uncertainty using the PDF onto the current timeline display. Using such visualisation it might be possible to extend the use of AMAN over a longer time horizon without requiring more accurate arrival time information.

Initial experiments do however show that an interface in which occupancy is presented as a CDF is more difficult to understand for novice users. Especially recognition of available buffer in spacing is more complex in the curved visualisation. To draw more definite conclusions, further experiments, with more training will need to be performed.

References

Barff, A., Favennec, B., Conroy, P., Bellesia, L., Greenwood, J.S., Clark, A., ... Linner, A. (2012). *SESAR P05.06.04 - D28 - Preliminary OSED Ed. 00.01.01*. (Tech. Rep.). SESAR Consortium

Bronsvoort, J., McDonald, G., Paglione, M., Garcia-Avello, C., Bayraktutar, L., & Young, C.M. (2011). Impact of missing longitudinal aircraft intent on descent trajectory prediction. In *30th IEEE/AIAA Digital Avionics Systems Conference*, Seattle, WA. doi: 10.1109/DASC.2011.6096062

Hasevoets, N., & Conroy, P. (2010). *AMAN Status Review 2010* (Tech. Rep.). Brussels: EUROCONTROL.

Hunter, G., (2004). Toward a Standardized Reference Set of Trajectory Modeling Errors: In *AIAA Modelling and Simulation Technologies Conference and Exhibit*. Providence, RI.

Hutchins, E. L., Hollan, J.D. and Norman, D.A. (1985). Direct Manipulation Interfaces. *Human-Computer Interaction,* 1(4), 311–338. doi: 10.1207/s15327051hci0104_2

JPDO. (2008). *NextGen Integrated Work Plan: A Functional Outline*. Retrieved from http://www.jpdo.gov

Mondoloni, S., Paglione, M., & Green, S. (2002). Trajectory Modelling Accuracy for ATM Decision Support Tool. In *International Congress of Aeronautical Sciences (ICAS)*. Toronto, Canada.

Mueller, T., Sorensen, J., & Couluris, G. (2002). Strategic Aircraft Trajectory Prediction Uncertainty and Statistical Sector Traffic Load Modeling. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*. Reston, VA. doi: 10.2514/6.2002-4765

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions On Systems Man And Cybernetics,* 13(3), 257–266.

Schaefer, D., Gizdavu, A., & Nicholls, D. (2004). The display of uncertainty information on the working position. In *23rd IEEE/AIAA Digital Avionics Systems Conference*, Washington D.C. doi: 10.1109/DASC.2004.1391334

SESAR JU. (2011). *SESAR Concept of Operations at a Glance ED 02.00.00*. (Tech. Rep.) SESAR JU.

Tattersall, A. J., & Foord, P.S. (1996). An experimental evaluation of instantaneous self-assessment as a measure of workload. *Ergonomics*, 39(5), 740–8. doi: 10.1080/00140139608964495

Vicente, K.J., & Rasmussen, J. (1992). Ecological interface design: theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics,* 22(4), 589–606. doi: 10.1109/21.156574

Whysall, P. (1998). Future Area Control Tools Support (FACTS). In *USA/Europe Air Traffic Management Research and Development Seminar*, Orlando, FL.