Supporting Arrival Management Decisions by Visualising Uncertainty

Maarten Tielrooij,
Clark Borst,
and Max Mulder
Faculty of Aerospace Engineering
Delft University of Technology
Delft, The Netherlands
Email: m.tielrooij@tudelft.nl

Dennis Nieuwenhuisen
National Aerospace Laboratory
Amsterdam, The Netherlands
Email: dennis.nieuwenhuisen@nlr.nl

***Abstract*—To balance the flow of inbound aircraft and the capacity at airports, more and more Air Navigation Service Provider (ANSP) use Arrival Manager (AMAN) systems. These provide decision support to sequence managers in planning inbound flights to optimize capacity, flight efficiency, and predictability. However, few systems support the planner in taking all aspects of the AMAN process into account. Secondly, 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. With increasing horizon, the quality of the system support therefore decreases. This paper proposes and tests a number of enhancements on the commonly used timeline diagram that provides support at multiple levels of abstraction and takes into account the uncertainty of the arrival time, allowing controllers to make the uncertainty a parameter in their decision making process.**

I. INTRODUCTION

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 to the sequence manager at the destination airport in deciding how to influence the 4D trajectories of the aircraft involved based on the —predicted— Estimated Times of Arrival (ETAs) of those aircraft. Assuming that aircraft fly an optimal trajectory from the airline operator's perspective, deviations from this trajectory due to Air Traffic Control (ATC) interventions should be kept to a minimum. Furthermore, the earlier in the flight a deviation can be adjusted for, the lower the cost in flight efficiency. For example, a smaller speed increase over a longer flight time is more fuel efficient than a larger speed increase over a shorter time, while achieving the same difference in time.

To improve performance of the AMAN process, and to support future trajectory-based operations, the planning horizon of future systems is envisaged to be increased from the current typical 100 NM to 200-500 NM [1], [2]. Nowadays, this planning horizon is constrained by three limitations: 1. the ability to get information on the ETA of aircraft at a larger horizon, 2. the ability to influence the aircraft further from their destination, and 3. the reliability of the predicted arrival times.

The first two of those constraints are being addressed in current developments: System Wide Information Management (SWIM) is foreseen to enable continuous sharing of all relevant information concerning a flight between all involved actors [3], [4]. And, through SWIM, different ANSPs are expected to 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 these developments resolve the first two limitations on the planning horizon, the third problem —prediction uncertainty— is also expected to reduce, but is unlikely to disappear altogether.

As disturbances (e.g., wind, changes in the choices of the Airspace User (AU), actions by other ANSPs) may influence the trajectory over a longer time, and new sources of error may be introduced, a larger horizon will increase the uncertainty in arrival time [5]–[7]. The actual uncertainty for each flight may vary due to for example weather, actual traffic, aircraft navigation capability, or Trajectory Predictor (TP) quality. However, this actual uncertainty is unknown to the operator. Therefore, it is likely that the planner will assume an effective horizon based on experience. Beyond this horizon, the planner will have experienced that decisions are too likely to require revision, and are therefore untrustworthy.

Research has demonstrated the ability to calculate the uncertainty in a particular trajectory [6], [8], [9]. It is hypothesised 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. Similarly, in situations with high uncertainty, the planner is hypothesised to be more able to balance the need for early decision making with the likelihood that such a decision may require revision.

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. The last three sections describe and discuss the setup and execution of an exploratory experiment to test the visualisation concept.

In evaluating the AMAN problem, the choice between (supervised) automation versus a human operator without any automated support is not addressed. Indeed, the AMAN may, in part, be very suitable for automated solutions. However, with the increasing horizon, the uncertainty may affect the ability to automate decision making. Finally, the automated system is likely to require monitoring by a human operator, who then has to have the appropriate information to verify correct decision making by the automation.

II. Approach

Most current AMAN display interfaces are based on a moving timeline on which the expected or planned arrival times are shown [10]. 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 spacing downstream). Such a representation provides the key parameter for AMAN, the ETA. As simple as these timeline interfaces may be, the actual reality is a far more complex system in which assigning aircraft to particular landing times involves many actors and many parameters.

The sequence managers at most ANSPs are experienced Air Traffic Controllers (ATCOs). Using their knowledge of the actual situation and experience from the past, they are often able to find the most appropriate solutions for the planning problem at hand. The constraints that limit the AMAN horizon are based on the accuracy of information available to these operators and not the operators' ability to use such information to make decisions.

Following the EID paradigm enables development of an interface that support expert operators, while not forcing processing at a higher level than the task requires. This allows the operator to become an active problem solver [11]. Through this method, sequence managers can still apply their knowledge of the situation, including information that is not available or not considered during design of the system.

EID aims to visualise the constraints in the environment relevant to the task. To do so, the process consists of two parts [12]: The Cognitive Work Analysis (CWA), and the design based on the outcome of that analysis. The first component of the CWA is an analysis of the work domain. In this section, the Abstraction Hierarchy (AH) [13] for this particular problem is developed to create a functional model of constraints that govern the AMAN problem (Figure 1).

A. *Abstraction Hierarchy*

The functional purposes of the AMAN system have been defined as the key performance areas of Single European Sky ATM Research (SESAR) which may be influenced by the AMAN process [14]. These are driven at the abstract function level by the separation required to prevent unsafe interaction between aircraft, legislative limitation on the operation of the airport (mainly for noise abatement), the relations between the complexity of air traffic and the resulting workload, the physics of flight including propulsion, and the economic pressure on the AU to arrive on time.

At the generalised function level, three phases are recognised: Selecting an appropriate runway configuration, assigning aircraft to the selected runways, and planning the individual arrival times of those aircraft. The task of optimising the sequence of aircraft is not yet considered in this paper.

At the two lowest levels, the sources of uncertainty become clear. These consists of factors that influence the available capacity (for example the headwind component at landing which influences landing intervals) and the possible errors in the predicted arrival times themselves. At shorter horizons, these errors may be caused by uncertainty in winds and aircraft behaviour. At longer AMAN horizons, especially in the European airspace, the lack of accuracy in the departure time of the inbound aircraft from their origin airport becomes a major contributor in the possibilities for error in the arrival time. The difficulty of handling such 'pop-up' flights often forms a limiting factor on the horizon used in operational systems.

The uncertainty in the exact arrival times, and the uncertainty in the future conditions at the airport (e.g., wind, visibility, availability of runways) translates to a difficulty in timely deciding on when runway combinations should be changed and the subsequently planning of the exact arrival times. Assigning aircraft to particular runways is generally based on their route to reduce complexity in the terminal airspace. Therefore, the effect of arrival time uncertainty in runway assignment is smaller.

B. *Limitations in current displays*

The AH in Figure 1 demonstrates a number of areas to be improved in the decision process. In this paper the following areas will be addressed: The relation between the inbound schedule and the higher level objectives, the relation between aircraft performance, flight efficiency, and the available solutions, and the effect of uncertainty on the process.

Current timeline presentations show the ETA, or the planned time of arrival. None of the current operational systems, and very few of currently developed or researched systems (for example [15]), show the required spacing between two aircraft. No explanation for the lack of this information could be found in literature. However, as Figure 1 shows, this parameter is the key factor in safety (i.e., minimal amount of spacing) and capacity (i.e., available room for spacing). The effect of these spacing requirements on the other objectives is only available after optimising the schedule for the spacing requirement and noting the subsequent effects on capacity and performance. The lack of such information results in either a need for extensive knowledge and experience of the planner, or lower overall performance.

An example of this problem exists when a number of aircraft are predicted to arrive with too little spacing: In present-day representations, the required delay on the last aircraft to arrive is only known once all previous aircraft have been planned. Once that is done, the performance of the entire schedule can be evaluated. An adjustment would then again require adjustment of all arrival times, which, since it is a continuous process, are nearer in the future, putting time pressure on the decision.

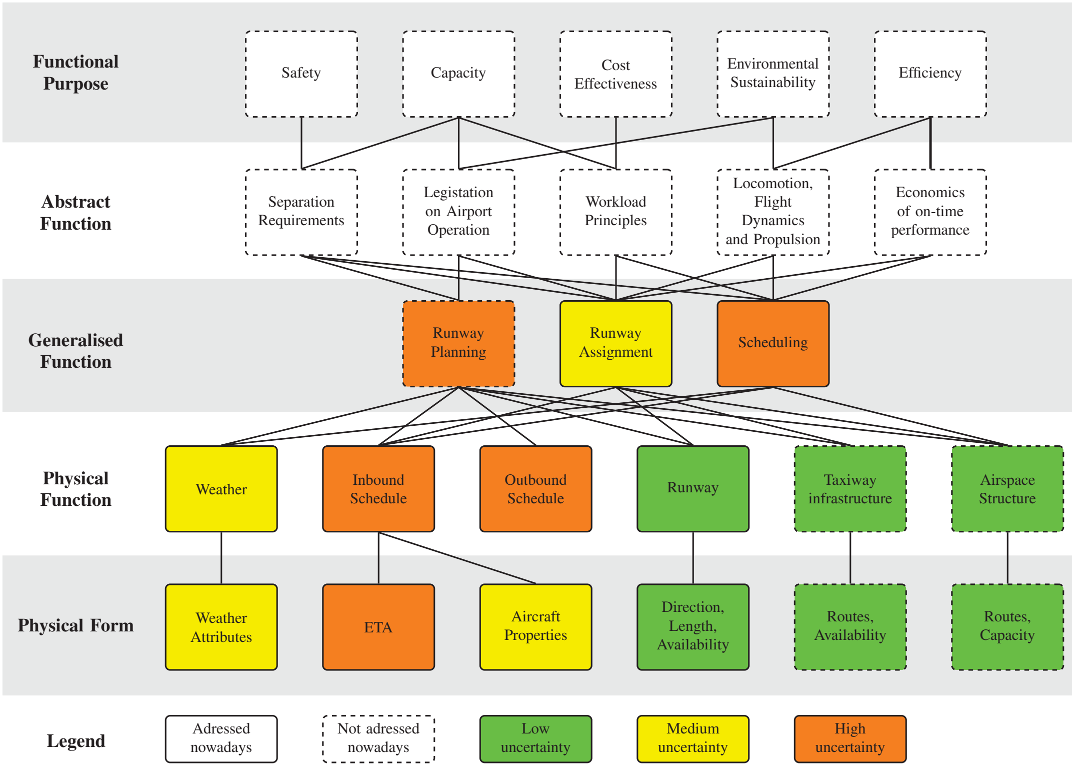


Fig. 1. The abstraction hierarchy for the arrival management problem. The figure indicates the aspects of the system addressed by present-day AMAN systems and the sources of uncertainty. As the uncertainty translates up the means-end relationship, the higher level aspects will always be uncertain.

This problem is exacerbated by the fact that not all possible adjustments in arrival time are available: aircraft have a maximum speed, which constraints the amount of time ahead of the ETA that aircraft can arrive. Similarly, aircraft have a finite endurance, which limits the maximum delay. Furthermore, either deviation will at some point no longer be efficient for the AU due to the resulting fuel consumption for earlier arrival or the cost of arriving later than planned.

Figure 1 demonstrates how uncertainties in the lowest levels of abstraction translate to uncertainties in the resulting performance. Decisions based on values with high uncertainty may need correction later. The resulting adjustments in flight profile may ultimately lead to lower performance than delaying the decision until the ETA is known with higher accuracy. However, late actions may require large deviations of the trajectory resulting in lower performance as well. Information on uncertainty could enable a planner to choose whether, and, if so, how to act by weighing the chance that actions may need revision due to a prediction error, versus the remaining control space to resolve the predicted conflicts.

III. Visualisation

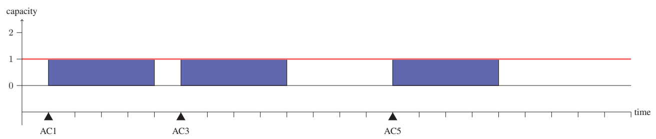
The AH does not yet define whether the task of optimising arrival schedules should be performed by an automated system, by a human operator, or, when in combination, how tasks should be divided. However, addressing the different constraints of the AMAN problem as shown in the AH will require data on the those constraints at the physical form level and subsequent modeling of their effects on higher levels of abstraction. Acquiring data for some of these aspects will be very difficult, if not impossible for automated systems. Examples are short term taxiway or runway maintenance or airport incidents.

Secondly, the modeling of some constraints may be either too complex or too dependent on the actual situation. A good example is the workload of the downstream ATCOs. The actual workload depends on many factors, such as for example: the number of flights, the complexity of the traffic presentation, and the complexity of the airspace. At the same time the maximum allowable task demand load depends on for example: the number of ATCOs available, the competency of active controllers, and system availability.

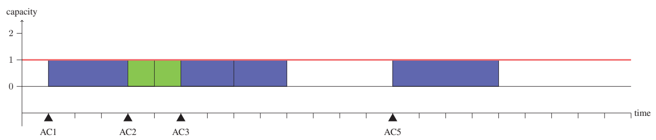
Finally, incidents or other deviations from normal situations, may require deviation from normal procedures. At these moments, the expert controller may be able to come up with more appropriate solutions than those proposed by an automated system, as that system would be addressing a situation not foreseen in design.

The second step in EID is to apply the analysis of working domain to design an interface using the skills, rules, and knowledge taxonomy [16]. By doing so, the operator is supported in performing tasks which have been envisioned in the design while not being limited in developing new strategies. Such new strategies might develop through the operator's knowledge of the system including aspects that the system is not aware off, or in situations that have not been foreseen in design. For this particular display the timeline will be extended to address a number of constraints that are shown in the AH, and provide information on the uncertainty in the underlying ETAs as well as the potential effect of that uncertainty on the predicted system performance.

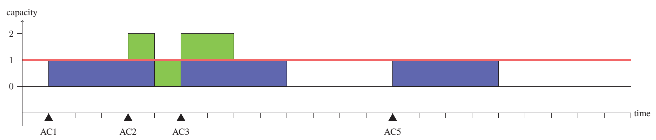
A. Visualising demand and capacity



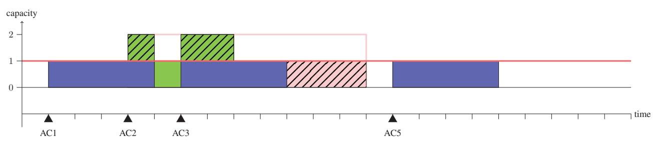
(a) Blocks indicating predicted use of a resource.



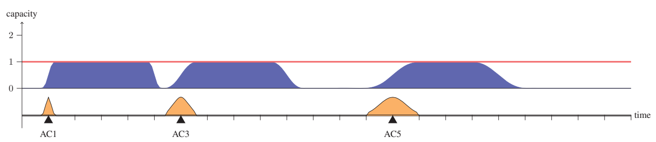
(b) Shortage of capacity (AC2, shown in green for clarity), not clearly visible.



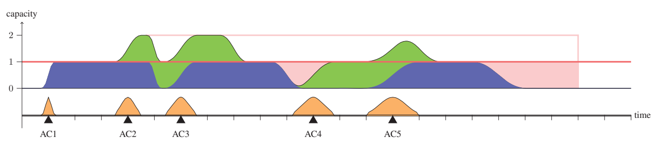
(c) By stacking use of resource, the relation between separation and capacity is visualised.



(d) Relating excess in demand to delay.



(e) Showing the PDF of the arrival time and the resulting expectation value for resource occupancy.



(f) Presentation of expected excess demand, and the time required to resolve these problems by delaying aircraft. The contributions in demand due to aircraft AC2 and AC4 have been highlighted for clarity.

Fig. 2. Development stages and elements of the enhanced timeline.

In the concept display, the required spacing is shown as blocks, see Figure 2(a). The block indicates the time that the aircraft is predicted to occupy the available landing capacity. Its surface then represents predicted demand (expressed in seconds). A single aircraft would use a capacity of one (i.e., one runway) for that amount of time. This provides the separation requirement and runway occupancy but, as Figure 2(b) 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 predicted demand at each moment in time. Any demand higher than the number of available landing slots represents a predicted shortage of capacity, see Figure 2(c). In this form, the equivalence (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. This equivalence is already shown by the means-end relationships in the AH between the separation requirements at the abstract function level and safety and capacity at the functional purpose level.

The area above the capacity limit represents demand for which no capacity is available. The unused area below the capacity limit represents unused capacity. To translate the shortage of capacity to potential delay, the area above the capacity limit has to be equal to the free area below the capacity limit (See Figure 2(d)). Beside providing an indication of potential delay under the current capacity and demand, the diagram now also provides a mental shortcut in available resolutions. Figure 2(d) for example, makes the needed three units delay for AC3 perceptually evident. Furthermore, it demonstrates that regardless of the chosen resolution, AC5 will be unaffected.

B. Visualising uncertainty

Uncertainty information can be added by displaying the Probability Density Function (PDF) of arrival over time on the timeline, see Figure 2(e). 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 time (the flattness).

When the ETA is provided as a PDF, the nature of the occupancy blocks changes as well: When an aircraft is predicted to have a given probability to arrive on a given time, it has an equal probability of occupying the resource from that time for duration of the separation interval after the time. 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 demand at a given time then becomes the integral of the arrival time probability for the spacing interval before it. This is demonstrated in Figure 3:

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

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

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

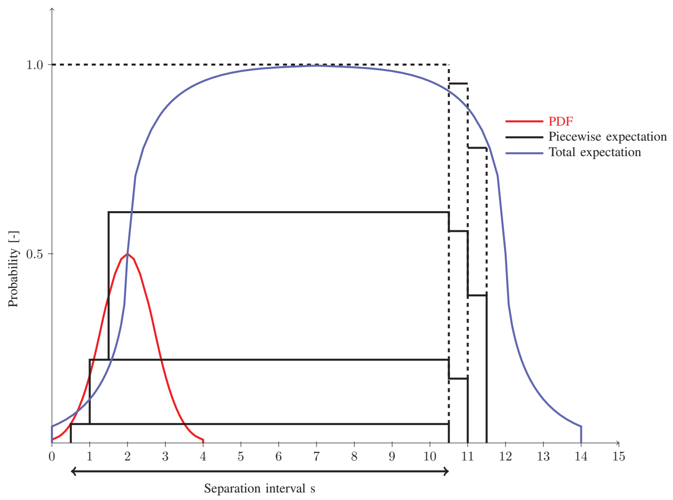


Fig. 3. Calculation of the expectation value for occupancy. The occupancy expectation integral PDF for the arrival time, subtracted by the integral of that PDF offset by their spacing interval. As time increases, parts of the PDF are more than the required interval from their contribution to the occupancy, therefore the total expectation will start decreasing again.

The summed occupancy expectations provide the expectation value for runway occupancy for all aircraft (visible in Figure 2(e) as the blue shapes). When the expectation is equal to the capacity, the runway is more likely to be occupied then not, 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 time, or sequence of the aircraft.

Especially in situations with high uncertainty, the value of the comparison between the area of excess demand and the area of available capacity is demonstrated (see Figure 2(f)). Even taking all uncertainty into account, it is clear at what time the demonstrated spacing problem will be resolved.

C. Visualising control options

The diagram in Figure 2 provides better support for working toward the Safety and Capacity objectives of the AH in Figure 1. The planner is now able to make decisions based on the required spacing and the available capacity even with uncertainties in the ETAs. However, these decisions do not yet include the limits (i.e., minimum and maximum ETA) and the effect of actions on the efficiency of the flight to the AU. By indicating the maximum and minimum ETA, the operator can search for potential solutions.

By combining the required delay shown in Figures 2(d) and 2(f) with the known limits on deviation, the possibility of delay as a solution can be evaluated. By indicating when the required delay is larger than the possible delay, the planner is directly made aware of the need for other options.

IV. Interaction

When the aircraft are displayed at their respective ETAs, the display only provides the current predicted arrival schedule. To support the controller in developing a suitable planning, the display allows the user to test potential modifications to the schedule directly on the display. These probes are implemented as a Direct Manipulation Interface (DMI) [17].

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 occupancy expectation, 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 occupancy of the aircraft being probed (shown green in Figure 2(f), 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.

V. Exploratory experiment

Note that the diagram described in this paper currently 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 ATC.

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 4).

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 per aircraft at a 2 hour horizon between 50 and 200 seconds (i.e., an approximate spread of the error between 2 and 10 minutes). These errors are of similar order of magnitude as errors in current operation [18]. This

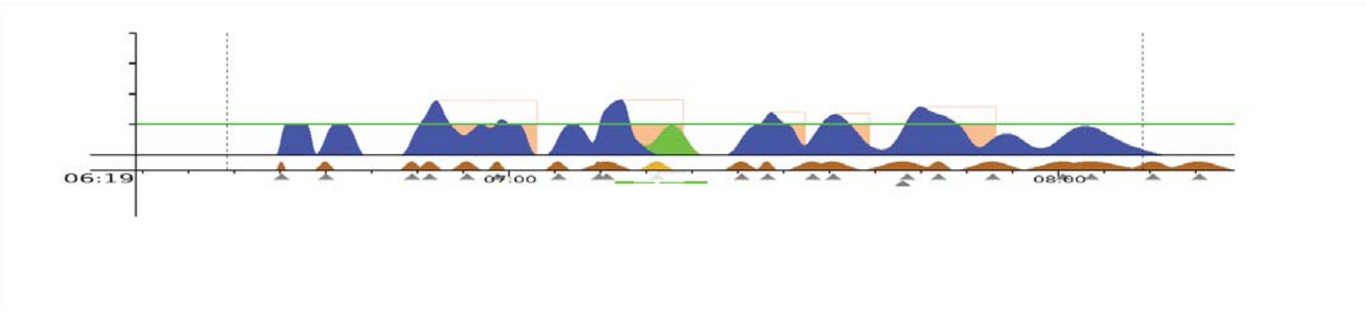


Fig. 4. The experiment display in the full configuration. For clarity, the background colour has changed from black to white. The green lines below the aircraft symbol show the control space available for that aircraft.

standard deviation would decrease linearly with remaining time to fly to a fixed, final standard deviation of 5 seconds (i.e., an approximate spread of the error of 30 seconds). The error was expressed in standard deviations from the mean. As the standard deviation decreased with decreasing horizon, so did the error. Finally, the normal distribution used for calculating the prediction error was provided with its mean on the erroneous ETA. The resulting PDF therefore gave an accurate representation of the possible error.

Aircraft were modeled to fly constant, identical speeds to the runway with an ability to accelerate or decelerate an equal amount. This resulted in control limits that would decrease with decreasing horizon. All aircraft had the same speed, and therefore the same control space at a moment in time.

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, a 5 point Instantaneous Self Assessment (ISA) probe appeared on the side of the screen every 30 seconds [19]. 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.

VI. 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 (Figure 5). 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

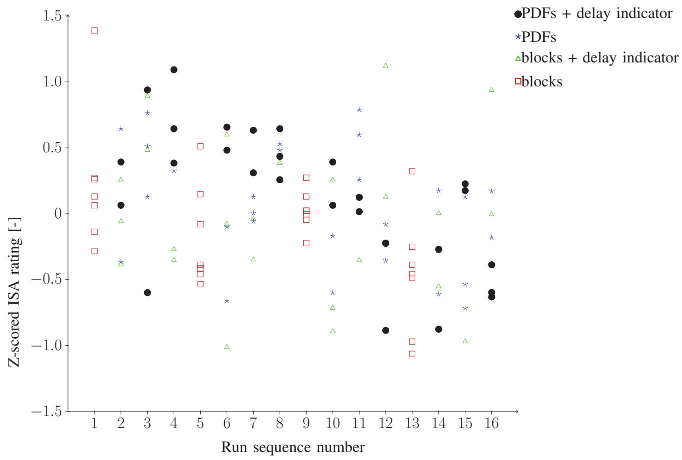


Fig. 5. Z-Scored workload rating over run sequence demonstrating training effect.

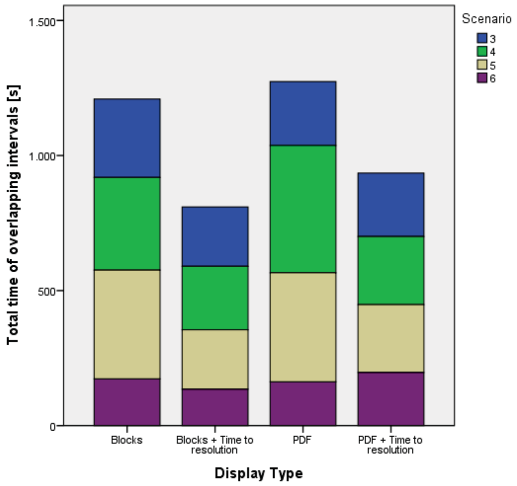
occupancy expectation was considered unpredictable. This may be due to the morphing shape as uncertainty decreased, but could also be due to insufficient training. In general, subjects preferred the blocks as they provided a more direct indication of the amount of buffer between two slots.

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 6(a). However, no statistical conclusions could be drawn. Figure 4 suggests that appearance of the resolution time indicator could help in identifying and highlighting conflicts by introducing a new colour whenever a spacing conflict existed. This potential effect was confirmed by remarks from the subjects.

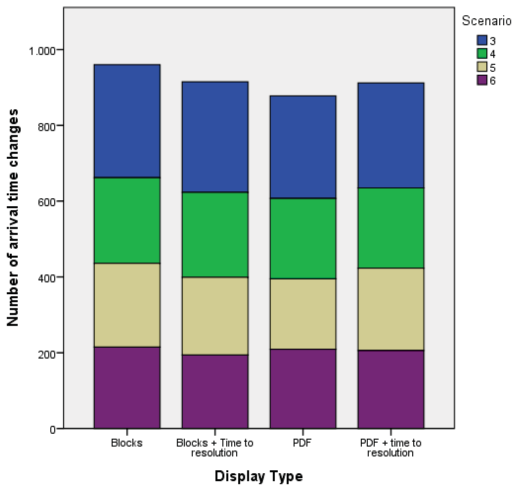
To eliminate the possibility that this indicator acted solely as more recognisable signal of a conflict, Figure 6(b) shows that the lower number of conflicts was reached without an increase in the total number of corrections. This result suggests that the display helps in establishing more appropriate spacing between aircraft.

VII. Discussion

The continuation of the learning curve suggests that subjects need more training for a true test of the effect of the display



(a) Total number of seconds of spacing violation per display type.



(b) Total number of changes to arrival times per display type. Note this is the total over 7 subjects, executing 4 scenarios. (i.e., 1000 represents about 40 adjustments within one 3 hour simulated interval.

Fig. 6. Effect of the display of time to resolution on prevention of conflicts.

on the planning performance. As this is true for all display types however, training may also be required for the subjects to become familiar with the system under control first of all: Prior work on EID stressed that the approach is aimed to develop interfaces for the control of complex systems by expert users of those systems [11], [20]. Bennet and Flach propose that, since the system is complex, the interface has to be complex as well to provide all information on the controlled system that could be of value in the decision-making process [20]. In the case of this experiment, the subject may first have to grasp the intricacies of managing arrival times in uncertainty, before elements on the display are meaningful to their decisions. Beside asking operational experts as subjects, users may furthermore need training to understand the unfamiliar presentation of —perhaps familiar— concepts, as noted by Jamieson for example [21].

While the use of the expectation of occupancy may provide

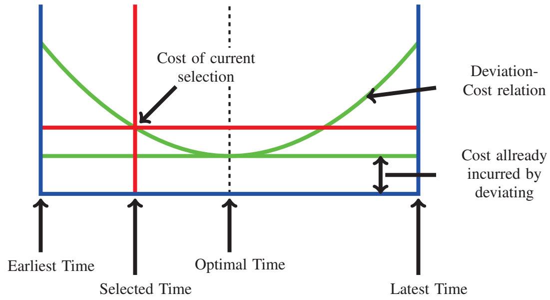


Fig. 7. A visualisation of the deviation-cost relationship supporting direct manipulation. The diagram directly shows the expected cost at landing of the currently probed deviation as a horizontal line (indicated here in red). The curve subsequently indicates which direction will improve performance toward the efficiency goal.

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. However, it could again be argued that this is partially due to a lack of understanding which could improve with training. Subjects did however, indicate that the size of the uncertainty helped them in estimating the required amount of buffer between two aircraft.

The current approach assumes that aircraft can make an equal adjustment in speed both faster and slower. In reality however, the available speed change may not be that flexible and 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 yet 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, which may cost considerably more fuel for the same gain in time. Similarly, 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. Next experiments will therefore include the cost-deviation diagram shown in Figure 7. This indicator visualises both the control space as well as the deviation-cost relationship.

The display assumes knowledge on an aircraft's ETA which is available at present but also on the uncertainty of that arrival time. The models described used in previous concepts were focused on the airborne segment of the flight [6], [8], [9] in particular addressing deviations due to aircraft behaviour and wind error. At the horizons considered in this concept, the models will also have to include the predictability of factors on the ground, as well as the possibility that upstream ATC will have to adjust the trajectory for separation purposes.

Next to the magnitude of the uncertainty, also the shape of the uncertainty needs research. For example, it is unlikely that the uncertainty is a normally distributed at large horizons as used in the exploratory experiment since departures can be delayed more than they may be advanced [18]. Therefore, additional research is needed on adequately predicting uncertainty of an ETA.

The lower right of the AH in Figure 1 shows a number of aspects of the system which influence the available capacity. Especially at airports where runway combinations are varied to accommodate varying demand, timely decisions will enable early trajectory decisions for arriving aircraft as well as early departure decisions for departing aircraft that compete for use of the same runway. A key problem in providing meaningful representation of multiple resources (i.e., runways) is that a distinction needs to be made between global excesses in demand (i.e., more aircraft than the airport can handle) versus local excesses (i.e., too little spacing at one runway). The first can be directly shown on the timeline by raising the capacity limit. However, the latter requires distinction of which resource is used by which aircraft.

The current concept does not yet address sequencing. Depending on the airport, sequence optimisation can be a valuable means to increase capacity. Since uncertainty in the arrival time will cause uncertainty in the available sequence, the resulting demand graph will have to take uncertainty in the required separation times into account.

Finally, an observation on the ISA was made by a number of subjects. As they were briefed on the meaning of the five points (excessive, high, comfortable, relaxed, under-utilized [19]) subjects would self-evaluate their condition on the ISA prompt. A part of this self evaluation would be to see whether the situation was still ‘under control’. Therefore, the ISA prompts would drive a scan cycle along all aircraft, followed by a correction cycle. Future experiments may well be better served by a —subsequently normalized— analog scale in which the users are not asked to try and describe their situation in words.

VIII. Conclusion

This paper presents a novel Arrival Manager (AMAN) display in which the operator is supported toward optimising all objectives of the arrival planning process while taking into account the uncertainty of the uncertainty in predicted arrival times. By visualising the Probability Density Function (PDF) onto the currently common timeline display, the sequence manager can actively balance the need for early trajectory adjustments with the likelihood that erroneous Estimated Times of Arrival (ETAs) force later corrections. This reduces the effect of the uncertainty on the effective working horizon of AMAN allowing far earlier trajectory adjustments when uncertainty is low. By making such early corrections, the effect on flight efficiency is minimised.

Initial experiments do show that an interface in which occupancy is presented as a cumulative expectation of resource occupancy is more difficult to understand for novice users without experience in arrival planning. To draw more definite conclusions, further experiments will need to be performed in which subjects receive more training, or have prior experience in arrival management.

Acknowledgment

This project is supported by the Knowledge Development Center Mainport Schiphol in collaboration with National Aerospace Laboratory (NLR), the Netherlands, and Delft University of Technology, the Netherlands.

References

[1] A. Barff, B. Favennec, P. Conroy, L. Bellesia, J. S. Greenwood, A. Clark, A. k. W. Wall, Y. Matsson, S. Törner, D. Chouvet, D. Nieuwenhuisen, E. Westerveld, and A. Linner, “SESAR P05.06.04 - D28 - Preliminary OSED Ed. 00.01.01,” SESAR Consortium, Tech. Rep., 2012.

[2] J. Bronsvoort, G. McDonald, M. Paglione, C. Garcia-Avello, I. Bayraktutar, and C. M. Young, “Impact of missing longitudinal aircraft intent on descent trajectory prediction,” in *30th IEEE/AIAA Digital Avionics Systems Conference*, Seattle, WA, Oct. 2011.

[3] SESAR JU, “SESAR Concept of Operations at a Glance ED 02.00.00,” SESAR JU, Tech. Rep., 2011.

[4] JPDO, “NextGen Integrated Work Plan: A Functional Outline,” 2008. [Online]. Available: http://www.jpdo.gov

[5] S. Mondoloni, M. Paglione, and S. Green, “Trajectory Modelling Accuracy for ATM Decision Support Tools,” in *International Congress of Aeronautical Sciences (ICAS)*, Toronto, Canada, Sep. 2002.

[6] T. Mueller, J. Sorensen, and G. Couluris, “Strategic Aircraft Trajectory Prediction Uncertainty and Statistical Sector Traffic Load Modeling,” in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, no. August, Reston, VA, Aug. 2002.

[7] G. Hunter, “Toward a Standardized Reference Set of Trajectory Modeling Errors,” in *AIAA Modelling and Simulation Technologies Conference and Exhibit*, no. August, Providence, RI, Aug. 2004.

[8] P. Whysall, “Future Area Control Tools Support (FACTS),” in *USA/Europe Air Traffic Management Research and Development Seminar*, no. December, Orlando, FL, Dec. 1998.

[9] D. Schaefer, A. Gizdavu, and D. Nicholls, “The display of uncertainty information on the working position,” in *23rd IEEE/AIAA Digital Avionics Systems Conference*, vol. 1, Washington D.C., Oct. 2004.

[10] N. Hasevoets and P. Conroy, “AMAN Status Review 2010,” EUROCONTROL, Brussels, Tech. Rep., 2010.

[11] K. Vicente and J. Rasmussen, “Ecological interface design: theoretical foundations,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 22, no. 4, pp. 589–606, 1992.

[12] K. J. Vicente, *Cognitive Work Analysis*. Malwah, NJ: Lawrence Erlbaum Associates Inc., 1999.

[13] J. Rasmussen, “A Taxonomy for Analysis of Cognitive Work,” in *IEEE Conference on Human Factors and Power Plants*. Monterey, CA: IEEE, Jun. 1992.

[14] SESAR Consortium, “D2 - The Performance Target,” SESAR Consortium, Tech. Rep., 2006.

[15] E. G. Knapen, “ERAT Arlanda RTS Controller Handbook,” National Aerospace Laboratory NLR, Amsterdam, The Netherlands, Tech. Rep., 2010.

[16] J. Rasmussen, “Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models,” *IEEE Transactions On Systems Man And Cybernetics*, vol. 13, no. 3, pp. 257–266, 1983.

[17] E. L. Hutchins, J. D. Hollan, and D. A. Norman, “Direct Manipulation Interfaces,” *Human-Computer Interaction*, vol. 1, no. 4, pp. 311–338, 1985.

[18] E. Gilbo and S. Smith, “Probabilistic prediction of aggregate traffic demand using uncertainty in individual flight predictions,” in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, no. August, Chicago, IL, 2009, pp. 1–20.

[19] A. J. Tattersall and P. S. Foord, “An experimental evaluation of instantaneous self-assessment as a measure of workload.” *Ergonomics*, vol. 39, no. 5, pp. 740–8, May 1996.

[20] K. B. Bennett and J. M. Flach, *Display and interface design: Subtle science, exact art*. Boca Raton, FL: Taylor and Francis, 2011.

[21] G. A. Jamieson, “Bridging the Gap Between Cognitive Work Analysis and Ecological Interface Design,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 47, no. 3, pp. 273–277, Oct. 2003.