CEAS Aeronautical Journal
https://doi.org/10.1007/s13272-024-00748-4

ORIGINAL PAPER

Impact of airtaxi operations in the control zone on air traffic controllers

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Received: 27 July 2023 / Revised: 18 December 2023 / Accepted: 3 June 2024

Abstract
Urban air mobility is one approach to reduce congested road traffic and door-to-door travel times. Introducing these vehicles into the urban areas challenges air traffic control once the designated corridors interfere with the control zone of an airport. In this paper, it is evaluated how the performance of air traffic controllers is affected by airtaxi operations in the control zone given the example of Hamburg airport. Moreover, it is assessed whether an enhanced airside situation display showing routes and labels is able to counteract adverse impacts on workload and situation awareness. As a method, eight controllers participated in three simulation runs: first with conventional air traffic, second with additional airtaxis, and third with airtaxis, and the enhanced airside situation display. It revealed that workload increases by more than 40% without reaching overload states in the simulation. The enhanced airside situation display is able to reduce some, but not all adverse impacts. Based on the results, further ways to handle UAM vehicles in the control zone are suggested.

Keywords Airport · Airtaxi · Air traffic control · Simulation · Vertiport · Urban air mobility

Abbreviations

ALDT	Actual landing time
ASD	Airside situation display
ATC	Air traffic control
ATOT	Actual take off time
ATS	Apron and tower simulator
DLR	German Aerospace Center
EOCVM	European operational concept validation method
IFR	Instrument flight rules
ISA	Instantaneous self-assessment
SASHA	Situation awareness for SHAPE
UAM	Urban air mobility
VFR	Visual flight rules

1 Introduction

Congested road traffic is one of the increasing challenges in urban areas (cf. [1, 2]). In Germany, the city of Hamburg has one of the highest congestion levels leading to more than 30 h of time lost per driver and year resulting in accumulated costs of almost 200 million for the city (cf. [3], p.19). One proposed solution to reduce congestion on the road is the introduction of air vehicles for transport in the urban area. This so-called Urban Air Mobility (UAM) suggests to use on-demand transport and among other procedures proposes to reserve independent air corridors (cf. [4, 5]). This approach is challenged by the structures of conventional airspace especially in case that a UAM corridor interferes with a control zone of an airport. According to current legislation, all airspace users entering a control zone have to report and comply with air traffic control (ATC; cf. [6], §27c para. 2). Hence, introducing UAM vehicles into areas with control zones, such as extended airport environments, will add additional load to the air traffic controllers depending on the level of traffic automation.

In this paper, we evaluate how tower controller's work is affected by additional UAM traffic. Moreover, we analyze if an assistant system can mitigate these effects. The evaluation is performed as a human-in-the-loop simulation (cf. [7], P.2.8.15, p. 124) in the Apron and Tower Simulator (cf. [8, 9]) of the German Aerospace Center (DLR). The simulation is conducted for the example of Hamburg as Hamburg has potential for UAM traffic (cf. [10]) and the airport being located close to the city with its control zone covering most of the urban area. Following the evaluation,

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the paper provides a critical discussion which is followed by a summary of possible optimization. These optimizations were suggested by the participating air traffic controllers. Concluding the paper, an outlook on general challenges and mitigation measures for any location intending to introduce UAM operations is given.

2 Existing work

ATC has early been identified as a constraint for the scalability of UAM traffic in controlled airspace (e.g., due to high density operations and equipage) such as control zones around an airfield (cf. [11, 12]), where interaction between pilots and controllers is inevitable due to current legislations (cf. [6], §27c para. 2). The introduction of large numbers of UAM vehicles is expected to be limited by increasing controller workload due to additional traffic, radio-frequency occupation, and higher probability of collisions due to more airspace users which, in addition, have strongly varying performance characteristics (cf. [11]).

Fast- and real-time simulations of an UAM network between three locations in the Melbourne Basin, Australia, revealed limitations as well as resulting requirements for the introduction of UAM traffic within control zones (cf. [13, 14]). When including UAM vehicles as traffic operating under Visual Flight Rules (VFR), the airspace quickly reached a saturation point within the human-in-the-loop simulations. Among others, controllers reported high mental workload and notable decrease in situation awareness due to the increasing task complexity resulting from the novel airspace users and the need to integrate them into existing air traffic flows while maintaining separation. One of the recommendations resulting from these trials was the introduction of dedicated UAM corridors within the control zone, implicitly separating UAM vehicles from other traffic. The effect of such corridors was then studied in fast-time simulations. It was found that the corridors reduced average flight times while increasing their predictability, increasing possible UAM movements per hour and reducing conflicts with other traffic due to the achieved traffic segregation. Introducing flow management intensified these benefits.

These results were applied in a fast-time simulation study introducing airtaxis to Hamburg and the control zone of the airport “Hamburg-Fuhlsbüttel” (cf. [15]). Within this study, flight paths of the airtaxis were separated from the conventional air traffic. This study also includes a discussion on an optimal landing/take-off spot (so-called vertiport) at the airport. It was shown that 15 airtaxis operations per hour can be conducted without a negative impact on the airport’s capacity if a vertiport with airtaxi flight routes independent of conventional air traffic flows is used. This result does not encounter operational ATC procedures (e.g. voice communications). Hence, an operational concept (cf. [16]) was defined which allows the controllers to integrate the airtaxis into ATC workflow. This concept foresees additional planning, guidance, and monitoring tasks for the controllers. Moreover, an enhanced air situation display is suggested to support the controllers.

Concluding the existing work, it has been shown that airtaxis in the control zone increase the workload of air traffic controllers. A study (cf. [15]) evaluating the integration of airtaxis at Hamburg airport shows that a completely independent operation is not possible and is expected to impact the work of air traffic controllers. Therefore, an operational concept and supporting tools have been suggested. Picking up research at this point, this paper will evaluate if the airtaxi operation at Hamburg airport is feasible from an ATC’s point of view by means of real-time human-in-the-loop simulations.

3 Methods

The European methodology to evaluate operational concepts (E-OCVM, [17]) suggests a large set of techniques for this purpose. To assess human factor aspects on a qualitative and quantitative level, either a human-in-the-loop simulations or field trials are proposed. As neither the airspace structures nor a sufficient number of UAM vehicles are existing today, human-in-the-loop simulations are chosen as the general method to be used. The simulations are carried out in the DLR’s Apron- and Tower Simulator (ATS).

The ATS is configured to the set-up used in the former Hamburg fast-time simulation (cf. [15]) to allow the evaluation of the proposed airspace structure and traffic load. As such, the airport “Hamburg-Fuhlsbüttel” and an airtaxi network connecting it to different locations within the city is modeled. The fast-time simulations represented a traffic scenario of 24 h. Therefore, a standard traffic day in summer time was chosen (cf. [15], p. 8). The simulation of a 24 h scenario is not feasible for a human-in-the-loop simulation without gaining fatigue effects of the participants. In consequence, a peak hour is selected and modeled in the ATS software for the execution of the study presented here. The scenario was varied in terms of callsigns and initial call timing in small margins, so that controllers were not able to learn and reproduce the traffic sequence.

The ATS provides a 360° virtual outside view, which is configured to represent the view from the position of Hamburg Tower. The controller working position is equipped with a ground situation display and an air situation display (ASD). Communication to pseudo pilots takes place via emulated radio for which a handheld microphone is provided. An overview of the tools within the simulator is shown in Fig. 1. The flight strip display indicates planned

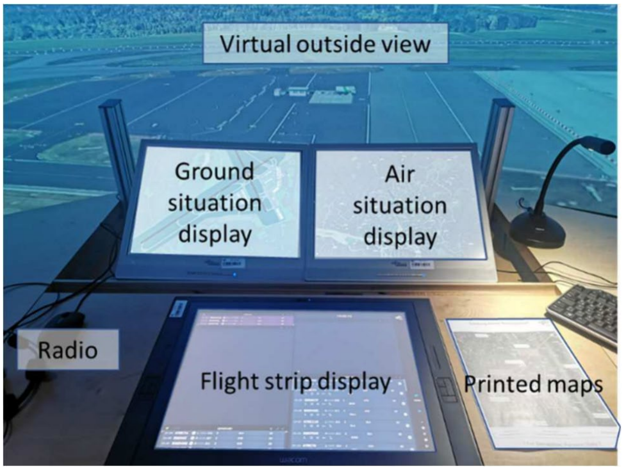

Fig. 1 ATC working space in the tower simulator

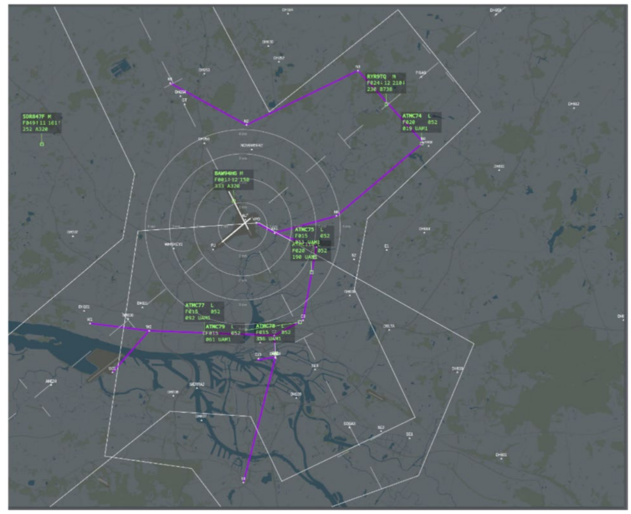

Fig. 2 Active airtaxi route network as displayed on the radar screen

and active conventional flights (left side) and airtaxis (right side). Additionally, a weather display (not shown in Fig. 1) provides the relevant weather information. The participants are equipped with printed maps of the airports and the call-signs of the operating airlines.

The simulation is conducted in three experimental conditions following a within-subject design (cf. [18], ch. 1, p. 1). First, a condition with only Instrument Flight Rules (IFR) standard fixed-wing traffic is conducted, called the baseline. Secondly, participants have to handle the IFR traffic and airtaxi traffic. This condition is called "airtaxi"-condition. In a final stage, the IFR traffic and airtaxis are active again while the air situation display is enhanced with an indication of the active airtaxi routes. This condition is called "airtaxi + eASD"-condition. Each of the three simulation runs lasts for one hour, representing variations of the traffic observed in the peak hour of Hamburg (44 conventional aircraft plus 15 airtaxis).

In the airtaxi + eASD condition, the air situation display is enhanced with information considering airtaxi routes. While in the airtaxi condition, only standard labels are shown for these airspace users. In the eASD, the airtaxi routes between the vertiports in the city and the one at Hamburg airport are marked in dark gray. Additionally, routes currently in use are highlighted in purple. This feature is intended to raise situation awareness to the parts of the control zone where airtaxis are traveling. Figure 2 shows the eASD.

Each experimental condition is evaluated following the main air traffic control objectives of safety and efficiency as required by the EU regulation 550/2004 (cf. [19], p. 1, para. 4). First, an analysis of throughput will provide an insight whether the additional airtaxis could be served while maintaining airport capacity. Second, safety is evaluated in terms of workload and situation awareness of the controller.[1] Having to control additional traffic can lead to a mental overload or loss of situation awareness for the controller. Third, efficiency is analyzed by assessing airtaxi flight duration and conventional air traffic taxi times. Airtaxi flight times reflect delay caused by detours and holding patterns commanded by the air traffic controller. Taxi times include the delay of takeoff and, specific to Hamburg, runway crossing of the landing traffic.[2] The summary of all indicators with the assigned hypothesis is

Table 1 Indicators and hypothesis

Key area	Indicator	Hypothesis
Safety	Workload	Baseline $<$ airtaxi Airtaxi $>$ airtaxi + eASD
	Situation awareness	Baseline $>$ airtaxi Airtaxi $<$ airtaxi + eASD
Efficiency	Throughput	Baseline $<$ airtaxi Airtaxi $\leq$ Airtaxi + eASD
	Airtaxi flight duration	Airtaxi $<$ airtaxi + eASD
	Taxi-out time	Baseline $<$ airtaxi Airtaxi $>$ airtaxi + eASD
	Taxi-in time	Baseline $<$ airtaxi Airtaxi $>$ Airtaxi + eASD

[1] ICAO suggests to measure safety via direct indicators such as number of accidents (cf. [20], Appendix E). As this is very unlikely to happen within the reduced simulation time, contributing factors out of human performance are chosen.

[2] The airport "Hamburg-Fuhlsbüttel" owns two crossing runways. Runway 23 is used most times for landing while runway 33 is used for take-off. Due to the apron location, landing traffic has to cross runway 33 once taxiing to the stand (cf. [22]).

shown in Table 1. The hypothesis indicates whether the distinct indicator is expected to be smaller, equal or greater comparing the three experimental conditions (Baseline, Airtaxi, Airtaxi + eASD).

The airtaxis are expected to increase workload and reduce situation awareness due to the additional tasks and areas which the controller has to perform and monitor. The taxi times of the conventional traffic can be increased due to the airtaxis as the conventional traffic has to wait until the controller has issued an airtaxi instruction.

The eASD is designed to reduce the effects of the airtaxis on the controller. Hence, workload is expected to be lower and situation awareness higher in comparison to the airtaxi condition following the concept that the highlighted airtaxi routes enable the controllers to identify possible conflicts with airtaxi more quickly. This effect should manifest also in shorter flight duration as the airtaxis can receive more shortcuts. Once the controller has more mental capacities and a better picture of the situation, it is more likely that a direct crossing if the final will be allowed for the airtaxis rather than a long downwind until a crossing below the approach is possible. Moreover, taxi times for the conventional traffic should reduce in comparison to the airtaxi condition because controllers should have more mental capacity to provide in time take-off and runway crossing commands.

The above presented hypotheses are evaluated based on the following metrics:

- Workload: During each run, the workload was measured using instantaneous self-assessment measurement (ISA, cf. [23–25]). The participants were asked to rate their level of workload on a five-point scale every five minutes within every run.
- Situation awareness: After each run, the situation awareness is measured based on the “Situation Awareness for Solutions for Human Automation Partnerships in European ATM” (SASHA, cf. [25, 27]) questionnaire. The participants have to rate six items on a six-point scale.
- Throughput: The runway throughput is derived based on landing and take-off times (ALDT/ATOT) as provided by the simulator. The indicator is calculated in 5-min intervals. The interval is used as Hamburg has implemented the airport collaborative decision-making concept (cf. [21]) including off-block and take-off planning on a granularity of at least five minutes accuracy (cf. [22]).
- Airtaxi flight duration: This effect is evaluated by calculation of the airtaxi flight duration from lift-off to touchdown using the simulator data.
- Outbound taxi time: The outbound taxi times is assessed based on the simulator data subtracting actual take-off time from actual off-block time.

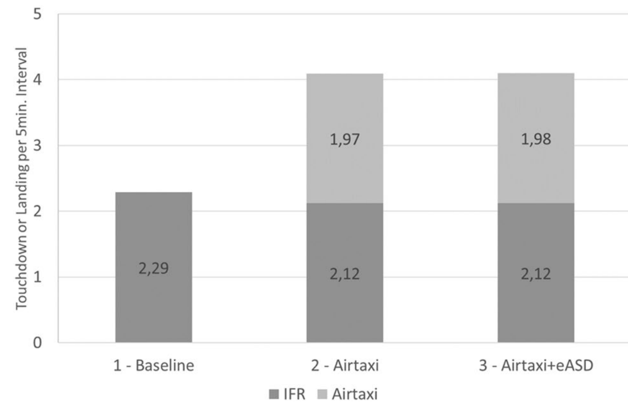

Fig. 3 Throughput

- Inbound taxi time: The inbound taxi times is assessed based on the simulator data subtracting actual in-block time from actual landing time.
- Debriefing: A semi-structured interview recorded the participants feedback at the end of each run.

For the metrics, it is assumed that changes of more than 1% can be operationally relevant and will be reported in the following. It will be explicitly stated if a metric shows statistically significant effects.

Between October and December 2022, ten operational experts (two females, eight males, average age 35.1 years, std. deviation 7.2 years) participated in the human-in-the-loop simulation trial. Each of them is a licensed air traffic controller. Prior to the simulations, they received training material, an introduction and a practice run. The practice run included IFR traffic and airtaxi traffic. It increased in traffic load as well as complexity until the level of the airtaxi condition. Afterwards, every controller participated in all of the three conditions in changing order to prevent training effects.

4 Results

As the first result, the runway throughput is presented to evaluate the hypothesis that air traffic control is able to increase the throughput once airtaxis are introduced to the airport. The below chart (cf. Fig. 3) shows the 5 min average for each condition.

The throughput increases from the baseline to the airtaxi condition by 75%. Impacts of the eASD in comparison to the airtaxi condition are below 1%.

The increase of the overall throughput from baseline to airtaxi condition is a consequence of the scenario and are as such expected. The calculation of a statistical significance is, therefore, not meaningful. But a focus on the IFR traffic which drops by 7% from baseline to airtaxi condition and

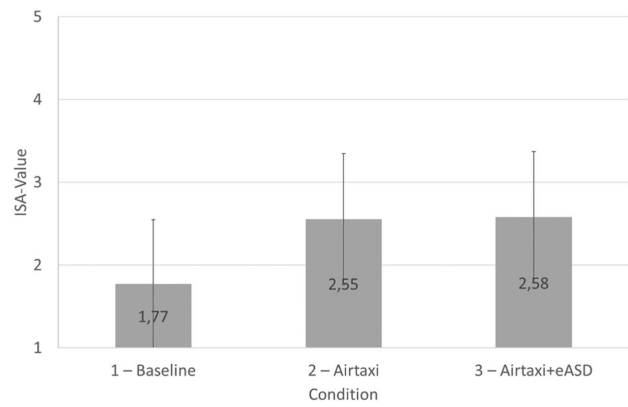

Fig. 4 Workload

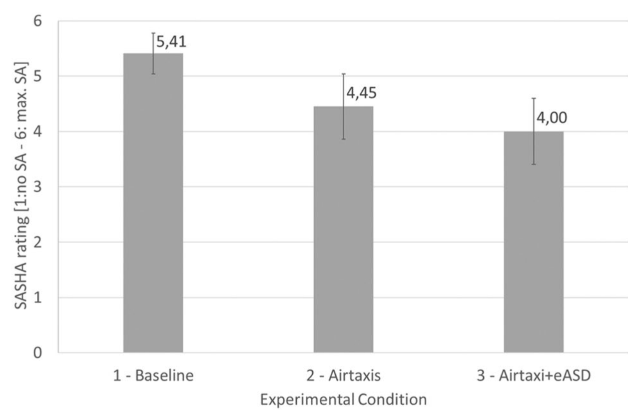

Fig. 5 Situation awareness

maintains the same level with the eASD is of operational significance as it shows that controllers were not able to handle IFR traffic in the same time as in the baseline.

A higher throughput can lead to a higher workload. The average of all ISA workload values of each condition were calculated in the aftermath and are shown in Fig. 4. The ratings translate to 1 = underutilized, 2 = relaxed, 3 = comfortable, 4 = high, and 5 = excessive.

The workload increases from the baseline to the airtaxi condition by 44%. The workload maintains on the same level once the eASD is introduced. The increased workload induced by the airtaxis is expected as the controllers have to perform additional tasks and handle more traffic. As the values are above 1 (underwhelmed) and below 4 (overwhelmed), it is assessed as acceptable (cf. [23]). This is in line with the feedback provided by the controllers in the debriefing. A decrease of workload by the eASD as initially expected is not observed. The workload increases slightly by 1%. The effect is not significant might be too small and unstable to be measured with ten participants.

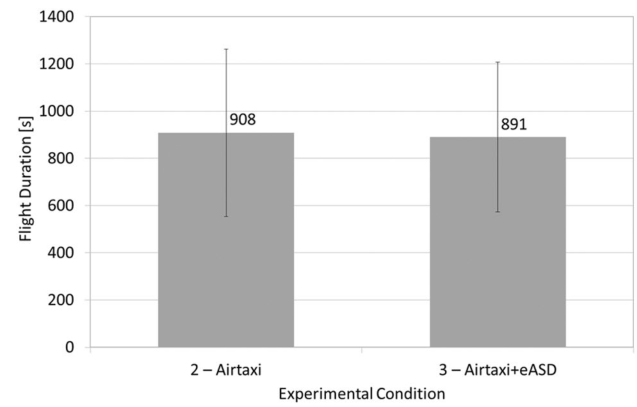

Fig. 6 Airtaxi flight duration

Workload owns a relation with situation awareness (cf. [26]). To evaluate the hypothesis that situation awareness is reduced by the additional airtaxi traffic, Fig. 5 represents the average value for each condition reaching from 0 (no situation awareness) to 6 (full situation awareness).

The airtaxi condition shows an 18% lower situation awareness than the baseline. The eASD reduces the situation by another 9% in comparison to the airtaxi condition. A reduction of the controllers' situation awareness induced by the airtaxis is expected as the controllers have to monitor and guide additional traffic in other areas of the control zone. An additional reduction in situation awareness by the eASD is the opposite of the expected effect. The eASD should provide additional situation awareness due to the highlighting of the active airtaxi routes. The decrease in situation awareness can either be the consequence of missing training with the eASD or missing functionality announced in the debriefing.[3] The controllers requested to also display airtaxi deviations they commanded from the route.

A higher workload and reduced situation awareness can lead to inefficiencies in traffic handling (e.g. advised holding patterns or delays due to delayed advisories). To evaluate if airtaxis are handled more efficiently with the eASD support than without Fig. 6 shows the average airtaxi flight duration per flight.

The baseline is not shown as no airtaxis are included in that condition. The airtaxi flight duration decreases by 17 s (2%) once the eASD is introduced. This effect is expected as the eASD highlights the active routes and provides the controller a perception where clearances are required and shortcuts are possible. This is in contrast to the reduced situation awareness. A possible explanation is presented in the discussion chapter.

[3] Further data and a discussion on possible training effects are presented in [28].

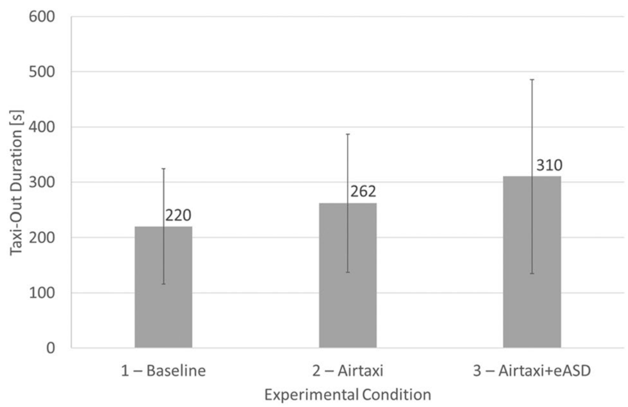

Fig. 7 Taxi-out duration

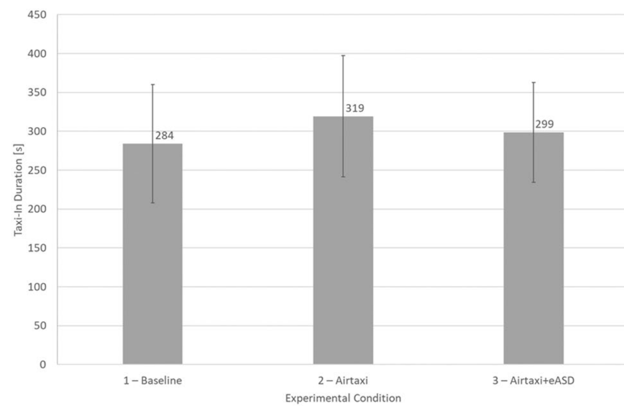

Fig. 8 Inbound taxi duration

Inefficiencies in terms of conventional air traffic manifests in delays on the ground. Therefore, the outbound taxi time is assessed. The below chart (cf. Fig. 7) shows the average of all taxi-out durations as received from the simulation data for each condition.

The outbound taxi duration increases from baseline to the airtaxi condition (+ 19%). It increases further when the eASD is introduced (+ 18%). The increase in outbound taxi time in the airtaxi condition is expected due to the fact that traffic increases and the airtaxis require attention in the control zone rather than on the runways. Therefore, controller attention is in another location than the runway. As such, take-off clearances might not be given with optimal timing. The additional increase in taxi times by the eASD is unexpected and cannot be matched with the feedback of controllers in the debriefings. A majority of the air traffic controllers stated in the debriefing that they were able to work better with the eASD. A possible explanation is an insufficient familiarization with the eASD. Besides the eASD other solutions were suggested such as delegation of UAM operations to automation or an additional controller.

Additional to outbound taxi duration, the inbound taxi duration can be impacted. In Hamburg airport the inbound traffic landing on runway 23 has to cross the departure runway 33 to get to the main apron. A higher workload and a reduced situation awareness due to the airtaxis can lead to delayed crossing clearances. To prove this hypothesis, the inbound taxi times is assessed and shown as an average over each experimental condition in Fig. 8.

The inbound taxi time increases by 35 s (+ 12%) from the baseline to the airtaxi condition. Once the eASD is introduced, it reduces by 20 s (− 6%). Both effects are expected. The airtaxis shift the focus away from the runway system. As such crossing clearances might be given delayed. The eASD provides highlighted routing which should make it easier for controllers to find airtaxis and shift back attention to the runway system quickly.

5 Discussion

Summarizing the results, the following impact by airtaxis is observed:

- Airtaxis increase the overall throughput (+ 75%)
- Airtaxis reduce the IFR throughput (− 7%)
- Airtaxis increase average workload (+ 44%)
- Airtaxis reduce situation awareness (− 18%)
- Airtaxis increase outbound taxi time of the conventional air traffic (+ 19%)
- Airtaxis increase inbound taxi time of the conventional air traffic (+ 12%)

All of these effects were expected due to the fact that additional traffic is introduced into the control zone and requires additional mental capacities from the controllers. Neither the controllers in the debriefing nor the measured values show a general exceedance of the acceptable limits.

An introduction of an eASD leads to the following observations:

- eASD increases the workload (+ 1%)
- eASD reduces the situation awareness (− 9%)
- eASD reduces airtaxi flight duration (− 2%)
- eASD increases the outbound taxi time of the conventional air traffic (+ 18%)
- eASD reduces inbound taxi time of the conventional air traffic (− 6%)

The effects on the airtaxi flight duration and the inbound flight duration are expected as the air traffic controller should gain a better overview of the situation and thereby provide more efficient commands. The observations on situation awareness and outbound taxi time show the opposite of the expected effects. One possible explanation is a missing familiarization with the eASD. Although the comments in the debriefing did not provide any evidence for this hypothesis.

These observations must be reviewed critically as they have been measured within one specific traffic hour of Hamburg airport with ten participants. As such, statistical validity is rather low resulting in none of the measured effects to be statistically significant. Nevertheless, the observations are of high meaningfulness (construct validity) for this example as the used metrics follow validated standards of EUROCONTROL and are a mixture of subjective and objective measures. Although the metrics themselves are validated, the observations might not be fully reliable due to a possible missing familiarization with the eASD (internal validity). In consequence, the results cannot be generalized for other airports, controllers and settings due to the low sample size and possible familiarization effects.

Anyhow, the qualified effects are in line with former research. Airservice Australia also expects an increase in workload (cf. [13]) while Ahrenhold et al. showed that additional 15 mov/h of airtaxis are within capacity limits (cf. [15]). Following this comparison, it can be stated that the quantified results are only valid for the provided sample, while qualified effects are expected to be valid in general.

6 Outlook

Ahrenhold et al. (cf. [15]) quantified the capacity impact of airtaxi operations at Hamburg airport. Metz and Schier-Morgenthal (cf. [16]) defined an operational ATC concept to include airtaxi operations into the controller workflow. The present paper validated this concept for the described set-up by a human-in-the-loop simulation. The results are in line with former research and show that airtaxis increase the workload of the controllers and reduce their situation awareness. Although workload and situation awareness are within acceptable safety limits, the efficiency is reduced in terms of flight duration and taxi times. An eASD is able to counteract these effects, but does not show benefits in all areas. A possible side effect might be a missing familiarization with the eASD or missing eASD functionality such as speed vectors for airtaxis, separation warnings or advisories. It must be further assessed whether eASD is a promising solution for UAM integration or if other solutions (e.g., work delegation and automation as suggested in the debriefing) can lead to better results.

The results show that there is additional work necessary to provide a smooth integration of airtaxis into areas with an active control zone of an airport. Although not observed in the simulations, it must be assured that the increase in workload does not exceedance the controller's mental capacities in operations. As such, an effective flow control is required. Therein, airtaxis must request the entrance to the control zone and receive target times by air traffic control. Flow control as well as an efficient support of the controller during airtaxi operation should be provided using the potentials of automation as suggested within the debriefings. Within the simulated operation, the controller was challenged by giving commands in the current situation while assessing his workload and planning actions in advance of more than 15 min (airtaxi travel time). This could be achieved by a digital assistant, providing the following services:

- Flow control: Provision of target times for the airtaxis calculated on the basis of controller workload models to prevent a mental overload.
- Airtaxi monitoring: In contrast to standard VFR traffic, airtaxis are expected to provide a high reliability in operations due to their professional character. Additionally, routes are well-predefined so that the digital assistant can takeover monitoring services and inform the human controller upon deviations.
- Attention guidance: The digital assistant can guide the attention of the controllers (e.g., by visual reference on the ASD or audio message) to the next item of interest. Thereby, controllers do not have to switch focus randomly between the conventional traffic at the runways and the areas where the airtaxis are operating, but are guided by a pre-assessment of the digital assistant.

Following this idea, a concept for airtaxis and even for conventional VFR traffic should be defined and evaluated where a digital controller takes over the suggested tasks from the human controllers to enable them to focus the attention on the most relevant decisions.

Funding Open Access funding enabled and organized by Projekt DEAL. This research received no external funding.

Data availability The data that support the findings of this study are available on request from the corresponding author. The data is not publicly available due to privacy protection of the reserach participants.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Informed consent Informed consent was obtained from all subjects involved in the study.

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