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Mulder, Max; Yang, Lei; Borst, Clark; Van Paassen, M. M.

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Solution-Space-based ATC Support for 4DT Heterogeneous Aircraft-Mix Control

Max Mulder[1], Lei Yang[2], Clark Borst[1] and M. M. van Paassen[1]

***Abstract*— Future Air Traffic Management concepts will require air traffic controllers to move from a tactical to a strategic way of operation. This paper evaluates two novel concepts which support controllers to perform four-dimensional trajectory management in a contingency situation. The Travel Space Representation and Time-Space Diagram are both solution-space based displays where automation calculates all possible actions in real-time. All decision-making is still to be done by the operator but is greatly facilitated by this automation, as it shows all possible actions at a glance. An experiment is described which evaluated the performance of novice controllers in managing a sector where suddenly a bad weather cell emerged, requiring them to re-route traffic in space *and time*. Results show that the display concepts work well and support operators even in complex situations with a heterogeneous mix of aircraft types and speeds. Performance and workload indicators become worse for the higher-density, higher-heterogeneity situations.**

I. Introduction

SESAR and NextGen are, respectively, European and American initiatives to re-think and re-structure the concept of Air Traffic Management (ATM) [1], [2]. Whereas current-day air traffic controllers mainly work on tactical control of individual aircraft, and are responsible for a safe and efficient flight, future air traffic control will be fundamentally different. Trajectory-based Operations (TBO) are foreseen, where aircraft have to maintain their agreed-upon four-dimensional trajectories (4DT), which are completely defined beforehand. Monitoring and revising aircraft trajectories in real time will become an integral part of the future air traffic controller. Working on four-dimensional (space *and* time) constraints is very challenging, however, and human operators need to be supported with more advanced automated tools.

Although the introduction of higher levels of automation is foreseen, the step towards full automation is not expected. On the contrary, SESAR clearly states that "*Humans will be central in the future European ATM system as managers and decision-makers*" [3]. From the many key challenges that need to be addressed, here we name just four. First, what will be the role of the human operator, exactly? Second, what allocation of tasks between human and automated systems is optimal, that is, how will the operator be supported by automated tools? Third, in such a highly-automated environment, when will the operator be required to 'take over', and how do we support her in doing that? Fourth, do operators accept the automation and the tools that come with it? [4]–[7]

[1]Control & Simulation, Aerospace Engineering, Delft University of Technology, The Netherlands. Email: {m.mulder, c.borst, m.m.vanpaassen}@tudelft.nl

[2]College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, China. Email: laneyoung@nuaa.edu.cn

Clearly, the introduction of increased automation in ATM should benefit from the lessons learned from similar developments in the aircraft cockpit during the past four decades. Here, the 'ironies of automation' are commonplace, [8], and the 'out-of-the-loop' problem has proven to be an extremely difficult problem to resolve. That is, current-day pilots show erosion of skills, often do not understand what the automation is doing or is capable of, and lack situation awareness when automation fails. Following this approach in ATM will definitely lead to similar problems, potentially threatening safety [9].

In developing interfaces and automated tools for future TBO-based ATM, we propose a different approach than that followed in cockpit automation, namely the design of a Joint Cognitive System (JCS) [10], where humans and automation work as a team [11]. An ecological approach to interface design [12], [13] is adopted where automation is built to support human thinking and creativity in dealing with foreseen, but especially unforeseen events [14]. The resulting human-machine system shows so-called "solution spaces", possibilities for actions of any human or automated agent afforded by the environment in which that agent operates. Our interfaces show constraints for actions, rather than automated advices or commanded actions [14]–[16].

Previous developments in both cockpit and ATM applications have shown that solution-space based interfaces allow human creativity, support human and automation team decision-making, and increase the acceptability of automated tools, even at higher levels of automation [17]–[23]. In this paper we will briefly explain two of our 4DT ATM interfaces, namely the Travel Space Representation (TSR) and the Time-Space Diagram (TSD), and discuss one of the ongoing evaluations of these interfaces. The experiment focused on the task of managing the effects of an unexpected, large disturbance (like a bad weather cell) in a horizontal sector, where all 4DT flights were separated and planned beforehand. It is these contingency situations, in which operators have to "step in and solve a situation", where our tools are designed for. We study the effects of a low and high number of aircraft, and a homogeneous versus heterogeneous mixture of aircraft velocities, in a factorial design.

The paper is structured as follows. In Section II we explain our solution-space based interfaces, followed by a description of the experiment in Section III. Section IV will discuss a sub-set of the experimental results, focusing on typical human performance metrics like workload. The paper ends with conclusions and recommendations in Section V.

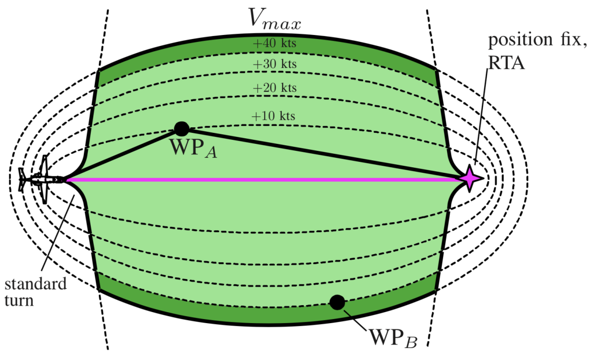


Fig. 1. Travel Space Representation (TSR).

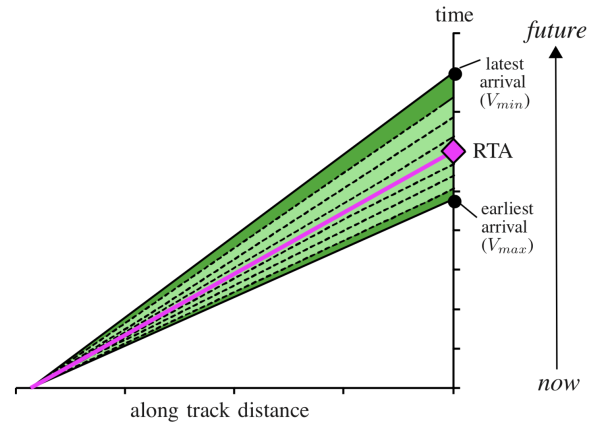


Fig. 2. Time-Space Diagram (TSD).

II. Solution-Space Interfaces

Van Paassen et al. [14] provide a general overview of the design philosophy adopted in ecological decision-support or locomotion control. In this section we will briefly explain two of the solution-space based interfaces which have been developed for future TBO 4DT ATM: (1) the TSR which can be seen as an ecological overlay that can be activated by the human controller when working with a traditional radar-like Plan View display (PVD), and (2) the TSD, which is a novel, separate display showing aircraft time-to-be- and distance-to-be-traveled to a sector exit point. Note that also a display showing the vertical aircraft trajectory constraints has been developed, but is not used here. This means that, effectively, we study 3DT rather than 4DT in this paper, but for the sake of simplicity we keep referring to 4DT.

A. Travel Space Representation

The TSR is based on earlier designs on collision detection and resolution of aircraft in cockpit [19] and air traffic control [24], but extended to 4DT operations, in a way proposed earlier in [20]. It will be briefly explained at the hand of Fig. 1, which shows the situation of a *selected* aircraft, which needs to be at a position fix (in our case the sector exit point) at a pre-defined Requested Time of Arrival (RTA). The original planned trajectory is indicated as the purple line, and we assume the aircraft to have a ground-speed V. Effects of wind are not considered here, but can be added.

Now, in case of an unforeseen event, such as bad weather, the aircraft may have to fly around a weather cell, requiring the (in this paper) controller to define an intermediate waypoint WP$_A$. Any waypoint that is not on the original trajectory means that the trajectory is *longer*, and in order to be still on time at the next position fix the aircraft must fly *faster*. Fig. 1 shows that an increase of V with 10 knots means that WP$_A$ can be positioned on *any* point of the inner-most ellipsoid. The outer-most ellipsoid indicates where the waypoint can be put when the aircraft is required to fly at its maximum velocity V_{max}. Placing the intermediate waypoint outside this ellipsoid means that the RTA cannot be reached, and the aircraft will arrive later at the position fix.

The TSR therefore shows *all possible* intermediate waypoint positions that allow the aircraft to meet its RTA. In addition, the TSR can show the effects of other aircraft flying in the sector, possibly constraining the waypoint position further when the trajectory manipulation would lead to a loss of separation. In such a way, the TSR shows all possible waypoint positions that (1) lead to a safe (separated) flight, and (2) have the aircraft reach its RTA at the position fix.

Note that without any automation support, this task would be extremely difficult for a human operator to perform, as it requires him or her to separate in position *and time*, while also adhering to a time-constraint at the sector exit. The TSR *does not automate* the task, but only provides support for operators to understand the situation at a glance, and act on it themselves. All decision-making is still in the hands of the operator, automation is there to compute and show all possibilities for actions, in real-time.

B. Time-Space Diagram

Whereas the TSR allows the operator to stretch the path, to avoid no-go-zones and/or potential conflicts with other aircraft, the TSD allows the operator to manipulate the 4DT directly. Fig. 2 shows the TSD, with the horizontal axis showing the along-track-distance (distance-to-go, in NM) for a selected aircraft to the (in this paper) sector exit, and the vertical axis the time-to-go for that aircraft to the sector exit.

The operator can drag the RTA on the time axis up and down, requiring the aircraft to fly slower or faster, respectively, and the minimum and maximum RTA's are indicated. Dragging the RTA down means that the aircraft will arrive at the exit waypoint *earlier*, but must therefore fly faster, with the maximum velocity V_{max} as the limit: an aircraft cannot arrive earlier than that. Similarly, dragging the RTA label up means the aircraft must fly slower, with the minimum velocity V_{min} as the lower limit. The aircraft cannot arrive later with the current trajectory, without path-stretching on the TSR.

Note that the TSD and TSR are connected, that is, the effects of any manipulation on any of the two displays is immediately shown on the other interface. For instance, what is not shown in Fig. 2 is that, when an additional waypoint is added on the TSR, the TSD area for that aircraft will be split-up in two, and the operator can manipulate the RTA at the intermediate waypoint. When more intermediate waypoints are added, the same is true. Another feature which is not shown, is that the TSD also shows the no-go zones caused by any other aircraft in time and space, in a similar way as the TSR. Note that the connection of the two interfaces is further strengthened through high-lighting any aircraft or no-go zone on the other display, when the mouse hovers on any no-go zone, or aircraft, respectively, on the display used.

Together with the TSR, the TSD provides ample opportunities for the operator to *directly manipulate* the 4DT, in a way that makes sense and, with some training, allows the operator to act on any disturbances in a safe and efficient mannner. These 4DT manipulations would be impossible without the help of the solution-spaces, which are computed by automation. But note that nothing else is automated, the decision-making authority lies still 100% with the human. The only thing that automation does, is provide in real-time a graphical indication on 'what is possible', i.e., what the current 4DT situation allows the operator to do (i.e., *affords*) to reach her goals. The next section briefly describes an experiment done to test the TSR/TSD combination.

III. METHOD

A. Participants and Instructions

Seven participants, all males from TU Delft aerospace engineering with an extensive multiple-day ATC training participated.[1] Participants were trained and instructed to perform a 3DT (horizontal movement + time) manipulation task, with the help of the TSR and TSD displays introduced above, in contingency scenarios where the sector was suddenly disturbed by a weather cell. Fig. 3 shows the 200 by 200 NM sector, with six routes and two exit points, and the weather cell with radius R. Aircraft on Routes 1, 2 and 3 fly from West to East and must leave the sector at Exit point # 1; aircraft on Routes 4, 5 and 6 fly from North to South and leave at Exit point # 2.

All aircraft were de-conflicted beforehand, but because of the weather cell all aircraft on Routes 2 and 5 had to be re-scheduled horizontally, possibly leading to knock-on effects with aircraft flying on other routes. Vertical commands were not possible. Participants were instructed to (1) safely, i.e., with no loss of separation, and then (2) timely, i.e., all aircraft were required to (preferably) arrive at their exit point *on time*, deal with the contingency situation.

B. Independent variables, experiment design

The experiment had two independent variables. First, the number of aircraft to be dealt with was varied (2 levels), the 'low-density' (L) and 'high-density' (H) situation. These two levels corresponded to 50% or 90% of the maximum inflow rate, respectively, where 100% represents the maximum sector capacity for the traffic mix considered.

[1]Obtaining professional controllers for experiments is notoriously difficult.

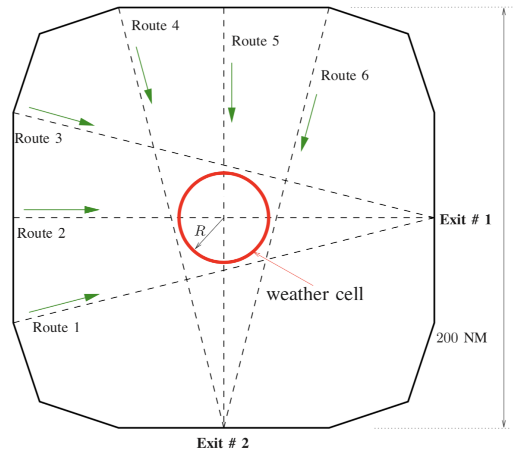


Fig. 3. Sector design, with 6 Routes and 2 Exit points; circular weather cell is shown in red; the direction of flight is indicated by the green arrows.

Second, the aircraft speed mix was varied (3 levels), where operators had to deal with 100% 'slow' aircraft (S) (velocity 390 knots, range $\langle 320, 460 \rangle$ knots), 100% 'fast' aircraft (F) (velocity 460 knots, range $\langle 390, 530 \rangle$ knots), and a 50/50% mix of the same slow and fast aircraft types. Aircraft motion was simulated using Eurocontrol's BADA framework [25].

A factorial design resulted in six conditions, referred to as L_S, L_F, L_SF, H_S, H_F and H_SF. The average number of aircraft per hour in these scenarios was 18, 23, 21, respectively, for the low-density conditions, and 34, 43 and 40, respectively, for the high-density conditions.

C. Simulation set-up

Participants used a conventional computer mouse and keyboard to manage traffic, and used two displays: (1) a Plan View Display (PVD) on which they could select an aircraft, resulting in showing the TSR overlay for that aircraft, and (2) the TSD. Fig. 4 shows a screenshot of both displays.

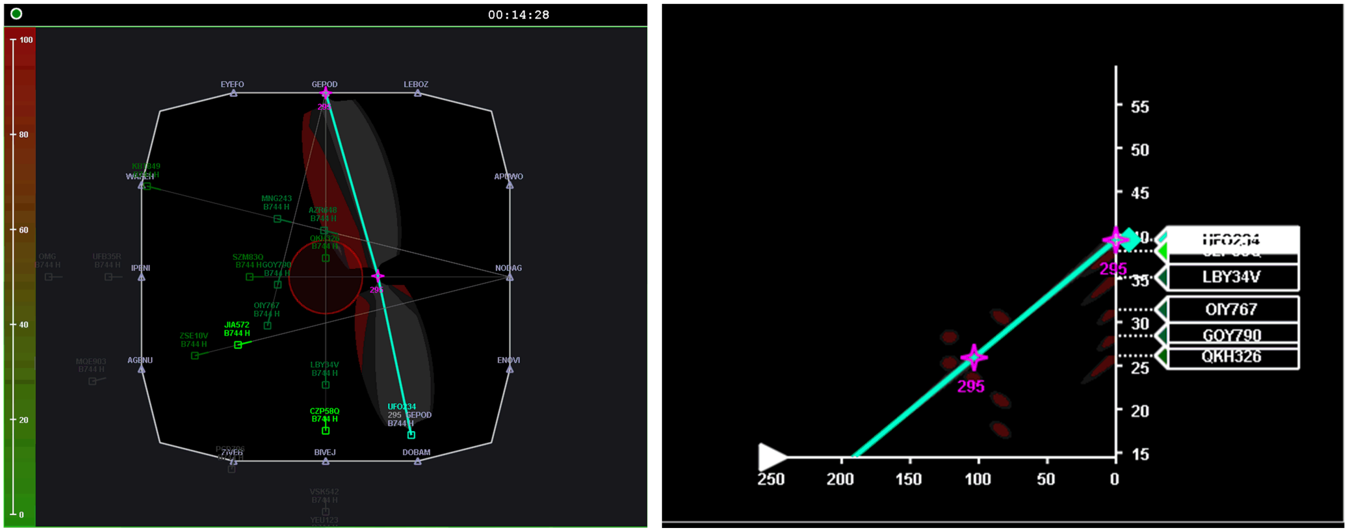
Traffic was simulated at four times faster than real-time, to increase operator workload and also reduce experiment time; Each scenario lasted approximately 15 minutes.

D. Dependent measures

A large number of dependent measures were measured and computed off-line, here only a small subset will be discussed.

The *performance* of participants was expressed in (1) the number of commands (NC) they used; (2) the scale of *potential* (i.e., not real, as these never happened) conflicts which emerged from their trajectory manipulations, and (3) the average increase in track miles flown by all aircraft.

The *workload* of participants was measured subjectively in two ways. During the run, subjects were asked every minute to give an Instantaneous Self-Assessment (ISA) [26]. After each run, they were requested to rate their overall workload during that run using the Rating Scale Mental Effort (RSME, Dutch version) [27], see Fig. 5.



(a) (b)

Fig. 4. Travel Space Representation (TSR): Plan View Display (PVD) on the left-hand side; Time-Space Diagram (TSD) on the right-hand side.

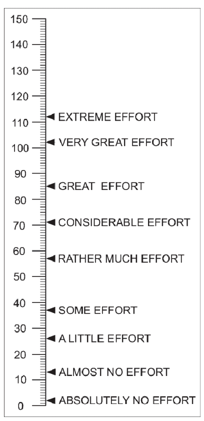


Fig. 5. Rating Scale Mental Effort (RSME), English version.

E. Hypotheses

We hypothesized that performance and workload of our operators will deteriorate (lower performance, higher workload) when the control task complexity increases. Traffic complexity increases with the number of aircraft which have to be controlled, and the extent to which the traffic mix becomes more heterogeneous [24], [28], [29].

IV. Results and Discussion

A wealth of data resulted from the experiment and only a small subset of results will be discussed in this paper, focusing on operator performance and workload. As most of the data were not normally-distributed, non-parametric statistical tests were used; effects were not-significant unless mentioned otherwise; significant effects refer to having p values lower than 0.05.

A. Operator performance

1) Safety: Fig. 6 shows the average scale of *potential* conflicts. Again note that these are not real conflicts, but situations where aircraft could (when the operator would do nothing) result in a conflict. This figure, and all that follow show the six conditions L_S, L_F, L_SF, H_S, H_F and H_SF at the bottom, and the data averaged over all subjects as box-plots, with outliers shown as stars.

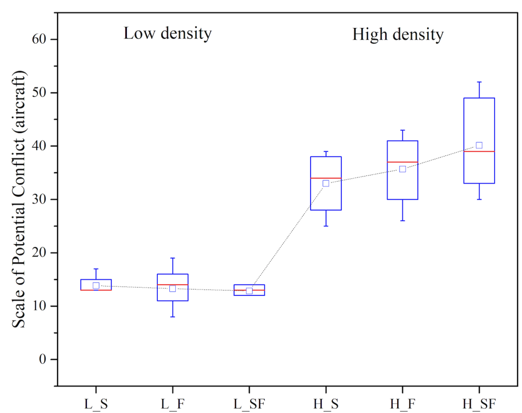


Fig. 6. Average scale of potential conflict (all subjects).

Regarding this safety-related metric, the average scale of potential conflicts is proportional with traffic density, a significant effect. Whereas for the lower density the traffic mix has no effect, it does so when the number of aircraft in the sector has approximately doubled (significant). Note that all potential conflicts were caused by the operators trying to resolve the contingency situation, where aircraft were forced to change their trajectory because of the weather cell.

2) Additional track miles: As one potential measure of performance the average additional track miles is shown in Fig. 7. Clearly, trajectory manipulations through adding one or more intermediate waypoints is one of the main functionalities that the TSR allows. The additional track miles can be easily calculated as the difference between the scheduled and flown trajectory. This metric is not only determined by the traffic situation as such, but can also be affected by the style of the controller, with some controllers more inclined towards speed changes and others working more along the lines of adding waypoints. Clearly, all aircraft on Routes 2 and 5 must be re-routed as these trajectories cross the no-fly zone.

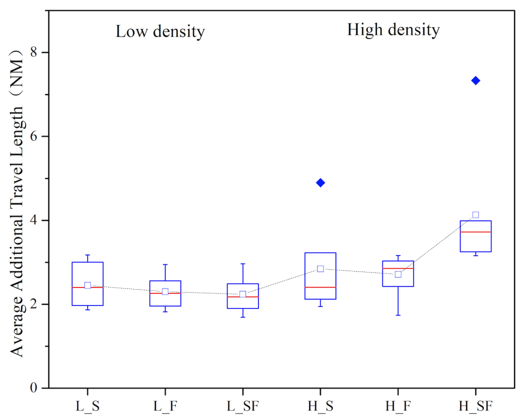


Fig. 7. Average additional track miles, in NM (all subjects).

For the low-density scenarios, the differences caused by the speed-mix were small and insignificant. For the high-density scenarios, the speed mix did cause an increase, but only significantly for the 50/50% condition, H_SF. Only in this condition our participants sent aircraft farther away from their original trajectories than the, on average 2.5 NM in all other scenarios.

3) Number of commands: The average number of commands that our participants used to manage traffic is illustrated in Fig. 8. Control commands were done using a mouse (clicking on the TSR or TSD) and keyboard (pressing "enter" issued the speed or trajectory change to the selected aircraft); in case both a speed and path-change command were given, these were counted as two separate commands.

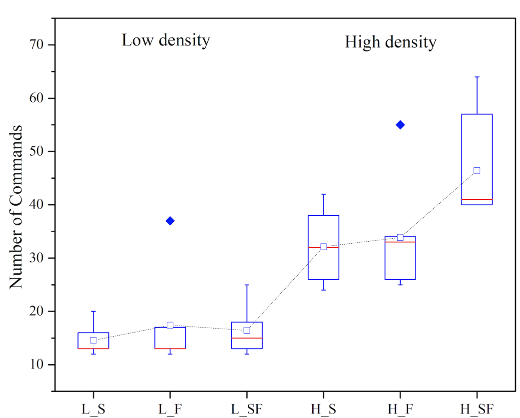


Fig. 8. Number of commands (all subjects).

As hypothesized, the number of commands increased significantly for the high-density scenarios with on average 21 more commands needed to manage the traffic. For the low-density scenarios, there was neither a trend nor any significant effect of the speed-mix, for the high-density scenarios the 50/50% speed mix led to a significant increase in the number of commands issued. Given that condition H_F had on average 3 more aircraft per hours as compared to condition H_SF (43 versus 40), we see that larger speed heterogeneity indeed results in significant more actions.

B. Operator workload

The average ISA ratings (measured every 1 minute) and RSME ratings (given after each run) are shown in Fig. 9. Both ratings are similar, as could have been expected; a Pearson correlation of 0.88 ($p < 0.01$) was found.

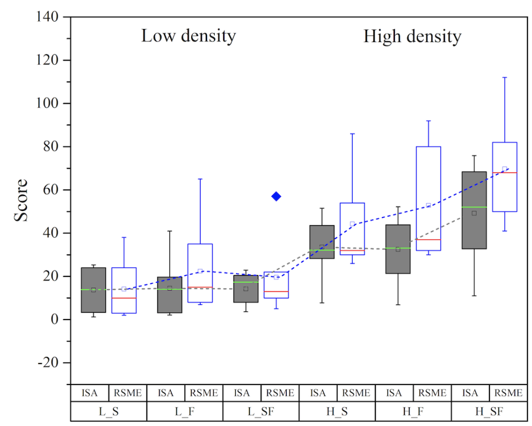


Fig. 9. ISA and RSME workload ratings (all subjects).

Both ISA and RSME ratings are significantly higher in the high-density conditions, as was hypothesized. For both metrics, there were no significant differences between the speed-mix conditions for the low-density scenarios. In the high-density scenarios only the 50/50% speed mix H_SF resulted in a significantly higher subjective workload relative to the other two speed-mixes, similar as the number of commands metric discussed above. Pearson coefficients of 0.85 and 0.90 were found ($p < 0.01$) between the latter metric, and the ISA and RSME scores, respectively.

C. Discussion

Overall, the hypotheses were partially confirmed. The low-density scenarios were relatively easy and the expected effects of a homogeneous or heterogenoeus speed mix were not found. This changed when the number of aircraft increased considerably, in the high-density scenarios, leading to significantly higher number of commands, workload ratings, and additional track miles. Here the 50/50% speed mix H_SF indeed led to higher workload and more commands (both significantly) relative to the other two scenarios H_S and H_F, where the latter scenario had on average 3 *more* aircraft/hour to be controlled. This finding corroborates the fact that aircraft speed mix indeed affects traffic complexity, and with that also the operator workload [28], [29].

One of the main take-aways from the experiment, was that our subjects were very well capable to deal with the contingency situation that was simulated. Although at times their workload was considerable, participants were able to solve the 4DT problem in a satisfactory way, and no conflicts (defined as a potential loss-of-separation) happened. Here one should keep in mind that our simulation was run at four times real time, so in reality the workload may be much lower, albeit the number of aircraft could be larger, and the sector much smaller. This is a topic of future research. Further note that our subjects were not professional controllers, but all engineers who obtained an extensive multiple-days conventional ATC training.

The TSR and TSD supported operators' decision-making, and allowed them to manage the contingency very well *without* any command or advice given by the automation. Remember that the automation was active at all times, but *only* served to compute and draw the solution spaces. Through painting the complete picture of the situation, including all constraints for action and providing a direct manipulation interface for operators to use the available means (actions on the TSR and TSD) for their ends (instructions and goals), we created a very workable interface.

V. Conclusions

The solution-space based interfaces allowed participants to manage contingency scenarios in a 4DT TBO-based ATM concept of operations. Clever automation tools are employed to show the time, position and velocity constraints of selected aircraft in real-time, which allows operators to see and directly manipulate their trajectories in space and time, adhering to all ATC performance goals (safe and efficient flights). It is shown that increasing the speed heterogeneity of the aircraft mix increases workload and reduces performance, but only in high-density traffic situations. Future work focuses on including a vertical solution-space based interface, and studying effects of sector size and traffic density in ATM scenarios with doubled or tripled numbers of aircraft.

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