Coordination between Federated Scheduling and Conflict Resolution in UAM Operations

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This work investigates two methods for coordination between scheduling and conflict resolution functions - two core traffic management functions in urban air mobility operations. A federated scheduling algorithm and a federated conflict resolution algorithm are first presented. Two methods for coordinating scheduling and conflict resolution functions are then introduced. The first coordination method utilizes the feedback from the arrival scheduler at the destination. The second method applies a flow interval, predefined to accommodate the capability of the conflict resolution, through the departure scheduler at the origin. High-density operation scenarios, where conflicts can not be completely resolved by the conflict resolution function alone, were used to study the performance of these two coordination methods. Experimental results show that both methods can perform well in coordinating scheduling and conflict resolution functions. With proper parameter setting, both methods can achieve similar performance in efficiency while achieving zero losses of separation.

I. Introduction

Scheduling and conflict resolution functions are two critical traffic management functions needed by Urban Air Mobility (UAM) operations [1, 2]. The federated autonomous Unmanned aircraft system Traffic Management (UTM) system [3–6] has been evolved into the foundational architecture for the UAM traffic system, where a federated system refers to a system operates collaboratively in overall goals while distributed in responsibility. It is important to develop federated scheduling and conflict resolution algorithms for the UAM system and investigate the coordination between these two functions to enable safe, efficient, and scalable operations. A federated system or function oper

Unlike existing commercial aviation in the National Airspace System (NAS), typical UAM missions are envisioned to be completed within one hour or less, indicating a need for more tightly coupled operations among origin, destination, and en-route phases of flight. More frequent and dynamic coordination will be expected than in the current NAS, and the coordination between departure and arrival schedulers and the coordination between schedulers and conflict resolution functions will play a paramount role in UAM safety and efficiency. In the current NAS, there are many coordination methods between downstream and upstream airports/airspace, such as Ground Delay Programs (GDP) [7, 8], Departure Spacing Program (DSP), Miles-In-Trail (MIT) [9], Minutes-In-Trail (MINIT) [10], Traffic Management Advisor (TMA) [11], Multi-Center TMA [12], and Time Based Flow Management (TBFM) [13]. However, considering the difference between UAM operations and existing NAS operations, these methods may not suit UAM's needs for a more agile, federated, and dynamic coordination among vertiports and airspace operations. Exploring and understanding various coordination methods and their parameter settings are important for UAM airspace management development.

This work first presents a federated scheduling algorithm and its data exchange needs. Two methods for coordination between scheduling and conflict resolution functions are then introduced. The first approach is constructed based on the feedback from the arrival scheduler at the destination and the second approach coordinates through the departure scheduler at the origin using the basic flow rate control. Experiments and trade space studies are conducted to compare these two methods using fast-time traffic simulations [14].

This work is organized as follows: Section II presents a federated scheduling algorithm. Section III introduces two different methodes for coordination between scheduling and conflict resolution functions. Section IV then shows the final results for comparing these two coordination methods. A trade-space study is also conducted to show how to tune parameters for better performance. Section V concludes the work.

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II. Methodology

Conflict resolution requires extra time or space, which are inadequate when the airspace is too congested. Therefore, when there are too many potential conflicts in congested airspace, it's unlikely that all conflicts can be completely resolved by the conflict resolution function alone. Similar to the existing GDP and MIT programs in the current NAS, it's important to have scheduling and conflict resolution services coordinate with each other when handling complex UAM airspace operations. This section introduces a federated scheduling algorithm and then presents two methods for coordinating scheduling and conflict resolution functions.
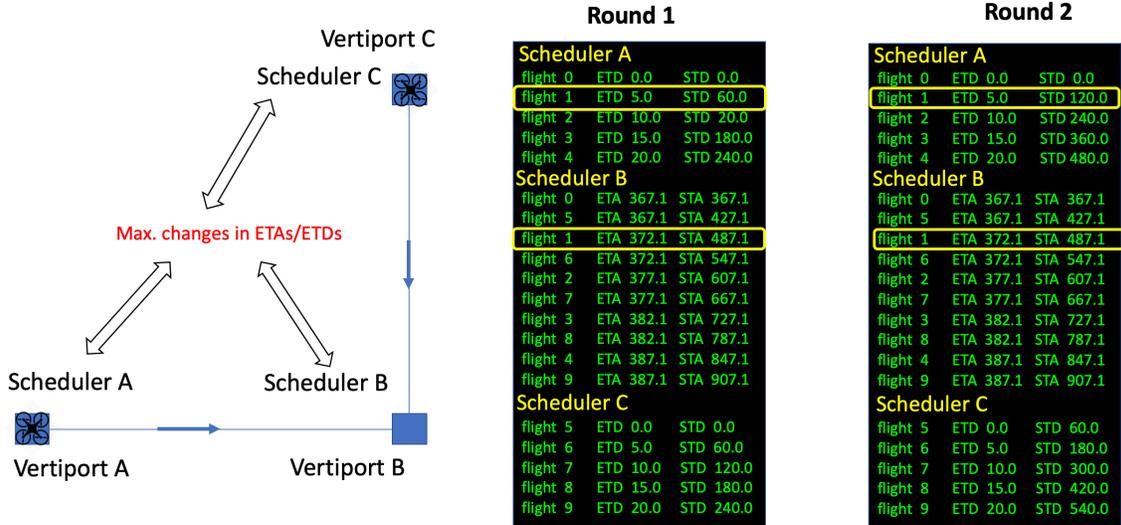
A. Federated Scheduling

Assuming that each vertiport has its own scheduling service/function, a federated scheduling algorithm can be formulated as shown in Fig. 1. At each vertiport, the scheduler arranges each flight based on its estimated time of arrival (ETA) or estimated time of departure (ETD) and its schedule flexibility (how much change in the ETA/ETD can the flight tolerate). Priority can be incorporated into the scheduling process if needed. The cost function can also be introduced if not first-come-first-serve. Once each vertiport finishes its first-round schedule, it then publishes changes in ETAs/ETDs for each flight involved and compares with others to determine if requested changes in ETAs/ETDs for all flights are the same/converged. If not, the second-round scheduling will start using the maximum difference in ETAs/ETDs until they converge. It's worth mentioning that a rolling time window technique might be needed to limit the flights involved each time to ensure convergence.
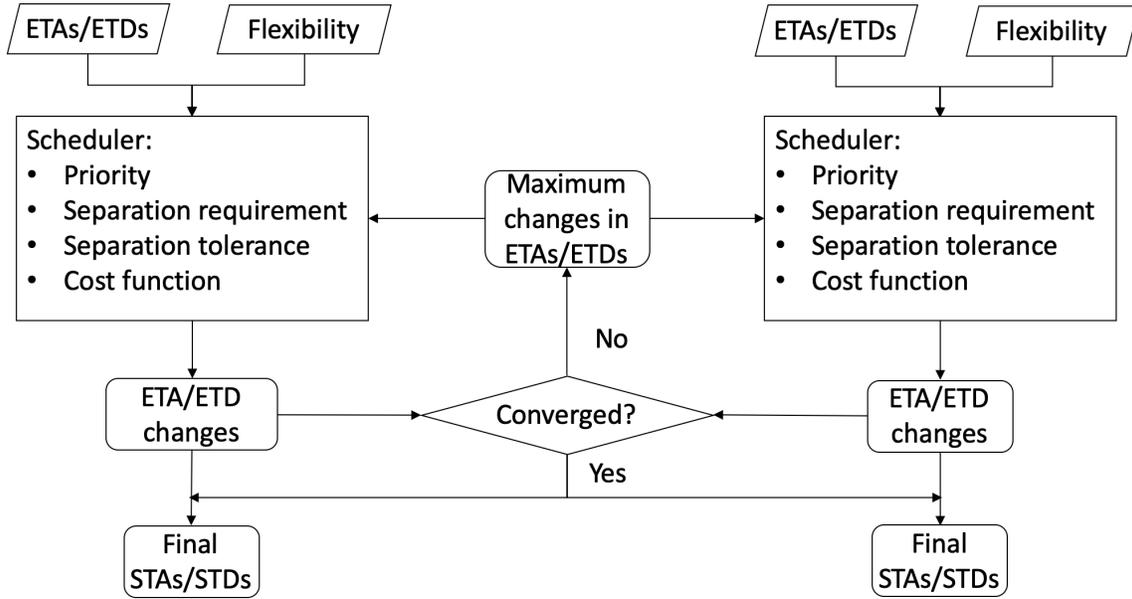
Fig. 1   Flow Diagram for Federated Scheduling

Figure 2 shows an example with flights departing from Vertiports A and C and arriving at Vertiport B. At the first round, departure schedulers at A and C and the arrival scheduler at B tried to arrange flights with a minimum separation requirement (60 seconds in this example) based on their initial ETAs and ETDs. It can be seen that at the end of Round One, Flight One was scheduled to be delayed 55s from 5s to 60s by Scheduler A (comparing the ETA to STA times), whereas Scheduler B schedules a delay of 155s (from 372.1s to 487.1s) because Scheduler B has to take flights from Vertiport C into account as well. Since the requested delays for Flight One is different between the two schedulers, the maximum delay of 155s is then fed into the second round. The flight schedules finally converge at Round Two.

Fig. 2 Example of Federated Scheduling

B. Coordination methods between scheduling and conflict resolution functions

This section introduces two different coordination methods between scheduling and conflict resolution functions. The first coordination is through the arrival scheduler at the destination, and the second coordination uses the departure scheduler at the origin vertiport.

1. Coordination through the scheduler at destination

Like the GDP in current NAS operations, coordination through the arrival scheduler at the destination vertiport is a good example of downstream operations that impose feedback control on upstream operations. In this coordination method, the arrival scheduler at the destination updates the delays needed for flights that have not departed from the origin based on the ETAs of those airborne flights shared by the conflict resolution function/service. It then sends these pre-departure delay requests to the schedulers at the origin vertiports (as shown in Fig. 3).
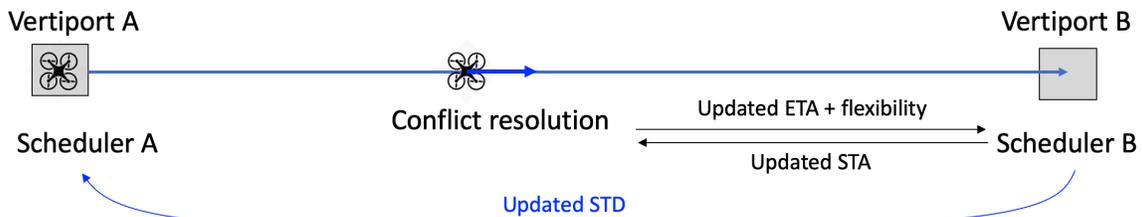
Fig. 3 Interaction through the destination scheduler

To illustrate this method, Figures 4(a), 4(b), and 4(c) present an example with ten flights departing from the same origin vertiport to the same destination vertiport. These ten flights were separated before departure with a 10-second separation interval each. Because their unimpeded flight times are the same, their ETAs at the destination were also separated by 10 seconds, as shown in Fig. 4(a). In Fig. 4(b), the first four flights departed (shown in blue) with unchanged ETAs at the destination. In Fig. 4(c), after the departure of Flight 5 and 6, it is assumed that some en-route conflict resolution maneuvers happened and the ETAs of Flight 1 through 4 were delayed (for example, due to conflicts with crossing flights in another corridor). The intervals among Flight 1 through Flight 4 became smaller, though their airborne separations were not violated. The arrival scheduler at the destination then started to reschedule flights with the initial separation requirement, which is 10s in the example. The desired STDs (in black) were then postponed and shown on the right side of the timeline. These STDs were then passed to the departure scheduler at the origin vertiport through the federated method introduced in the previous section. Flight 7 through Flight 10 were then postponed by the

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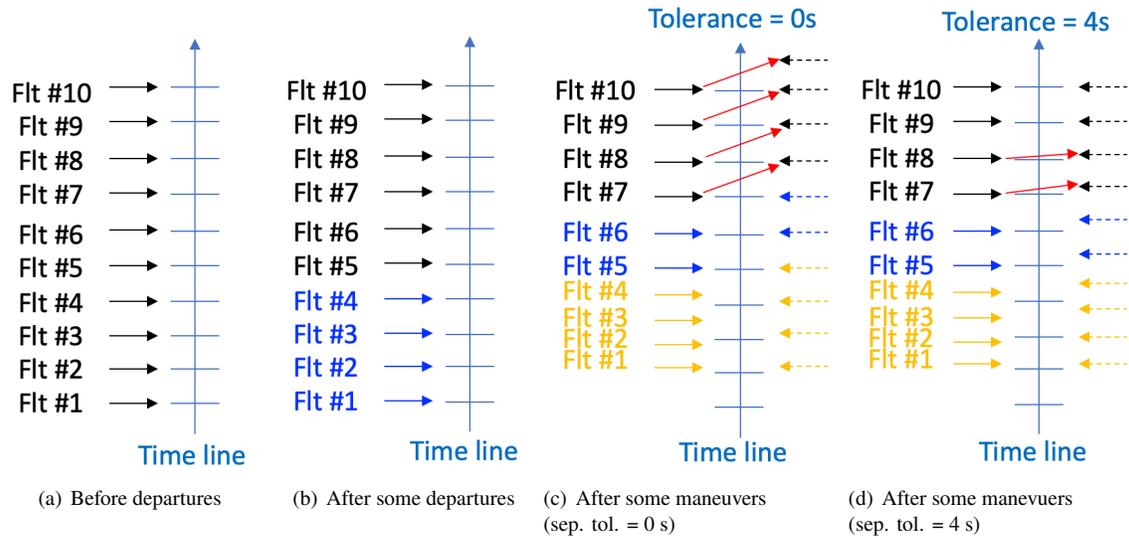
Fig. 4   **Updated ETAs and STAs with different tolerances**

departure scheduler at the origin vertiport.

When the minimum separation interval (10s in this study) is strictly applied, as shown in Fig. 4(c), it may cause excessive intervals between flights. An additional parameter called separation tolerance is added to adjust the tightness of this feedback control. The separation tolerance can be anywhere between zero and the minimum separation interval. When the separation tolerance is zero, the minimum separation interval, 10 seconds, will be strictly imposed. Whereas if the separation tolerance is some positive value, e.g. four seconds as shown in Fig. 4(d), the arrival scheduler will use six seconds as the minimum separation interval, which results in relaxed departure control with only Flight 7 and 8 delayed. If the separation tolerance is equal to the minimum separation interval, then the required time separation in the arrival scheduler becomes zero, which essentially turns off the feedback from the destination scheduler.

2. Coordination through the scheduler at the origin

Another method is to coordinate through the departure scheduler at the origin vertiport. Similar to the existing Departure Spacing Program in the current NAS operations, where constant or dynamic separation intervals can be imposed between departures, this approach ensures the conflict resolution can manage all the en-route conflicts that might arise for en-route operations. As an initial work, this study focuses on constant intervals, where experiments will help decide the most efficient interval with the least delay.
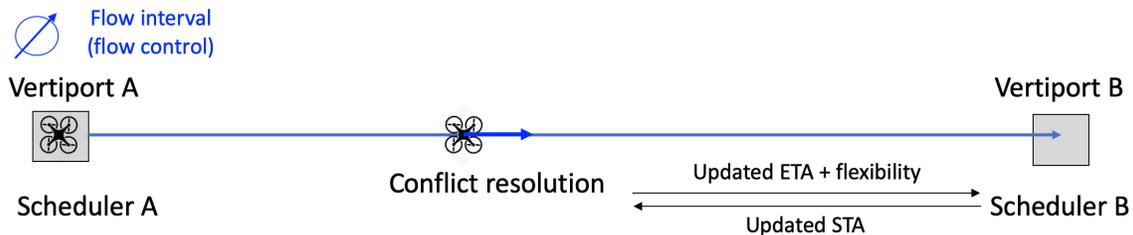

Fig. 5   **Flow control through the departure scheduler**

III. Experiment scenarios

Experiments and trade space studies are conducted to compare these two methods using the Fe^3 fast-time simulator [14]. The Fe^3 simulator includes a 6-DOF trajectory model developed based on NASA's UAM concept vehicle [15] along with the aforementioned federated scheduling algorithm and configurable federated conflict resolution algorithm.

Experiments were constructed using route-structure-based scenarios, where two flows of flights cross each other at a 60-degree angle and arrive at their destination vertiports, respectively. The UAM vehicle is assumed to fly at 120 kts, and the minimum separation between flights is set to 1,000 ft. A federated conflict resolution algorithm is applied to individual aircraft to resolve potential conflicts using speed control while following predefined rules. The basic principle of these rules is to give the right of way to the flights whose estimated arrival time to the crossing point is earlier. Details about the federated conflict resolution algorithm can be found in another work [16]. To stress the conflict resolution algorithm, three scenarios with different numbers of flights were used: one scenario includes 30 flights with 15 flights in each flow, the other two scenarios include 40 and 60 flights, respectively. As shown in Fig. 6, Vertiport A and C are origins with departure schedulers A and C, and Vertiport B and D are destinations with arrival schedulers B and D.
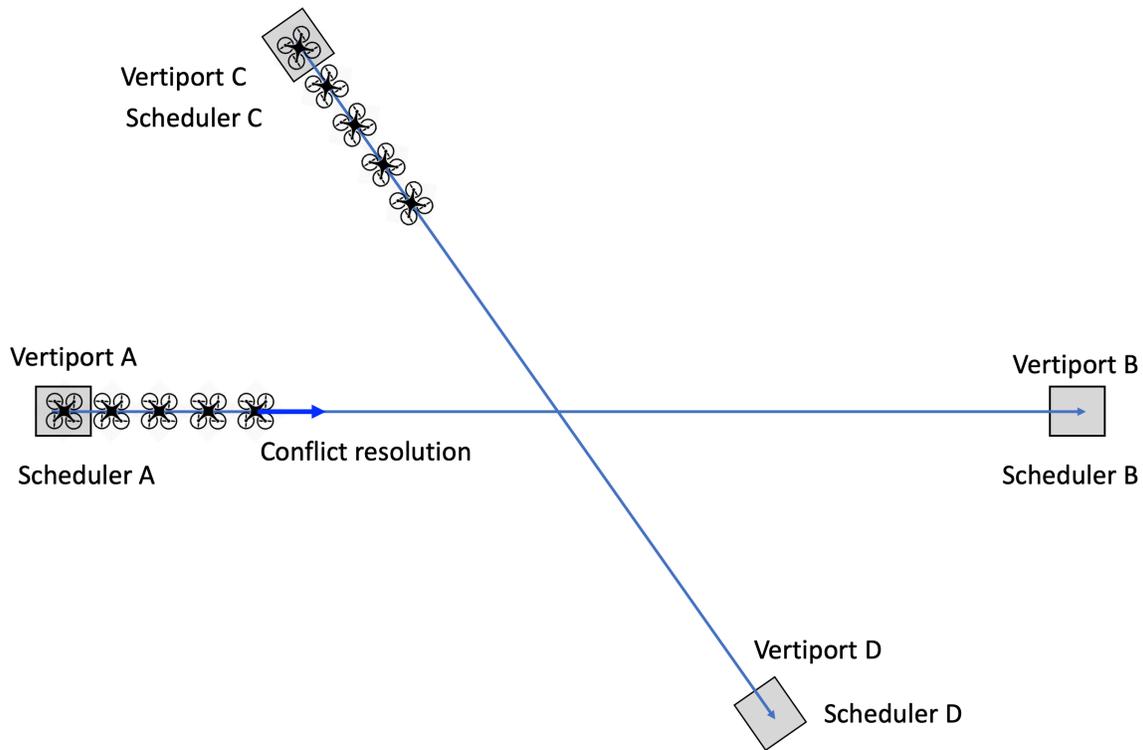
Fig. 6   Experiment scenario notional graph

In all three scenarios, flights are initially separated with 10 seconds between departure times. When there are more than 15 flights in each flow, if only the conflict resolution function is allowed (without schedulers), experiments in this study (when number of flights exceeds 30) showed that loss of separation would happen because there isn't much room for conflict resolution functions to space these flights apart. In the following experiments, two proposed coordination methods were examined to understand the impact of coordination between conflict resolution and scheduling on safety and efficiency.

IV. Results

This section presents the comparison between the two proposed coordination methods. Sensitivity studies are also conducted for each approach to explore the trade space and identify the best parameter setting.

A. Coordination through arrival schedulers: impact of separation tolerance

For the coordination method through arrival schedulers, the coordination is tightened when the separation tolerance is set to zero and gets relaxed with increased separation tolerance. Figure 7 presents the impact of different separation tolerance levels for the 30-flight scenario. When the separation tolerance is zero, the schedulers apply the strict 10-second interval and have the most impact on departures (as shown in the orange bar representing ground delay). The total delay for these 30 flights is 1,717 seconds with 1,462-second ground delay. With the increased separation tolerance, the required interval between flight ETAs decreases. When the separation tolerance is nine seconds, the arrival scheduler allows the ETA interval to be as small as one second. This yields the most efficient operations with 1,402 seconds for the total delay and 1,000 seconds for the ground delay, 32% less ground delay than the setting with a zero-second separation tolerance. The trend shows that smaller ETA intervals for pre-departure flights help shift delay from ground to airborne while slightly reducing the overall delay. This indicates that increased separation tolerance helps introduce flexibility and improve operational efficiency. Although only delays are shown in this figure, in all experiments shown in this figure, no losses of separation were observed. However, it's worth mentioning that when the tolerance increases to 10 seconds, loss of separation happened because schedulers didn't help at all, when the required ETA interval is zero seconds.
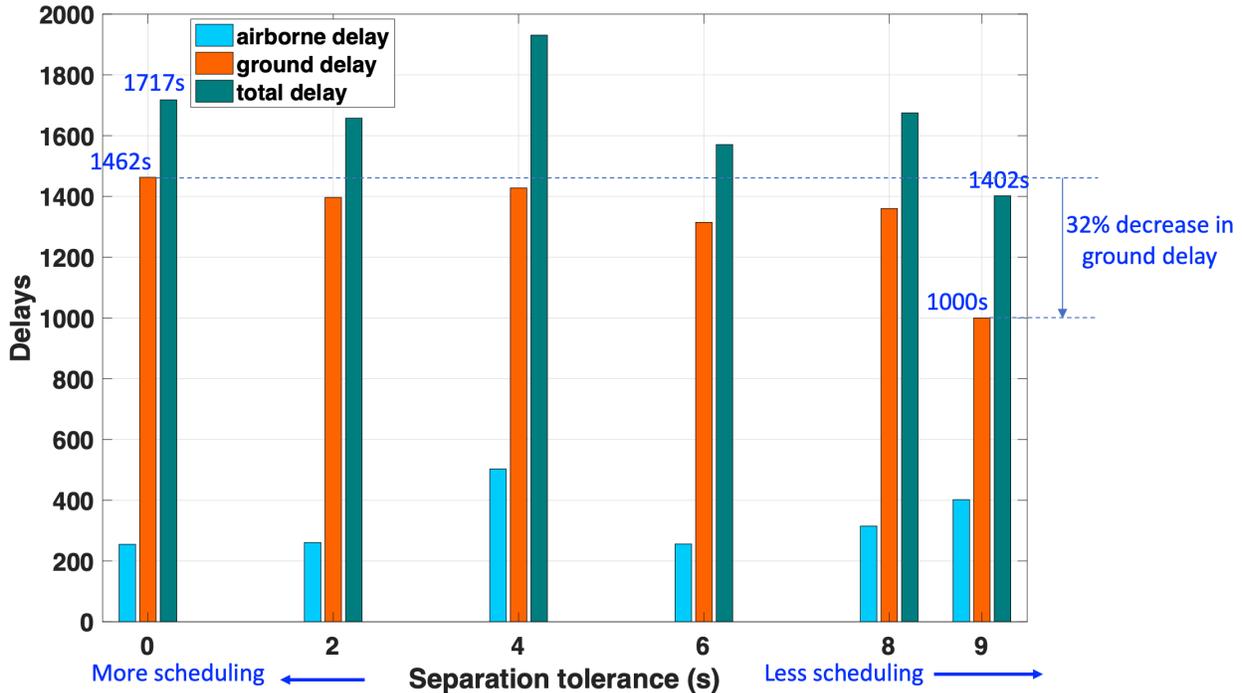

Fig. 7   Delays with different Separation Tolerances for the 30-flight scenario

Figure 8 shows the comparison in maneuver effort using the total number of maneuvers. Since the resolution maneuvers are updated every second in the conflict resolution algorithm, the number of maneuvers can also be treated as the total maneuver duration. It is noted that when the control from arrival schedulers is relaxed, the conflict resolution function had to work hard to resolve conflicts. When the separation tolerance is higher than six seconds, the number of maneuvers jumped from 1,300 to 2,100 at the 9-second separation tolerance, a 63% increase.

Figures 9(a) and 9(b) present the comparison of intervals and departure times for Flow 1 with two extreme separation tolerances, whereas Figures 9(c) and 9(d) show the comparison of intervals and departure times for Flow 2. It is noted that the 462-second ground delay saving with a 9-second separation tolerance is mainly contributed by Flow 2, where some flights depart earlier due to the relaxed departure control from the arrival scheduler at the destination.
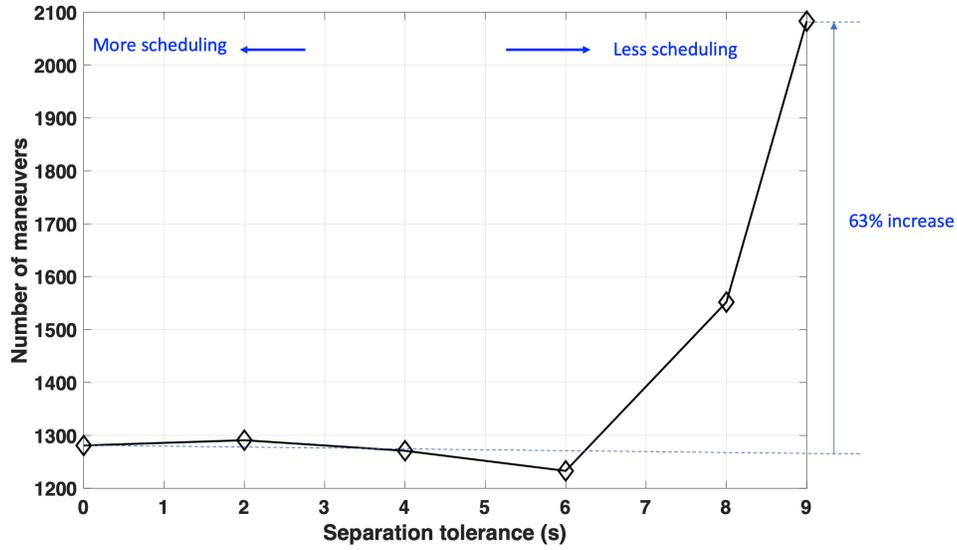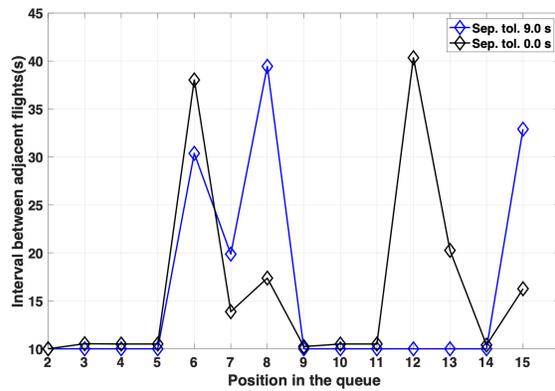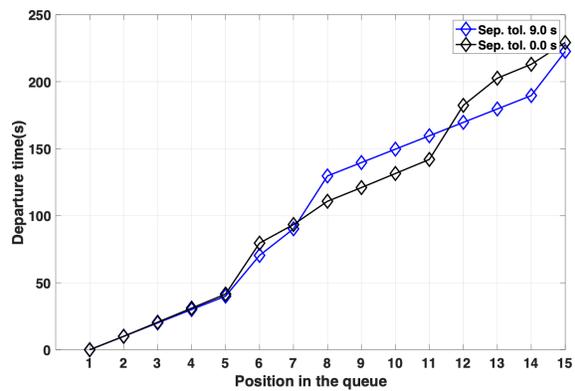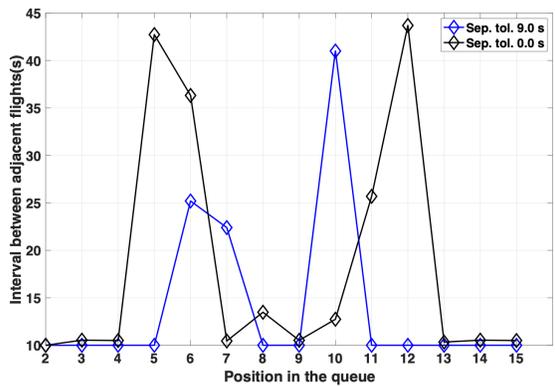
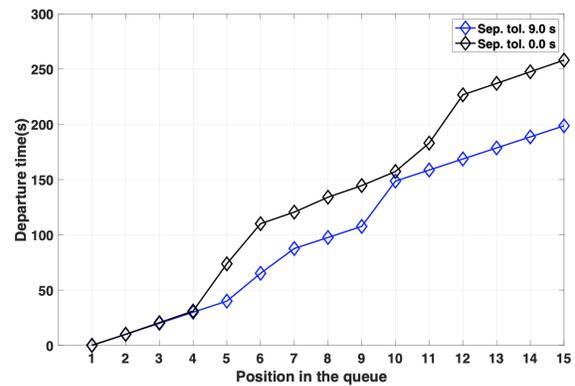**Fig. 8   Number of Maneuvers with different Separation Tolerances**

(a) Intervals between flights for Flow 1

(b) Departure times for Flow 1

(c) Intervals between flights for Flow 2

(d) Departure times for Flow 2

Fig. 9   Comparison with and without coordination with the arrival scheduler

B. Coordination through the departure scheduler: flow interval

The second method coordinates the conflict resolution function with the departure scheduler through a flow interval. Experiments conducted in this section to revealed the relationship between the flow interval and safety and efficiency measurements.

Experiments showed that any separation under 12 seconds would result in losses of separation with the current setting (a cruise speed of 120 kts and a minimum separation of 1,000 ft). Figure 10 reveals the relationship between efficiency (delay) and flow interval when no loss of separation happened. This figure shows that the least delay was achieved when the flow interval was 14 seconds with a 408-second airborne delay, much less airborne delay than the case with a 12-second flow interval. When the flow interval is longer than 16 seconds, the airborne delay is reduced relative to 14 seconds, but no further airborne delay reduction are observed at the 18-second and 20-second intervals. However, the ground delay increased when airborne delay already reached the minimum at a 16-second interval. The minimum airborne delay is purely caused by the initial offset between two flight flows and there is no potential conflict between flights in the same flow. Therefore, increasing the flow interval doesn't help conflict resolution function further. This finding indicates that large flow intervals with 18 and 20 seconds are unnecessary.
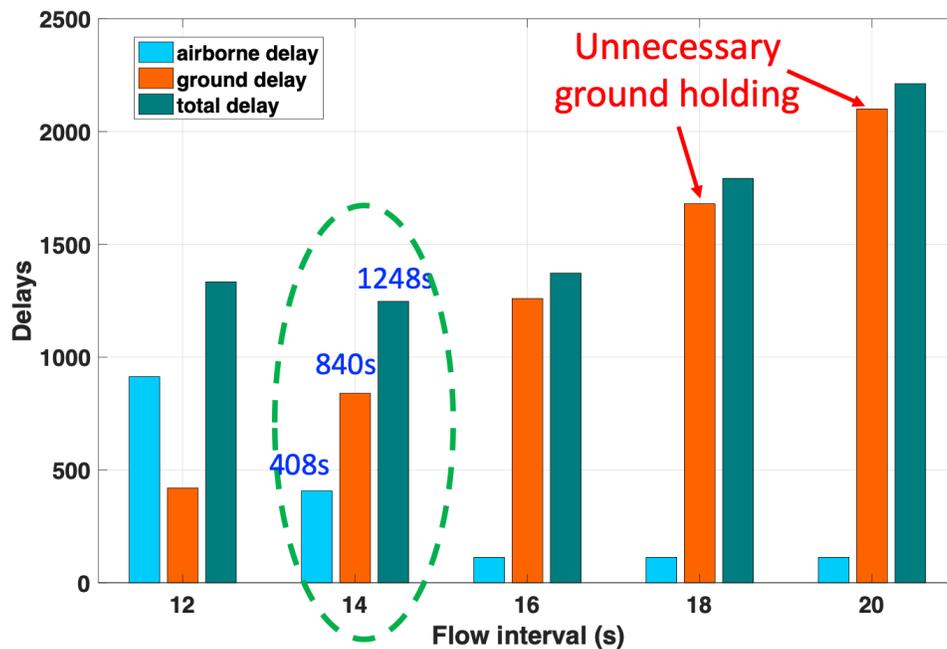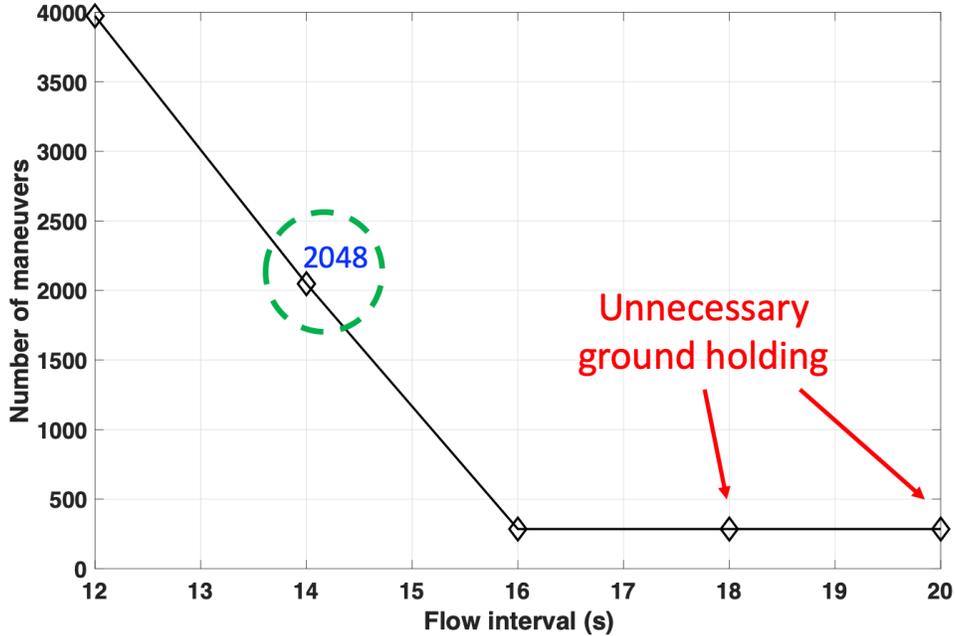

Fig. 10   Delays with different flow intervals

Figure 11 shows the number of maneuvers corresponding to different flow intervals, where the maneuver effort reaches a minimum when the flow interval is 16 seconds. The number of maneuvers at 18 and 20 seconds also verifies that the excessive flow interval doesn't help conflict resolution and becomes unnecessary.

C. Discussion

The first coordination method is a closed-loop control with the feedback coming from the arrival schedulers. The second coordination method through the flow interval is an open-loop control. However, if comparing these two methods with their more efficient settings – 9-second separation tolerance for the first and 14-second flow interval for the latter, both methods have a similar total delay with 1,402 and 1,248 seconds, respectively. They have almost the same airborne delay, 402 seconds for the former one and 408 seconds for the latter. In addition, both methods request a similar amount of maneuver effort: 2,100 for the former and 2,048 for the latter. This study shows that both methods can be used to coordinate scheduling and conflict resolution functions and help improve safety and efficiency. However, both approaches need to tune their parameters to achieve their best performance.

This work only utilized two simple metrics, separation tolerance and constant flow interval, respectively. Advanced metrics like complexity metrics [17, 18], flexibility metrics [19], and other flow management metrics might have the

Fig. 11   Number of Maneuvers with different flow intervals

potential of improving their performance.

Furthermore, the feedback from arrival schedulers in the first coordination method was static, and introducing an adaptive feedback control can help develop a self-learning coordination approach, which should help handle more dynamic and sophisticated situations. Although the ground transportation system deals with much simpler vehicle dynamics, it may be interesting to revisit some adaptive ramp metering algorithms in ground transportation system work [20].

V. Conclusions

Scheduling and conflict resolution functions are two fundamental traffic management functions in UAM operations. Exploring and understanding coordination between these two functions is critical for developing a safe, efficient, and scalable UAM traffic system.

This work first introduced a federated scheduling algorithm and its data exchange needs. It then presented two different methods for coordination between scheduling and conflict resolution functions. The first approach coordinates through the arrival scheduler at the destination. Another one utilizes the departure scheduler at the origin to control the flow interval. Experiments and trade space studies are conducted to compare these two methods using fast-time traffic simulations. Results showed that both methods helped resolve all potential conflicts and had similar performance in operational efficiency and safety. With proper parameter settings, both methods can achieve similar performance in improving efficiency while meeting safety requirements.

References

[1] Thipphavong, D., Apaza, R., Barmore, B., Battiste, V., Burian, B., Dao, Q., Feary, M., Go, S., Goodrich, K., Homola, J., Idris, H., Kopardekar, P., Lachter, J., Neogi, N., Ng, H., Oseguera-Lohr, R., Patterson, M., and Verma, S., "Urban Air Mobility Airspace Integration Concepts and Considerations," *AIAA Aviation 2018*, Atlanta, Georgia, 2018.

[2] Mueller, E., Kopardekar, P., and Goodrich, K., "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," *AIAA Aviation 2017*, Denver, Colorado, 2017.

[3] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., 2016.

[4] *Unmanned Aircraft System (UAS) Traffic Management (UTM)*, FAA, 2018. URL `https://utm.arc.nasa.gov/docs/2018-UTM-ConOps-v1.0.pdf`.

[5] Rios, J., Smith, I. S., Venkatesan, P., Smith, D. R., Baskaran, V., Jurcak, S. M., Strauss, R., Iyer, S. K., and Verma, P., "UTM UAS Service Supplier Development: Sprint 1 Toward Technical Capability Level 4," Tech. Rep. NASA/TM-2018-220024, NASA, 2018.

[6] Rios, J., Smith, I. S., Venkatesan, P., Smith, D. R., Baskaran, V., Jurcak, S. M., Iyer, S. K., and Verma, P., "UTM UAS Service Supplier Development: Sprint 2 Toward Technical Capability Level 4," Tech. Rep. NASA/TM-2018-220050, NASA, 2018.

[7] Ball, M. O., and Lulli, G., "Ground Delay Programs: Optimizing over the Included Flight Set Based on Distance," *Air Traffic Control Quarterly*, Vol. 12, No. 1, 2004, pp. 1–25.

[8] Vranas, P., Bertsimas, D., and Odoni, A., "The Multi-Airport Ground Holding Problem in Air Traffic Control," *Operations Research*, Vol. 42, 1994, pp. 249–261.

[9] Gree, S. M., "En route Spacing Tool: Efficient Conflict-free Spacing to Flow-Restricted Airspace," *3rd USA/Europe Air Traffic Management R&D Seminar*, Napoli, Italy, 2000.

[10] *Traffic Flow Management in the National Airspace System*, FAA, 2009. URL `https://www.fly.faa.gov/Products/Training/Traffic_Management_for_Pilots/TFM_in_the_NAS_Booklet_ca10.pdf`.

[11] Swenson, H. N., Hoang, T., Engelland, S., Vincent, D., Sanders, T., Sanford, B., and Heere, K., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," *1st USA/Europe Air Route Traffic Management RD Seminar*, Saclay, France, 1997.

[12] Farley, T., Foster, J. D., Hoang, T., and Lee, K. K., "A Time-based Approach to Metering Arrival Traffic To Philadelphia," *1st AIAA Aircraft, Technology Integration, and Operations Forum*, Los Angeles, CA, 2001.

[13] *Time Based Flow Management*, FAA, 2017. URL `https://www.faa.gov/nextgen/cip/tbfm/`.

[14] Xue, M., Rios, J., Silva, J., Ishihara, A., and Zhu, Z., "Fe^3: An Evaluation Tool for Low-Altitude Air Traffic Operations," *AIAA Aviation Forum*, Atlanta, GA, 2018.

[15] Silva, C., Johnson, W., Antcliff, K. R., and Patterson, M. D., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," *Aviation Technology, Integration, and Operations Conference*, Atlanta, GA, 2018.

[16] Xue, M., and Kowalski, M., "Parametric Study of Federated Conflict Resolution for UAM Operations using DOE Analysis," *AIAA Aviation Forum*, Virtual Event, 2021.

[17] Xue, M., and Do, M., "Scenario Complexity for Unmanned Aircraft System Traffic," *AIAA Aviation Forum*, Dallas, TX, 2019.

[18] Bulusu, V., Sridhar, B., and Xue, M., "An Impedance Based Complexity Metric for Unmanned Aircraft System Traffic Scenario Classification," *AIAA Aviation Forum*, Virtual Event, 2020.

[19] Idris, H., Wing, D. J., Vivona, R., and Garcia-Chico, J., "A Distributed Trajectory-Oriented Approach to Managing Traffic Complexity," *The 7th AIAA Aviation Technology, Integration and Operation Conference*, Belfast, Northern Ireland, 2007.

[20] Mizuta, A., Roberts, K., Jacobsen, L., and Thompson, N., "Ramp Metering: A Proven, Cost-Effective Operational Strategy-A Primer," Tech. Rep. FHWA-HOP-12-020, Department of Transportation, Federal Highway Administration, 2014.