Performance Review of Non-Nominal Scenarios in a Validation Exercise of the Flight Centric Air Traffic Control Concept

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***Abstract*—A validation campaign was set up to evaluate the flight centric ATC concept within the Hungarian airspace. Part of this validation campaign was a focus on non-nominal conditions (emergency decompression, radio failure and thunderstorms). An analysis of the results of these scenarios was performed. On the one side, the conflicts both medium-term and short-term, were analyzed with respect to their detection horizon and subsequent resolution timeframe, as well as their respective resolution method. Further, human performance data in terms of workload and situational awareness were analyzed to better understand how the controllers handled these specific scenarios. The results show that both situational awareness and workload ratings of the controllers are within acceptable ranges. Further, it was seen that if the controllers did not follow the conflict resolution advisory given by the tools, they preferred conflict resolution methods that required a single command, like a direct to, heading or flight level change.**

***Keywords*—Flight Centric Airspace; Performance Analysis; Workload; Situational Awareness; Medium-Term Conflict; Short-Term Conflict**

I. Introduction

In current operations, an airspace controlled by an Air Navigation Service Provider (ANSP) is split up into smaller areas, called sectors. In Europe each sector is assigned to a team of controllers, which consist of an Executive Controller (EC) and Planner Controller (PC). The team's main responsibility is to provide separation for all aircraft within the sector.

Most research has focused on increasing sector capacity by means of better airspace utilization (e.g. dynamic sectorization [1]) or by the introduction of automation (e.g. arrival manager (AMAN) [2], departure manager (DMAN) [3], etc). While these solutions lead to an increase in airspace capacity, they do not solve the bottleneck of airspace structure.

Flight Centric ATC takes a different approach to solving the airspace capacity problem. In the Flight Centric ATC concept, the controllers are no longer responsible for a given sector, but instead are assigned a number of aircraft within the airspace. They are responsible for these from the moment they enter the airspace until they exit. The result is an airspace where conflicting aircraft might be handled by different controllers.

The Flight Centric concept was first introduced by Duong, Gawinowski, Nicolaon and Smith [4] in 2001. Within the German Aerospace Center, research has been conducted on the Flight Centric ATM concept since 2008, first in close cooperation with the German ANSP DFS Deutsche Flugsicherung [5], later in cooperation with the Hungarian ANSP HungaroControl [6], [7].

Previous publications have investigated several aspects of the concept: General feasibility of the concept for upper airspace was proven in 2011 [8]. A 2010 paper discussed the compatibility of sectorless ATM within the Single European Sky ATM Research (SESAR) [9]. Further research covered a first set of priority rules [10], assignment strategies [11], the controller's mental model [12], controller tasks [13], [14], a safety assessment [15], transition strategies [16], and the human-machine interface [17].

This paper will introduce results of the PJ.10-W2-73-FCA EXE 02 validation exercise.

II. Methods

A. Scenarios

The exercise was performed as a real-time human-in-the-loop simulation, which took place at the DLR Institute of Flight Guidance in Braunschweig. This validation exercise is the successor of the EXE-PJ.10-01b-V2-001 validation campaign that took place in 2019 at HungaroControl. This previous validation campaign focused on proving the general feasibility of implementing Flight Centric ATC within the Upper Budapest Control area ranging from FL325 to FL660.

In the following exercise, feedback from the 2019 validation campaign was implemented and the improvements were tested in nominal, non-nominal, as well as degraded mode of operations. In addition to the different operational conditions, the complexity of the scenarios was varied between medium, high and very high. Table I shows the complexity as well as the scenario conditions for each of the scenarios used in the validation exercise.

This paper will mainly focus on the non-nominal conditions, with a special focus on the emergency (2 and 7), radio failure (4) and the thunderstorm scenarios (6).

Table II shows a more detailed overview of the Medium and High complexity scenarios used in the non-nominal conditions.

TABLE I. SCENARIO DESCRIPTIONS OF THE VALIDATION CAMPAIGN

Scenario Number	Traffic Complexity	Scenario Condition	duration (minutes)
1	Very High	Normal	60
2	High	Emergency Aircraft	20
3	High	Normal	60
4	High	Radio Failure	40
5	Very High	(No Probing)	60
6	Medium	Thunderstorm	60
7	High	Emergency Aircraft	20
8	High	MTCD Failure	60
9	Very High	Normal	60
10	Very High	WAC System Failure	60

TABLE II. COMPLEXITY DETAILS

Characteristic	Medium Complexity	High Complexity
Number of aircraft per minute	51-58	62-84
Total number of aircraft	242	326
Number of datalink equipped (randomized, jets only)	80 (30%)	97 (30%)
Number of aircraft in climb phase	12	20
Number of aircraft in descent phase	19	30
Total amount of conflicts	85	160
Total amount of conflicts inside HUFCA	26	67
Total amount of conflict with multiple conflict partners inside HUFCA	3	14
Total amount of entry/exit conflicts	9	0

1) Emergency Scenarios: In each of the emergency scenarios (runs 2 and 7), two aircraft incurred a decompression emergency, leading them to making an emergency descent to the nearest airport. The other controllers were informed of this emergency via the aircraft label of the affected aircraft. The duration for these scenarios was about 20 minutes.

In run 2, the first decompression emergency occurred approximately after eight minutes in the simulation. The descending aircraft caused a conflict with four other aircraft. The second decompression emergency took place approximately seven minutes later, resulting in two more conflicts.

During run 7, the first emergency takes place after six minutes, causing five conflicts, while the second about two minutes later caused an additional two conflicts.

2) Radio Failure Scenario: In this high complexity scenario, one aircraft lost communication with the assigned controller. The other controllers were informed of this communication loss via the aircraft label of the affected aircraft. This scenario lasted for 40 minutes.

3) Thunderstorm Scenario: In run 6, a thunderstorm blocked a major part of the Hungarian airspace a few minutes after the start of the simulation run. The thunderstorm then remained, while sporadically moving from west to east for the rest of the scenario.

B. Technical Setup

The software used within the validation exercises was implemented in DLRs TrafficSim platform. The Human-Machine Interface of the radar display, flight labels and their interactions as well as all tools were based on those used by the Hungarian ANSP, HungaroControl. Furthermore, the parameters for the medium-term conflict detection and tool behaviors were tweaked to resemble those of HungaroControl.

One key difference compared by the usual radar display used in the Hungarian airspace, is the fact that the whole airspace is represented on the display monitor, as seen in Figure 1.

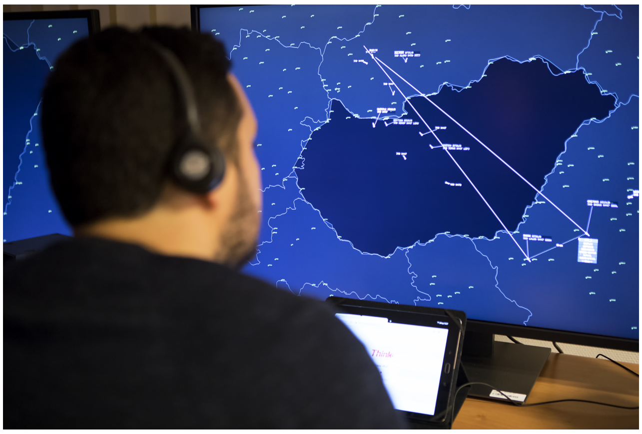


Figure 1. Radar HMI of the Flight-Centric Hungarian Airspace

The controllers had a set of tools available to support them in their tasks:

- Medium-Term Conflict Detection (MTCD): The MTCD detects conflicts that will have a break of separation minima within a timespan of the next 20 minutes. The vertical separation in level flight was 1000ft with an increase to 3000 ft for vertical crossing aircraft. The calculation used by the MTCD tool is trajectory-based. For conflicts detected by the MTCD tool, resolutions proposals were calculated and suggested by the system
- Short Term Conflict Alert (STCA): The STCA tool identifies short-term conflicts. These are defined as a situation where two aircraft will experience a loss of separation (lateral separation smaller less than 5 NM, vertical separation lower than 1000 ft) within two minutes. The calculations of the STCA tool are vector-based.
- Probing: Calculates if the selected maneuver is conflict free. Both flight level changes as well as trajectory changes could be probed.
- Route Adherence Monitoring: Indicates if a aircraft under control is not following its cleared route. This can be both in terms of cleared flight level as well as cleared route.
- Filtering: The aircraft are filtered so that only aircraft of relevance to the aircraft under control are shown on the radar display. The controllers can chose to turn the filtering on or off. In case it is turned of, all aircraft within the airspace are visible.

The voice communication was simulated through a wide-area communication system (WAC) provided by Frequentis. This system was used for both the ground-air and ground-ground communication during the validation exercise.

In total ten working positions were set up distributed over two different rooms (four controllers in one room, six in another other room). Figure 2 shows the seating layout within

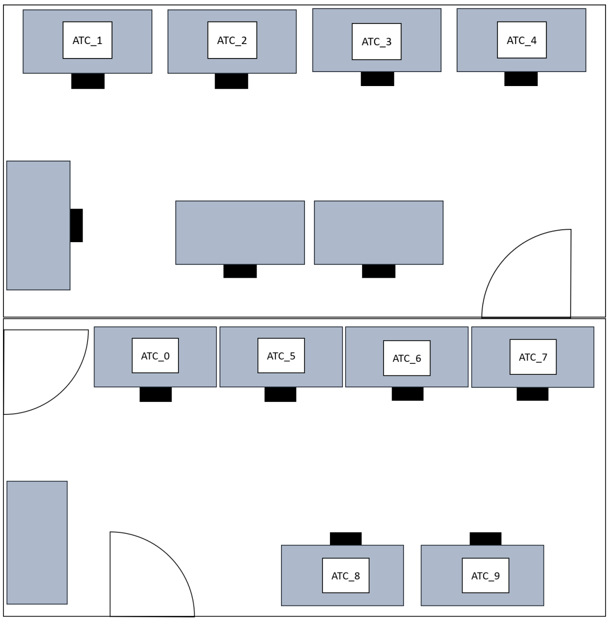


Figure 2. ATCO rooms setup

those rooms. This design choice was made because of the SARS-COV-2 related regulations that were imposed by DLR.

Communication with neighboring sectors was simulated by five additional licensed air traffic controllers, known as feeders, that handled the requests for these sectors. Additionally ten pseudopilots supported each validation run (a pool consisting of a total of 31 volunteers). Each controller was assigned one of these pseudopilots, who simulated all air-ground communication. These pseudopilots were also responsible for inserting the clearances given by the controllers into the system for the appropriate aircraft.

C. Participants

Ten controllers took part in the validation exercise as Flight centric controllers. They originated from six different ANSPs (PANSA, ENAV, Oro Navigacija, Enaire, DFS and ukSATSE). Eight of the controllers were men and two were women. Their experience ranged from 1.5 to 30 years (M = 16.3, SD = 9.1). Another five controllers were deployed as feeders. These controllers did not rotate into the Flight Centric controller positions, but rather stayed active as feeders during the whole validation exercise.

Since the controllers were from different ANSPs, they did not have any knowledge about the Hungarian airspace. Also the tools their ANSPs use had different parameters. It however did allow for the gathering of data from different perspectives and to understand how controllers handle unfamiliar airspaces that they have no prior knowledge of.

D. Procedure

As indicated before, in the real-time simulation ten ATCOs were tasked with handling the aircraft within the HUFCA flight centric airspace. Further five pseudo-controllers represented both the lower Hungarian airspace (below FL 325) and the neighboring sectors.

Training took place on the first one and a half days of the validation campaign. On the first day the controllers were given a short introduction to the Flight-Centric concept, followed by some practical training on the medium complexity scenario without any of the special conditions that would occur within the validation campaign. On the next day, the controllers requested a more challenging scenario for training, thus training resumed with the high complexity scenario.

The subsequent ten validation runs took place over two and a half days. During the simulation runs, controllers rotated through the different controller working positions, as well as through the two different rooms that were used to set up the controller positions. This ensured that each time the controller was sitting next to different controllers. There was never a rotation between feeders and controllers, as this would have required training fifteen controllers instead of ten.

E. Data Recording

One source of data during the validation exercise consisted of three questionnaires:

- pre-validation questionnaire
- post-run questionnaire
- post validation questionnaire

The pre-validation questionnaire covered the training that the controllers received; the post-run questionnaire was conducted after each validation run and contained questionnaires to assess workload and situational awareness (SASHA) [18] as well as simulation specific questions. Finally, the post-validation questionnaire was given at the end of the validation campaign and consisted of a standardized questionnaire to assess the trust in the platforms (SATI) [18] and a tailor-made questions connected to the success criteria.

In addition to the questionnaires, other data sources were recorded to assess the performance during the validation exercises.

For each controller working position, the HMI interactions were recorded. These data can be used to extract information about how conflicts were analyzed and solved, as well as other tasks performed during the scenario. These data are supplemented by screen recordings of each controller working position. Any unclear interactions or evolution of conflict could be checked in these recordings to have a better understanding of the controller's interactions.

For further information about conflicts, as well as state vectors of each of the aircraft within the scenario, datapool recordings were used. From here a full replay of the scenario also gave insights as to the full flown trajectories of the aircraft.

For recording workload, the controllers had an iPad with an instantaneous self-assessment (ISA) [19] app. This app would give a signal every five minutes, in the form of a loud beep, after which the controllers had 30s time to evaluate their workload on a scale from 1 to 5. A value of 1 indicated that the controllers had nothing to do, while a value of 5 indicated that the controller was overloaded, i.e. a higher score indicates a higher workload. The full meaning associated with each level of the ISA scale, is shown in Table III.

TABLE III. INSTANTANEOUS SELF-ASSESSMENT SCORE DESCRIPTIONS

Level	Workload	Spare Capacity	Description
1	Under-utilized	Very Much	Little or nothing to do. Rather boring
2	Relaxed	Ample	More time than necessary to complete the tasks.
3	Comfortable	Some	The controller has enough work to keep them stimulated
4	High	Very little	Certain non-essential tasks get postponed.
5	Excessive	None	Some tasks are not completed. Controller is overloaded.

Finally, each validation run ended with a debriefing, where the controllers discussed the events that had taken place. After this debriefing, the controllers filled in the post-run questionnaires.

As mentioned before, as part of this post-run questionnaire, situation awareness (SA) was evaluated by means of a standard questionnaire SASHA. In this questionnaire, the controllers had to rate six different sentences on a 7-point never-always scale (never / rarely / sometimes / often / frequently / most of the time / always). Each of these ratings corresponds to a number from 0 to 6, used to calculate an overall score. The higher this overall score, the higher the SA. Furthermore, in the post-run questionnaire, there was a general question about the level of SA on a 7-point scale from very poor to very good (very poor / quite poor / poor / okay / good / quite good / very good).

III. RESULTS

For the performance analysis, the medium-term conflicts (MTCs) should be analyzed. An MTC is a conflict that is detected by the MTCD tool that will have breach of separation minima within a timespan of the next 20 minutes. The vertical separation in level flight was 1000ft with an increase to 3000 ft for vertical crossing aircraft. The actual parameters for this breach of separation minima defined within the MTCD tool changed during the validation exercise. Between Run 1 and 5 the lateral separation for the MTCD tool was set to 10NM while from Run 6 onwards it was set to 6NM. This change in lateral separation minima from Run 6 onwards was made following requests from the controllers, who usually work with stricter margins in their systems. Figure 3 shows the number of MTCs that each ATCO experienced and which they were responsible to solve.

To further analyze the MTCs, the distribution between the different detection categories can be conducted. These are determined by safety requirements to be: long term (15-20 min), medium term (4-15 min) and short term (2-4 min). These time points are defined as the time to closest point between the two aircraft or till a separation of 5 NM is breached. These data are represented in Figure 4.

After the categorization of the conflict detection in the different time categories, their respective resolutions can be categorized in the same manner. However, there are some more categories here to be taken into consideration: a conflict that is solved in the 0-2 min time to start of conflict; and those conflict that were not solved. Due to the difference in parameters used in medium-term conflicts and short-term conflicts, the previous categories can be further split up into those leading to a short term conflict (or loss of separation for the "not solved" category) and those not leading to a STC (or loss of separation). Figure 5 show the resulting analysis where each category of conflict detection is split up into conflict resolution time horizons.

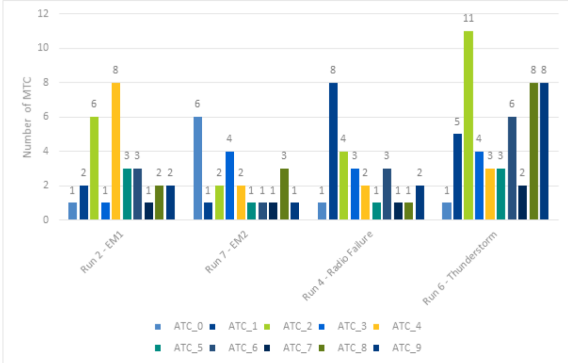


Figure 3. Distribution of MTCs according to responsible controller during the non-nominal condition scenarios

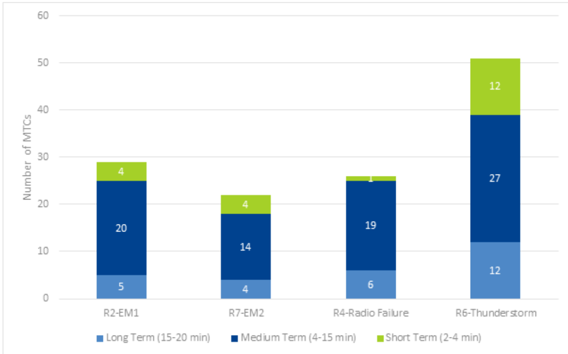


Figure 4. Distribution of MTCs in the detection categories during the non-nominal condition scenarios

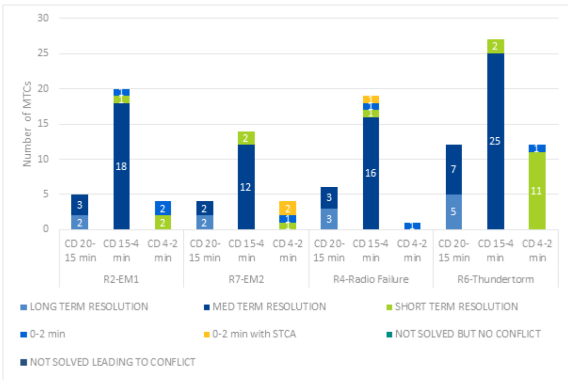


Figure 5. Resolution timeline for each detection timeline for MTCs within non-nominal conditions

The next step was to considers how the conflicts were solved and by whom. Figure 6 shows the percentage of conflicts that were resolved using the conflict resolution advisory and whether they were solved by the responsible controller or by another controller. Further it shows the percentage of conflicts that were not solved leading to an STCA or a loss of separation.

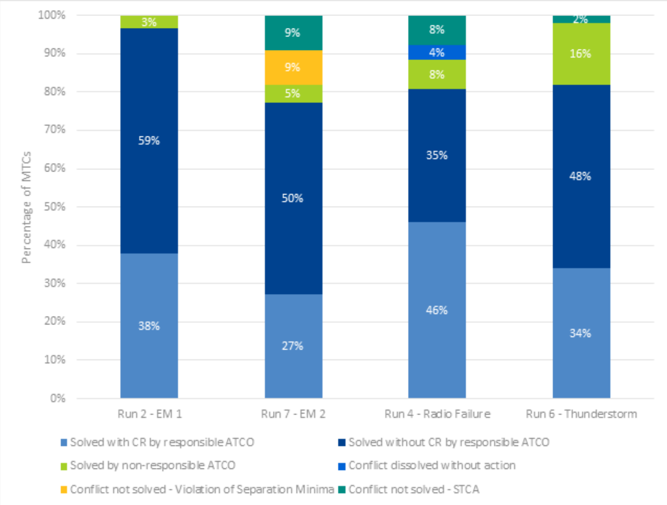


Figure 6. Resolution actor for MTCs within non-nominal conditions

Figure 7 shows the types of clearances that were given to solve the conflicts. The different categories are: level, heading and speed changes as well as direct to; following the conflict resolution advisory; In case of a descending aircraft, delaying the top of descent in order to avoid a conflict during the descent; and finally, a combination of multiple solutions from the level, heading, speed and "direct to" categories.

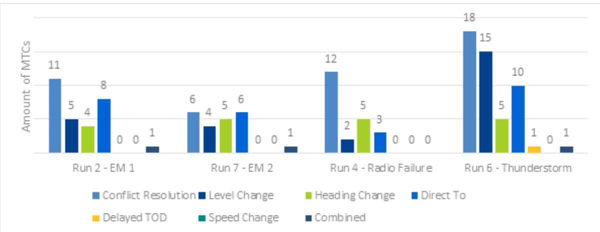


Figure 7. Resolution type for MTCs within non-nominal conditions

As seen earlier, some medium-term conflicts evolved into short term conflict. These are defined as a situation where two aircraft will experience a loss of separation (lateral separation less than 5 NM, vertical separation lower than 1000 ft) within two minutes. Additionally, there might be conflicts that arise directly as STCs, i.e. not preceded by an MTC. All STCs combined are shown as a distribution between the different controllers in Table IV. Again here note that the STCs are only shown for the controllers who are responsible to solve the STC.

Table V combines data from the MTCD resolution bar charts in Figure 5 with data from the STCs in Table IV to show a distribution between the number of STCs that were preceded by an MTC and those that were not.

Table VI shows the average ISA and SASHA ratings and their standard deviation (SD) during the non-nominal scenarios. Due to technical issues and connection losses, ISA data from some controllers were not available in some runs. For this reason, the N-column indicates the number of controllers for whom data were available.

TABLE IV. STC DISTRIBUTION BETWEEN CONTROLLERS

Controller	R2-EM1	R7-EM2	R4-RF	R6-TS
ATCO_0	-	-	-	-
ATCO_1	-	-	1	-
ATCO_2	-	-	-	1
ATCO_3	-	1	1	-
ATCO_4	-	-	-	1
ATCO_5	-	-	1	1
ATCO_6	1	1	-	-
ATCO_7	-	-	-	-
ATCO_8	-	1	-	2
ATCO_9	-	1	1	-

TABLE V. NUMBER OF STCS DURING NON-NOMINAL CONDITION SCENARIOS

Run	STC	STC preceded by MTC	STC not preceded by MTC
R2-EM1	1	0	1
R7-EM2	4	2	2
R4-Radio Failure	4	1	3
R6-Thunderstorm	5	0	5

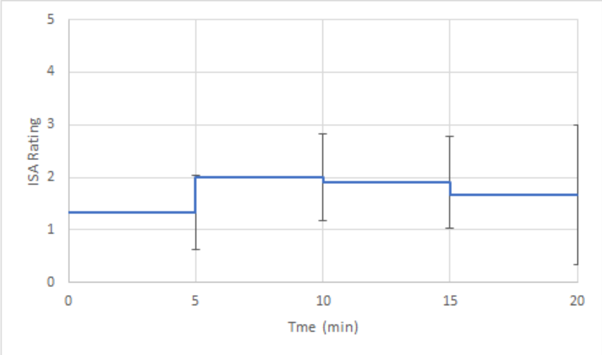
TABLE VI. AVERAGE ISA AND SASHA RATINGS (AND SD) IN THE NON-NOMINAL CONDITIONS SCENARIOS

Run	N	ISA Average (SD) (1 to 5)	SASHA Average (SD) (0 to 6)
R2-EM1	10	1,73 (0,79)	4,75 (0,79)
R7-EM2	9	1,81 (0,68)	4,25 (0,98)
R4-Radio Failure	10	1,59 (0,55)	4,57 (1,09)
R6-Thunderstorm	9	1,74 (0,45)	3,83 (1,05)

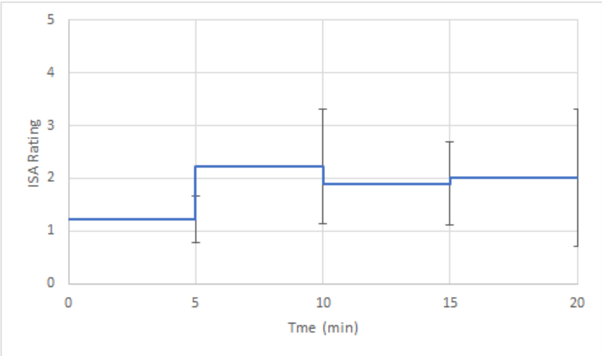
Figure 8 shows the average ISA rating, as well as the standard deviation at each ISA timestamp. Figure 8a shows the ISA data for the R2-EM1 scenario, Figure 8b show data for the R7-EM2 scenario, Figure 8c for the R4-Radio Failure scenario, and Figure 8d for the R6-Thunderstorm scenario.

IV. DISCUSSION

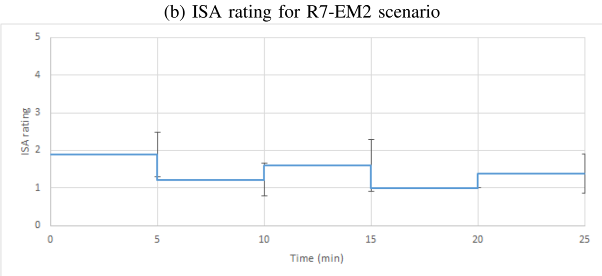
From Figure 4 it can be seen that most conflict were detected within the medium-term conflict detection category in all non-nominal condition runs. More conflicts occurred within the thunderstorm scenario, which consists with feedback received from controllers that reported that not many conflicts took place during both emergency and the radio failure scenarios. One ATCO indicated that in these three scenarios, all ATCOs immediately started giving clearances to their aircraft, reducing the workload for the ATCO affected by the non-nominal operational aircraft, reducing the need for coordination between controllers. Recall that the other controllers were informed of the emergency and the communication failure via the aircraft label of the affected aircraft. This is unlike what happens in normal sectored airspace, where the affected controller would need to handle both the emergency aircraft and all traffic surrounding it.



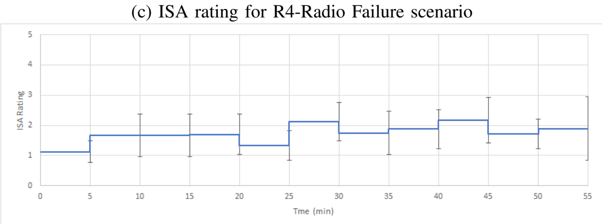
(a) ISA rating for R2-EM1 scenario



(b) ISA rating for R7-EM2 scenario



(c) ISA rating for R4-Radio Failure scenario



(d) ISA rating for R6-Thunderstorm scenario

Figure 8. Average ISA ratings and standard deviation of the non-nominal condition scenarios

As expected, in the thunderstorm scenario, the number of conflicts was greater and controllers reported more problems handling these conflicts. Several of them were triggered suddenly and there was not a lot of time to coordinate with other controllers. This is further supported by the conflict detection bar charts in Figure 4, where it can be seen that a lot more conflicts were detected within the short-term category, where a conflict will result in a loss of separation within 2-4 minutes. One issue pointed out here by the ATCOs, was that the system did not take into account the thunderstorm in conflict resolutions and probing calculations. Information regarding the thunderstorm was only relayed to the pseudopilots who got suggestions on a heading to steer clear of the thunderstorm. Since the system's calculations did not consider the thunderstorm, it did also not take into account that multiple aircraft had to deviate from their trajectories to avoid said thunderstorm. Since conflict resolutions might sometimes lead the aircraft back into the thunderstorm area, controllers indicated that they had to find their own conflict resolutions. Further, in this run there were cases where the controllers indicated they were willing to trigger a conflict since the other aircraft would also have to deviate from the thunderstorm and thus change their trajectory ("I knew it would work and I was right"). System limitations in handling scenarios where the controllers are handling several potential conflicts, some of them consciously triggered, and which might show up quite suddenly, means that coordination between ATCOs becomes extremely important. Several suggestions were made and discussed to improved the system and support the ATCOs. As just an example, the aircraft deviating should always be the one given priority for conflict resolution.

In all four runs, average SASHA scores were above 3, which is the median point in its scale. Levels of situation awareness were lower in the Thunderstorm scenario compared to the other 3 runs, which is caused by the higher number of conflicts. This was further confirmed when the ATCOs were directly asked about their situation awareness, as three controllers reported "poor" SA, which is consistent with the sudden appearance of conflicts triggered by several aircraft deviating from the thunderstorm (as expected) and willingness of the controllers to cause conflicts because it will work out according to them . All other ratings were "okay" or better in this and other runs. In other words, in the non-nominal runs described here no ATCO reported "quite poor" or "very poor" SA.

From Figure 7 it can be seen that the controllers did not often consider the conflict resolution advisory. Figure 6 shows that in the cases where controllers did not use the conflict resolution advisory, they preferred conflict resolution methods that required a single command (e.g. "direct to"s, heading or speed changes). Only in some cases a combination of these single command resolution was used.

Looking at the average workload ratings during the runs (Table VI and Figure 8), it can be seen that these were not very high. Individual ISA ratings, however, varied between the ATCOs and some reported high workload levels (rating of 4 in the ISA scale) during at least one 5-min interval. Note, however, that no ATCO gave a rating of 5 (Excessive workload) in any of these runs, with the exception of one ATCO once in the first Emergency run.

V. Conclusion

In the validation runs described in this paper, the Flight-Centric ATC concept was tested in non-nominal conditions within the Hungarian airspace. During the validation runs of the non-nominal conditions, the workload ratings given by the controllers were relatively low. Arguably, ISA workload scores did not completely capture the difficulties ATCOs felt during the runs. As an example, ratings from the Thunderstorm scenario were lower than expected considering the number and type of conflicts experienced and the comments made by the ATCOs after the run. It would be important to compare these with those of a baseline condition in the sectored airspace. We believe, however, that these workload data provide a valuable contribution to the assessment of the Flight Centric concept and to plan future research. Regarding situation awareness, while values were above the average, sometimes controllers felt overwhelmed, thus further improvements have to be achieved here.

Where some problems were seen with respect to situational awareness, paired with an increase in conflicts, was in the thunderstorm scenario. This scenario was unpredictable due to the actions of other controllers. This was particularly the case because some controllers were willingly causing conflicts, as they knew the other controller's aircraft would also avoid the thunderstorm.

With respect to the emergency decompression scenarios and the radio failure scenario, it can be said that these situations did relieve the controller responsible for the emergency aircraft of some workload, as it was observed that by giving the avoidance responsibility to the other aircraft around the emergency aircraft, the controller responsible for the emergency could focus on this aircraft, while the other controllers cleared the trajectory of conflicts. In the sectorized air traffic control environment the controller handling the emergency aircraft would also be responsible for all aircraft around it, thus having both tasks of clearing the airspace for the emergency aircraft trajectory as well as handling the emergency itself.

It can also be seen that while the controllers did not always use the conflict resolution advisories provided by the tool, they preferred simple solutions (e.g. "direct to"s, flight level or heading changes). Only in a handful of cases did the controllers themselves search for a combination of these or did they use any other method of solving a conflict.

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