Insights from Data Analysis of Strategic Conflict Management Simulations for Urban Air Mobility Operations

Kushal A. Moolchandani[1]

Universities Space Research Association, Moffett Field, California, 94035, USA

Hanbong Lee[2], Heather Arneson[3], and Annie Cheng[4]

NASA Ames Research Center, Moffett Field, California, 94035, USA

Chin Seah[5]

METIS Technology Solutions, Moffett Field, California, 94035, USA

Levin Guillermo[6]

NASA Ames Research Center, Moffett Field, California, 94035, USA

This paper presents the lessons learned from the data analysis of simulations of Urban Air Mobility (UAM) operations that will be used to provide recommendations for future UAM system architecture and airspace services improvements. In support of the gradual maturation of the UAM industry, NASA has been conducting a series of UAM air traffic simulations. With industry partners for UAM airspace services, NASA recently completed collaborative simulations – collectively referred to as X4 – focusing on strategic conflict management. The architecture of the simulation system includes various software modules that were independently developed and integrated to provide airspace services to UAM operators. A detailed analysis of the data collected during simulations was conducted to support performance assessment of the X4 system architecture. This paper describes the results of the data analysis including metrics such as throughput at various resources, the detection and resolution of simulated demand-capacity imbalances using pre-departure delays, and conformance of operations to their operational intents.

[1] Aerospace Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, kushal.a.moolchandani@nasa.gov. AIAA Member.

[2] Aerospace Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, hanbong.lee@nasa.gov. AIAA Member.

[3] Aerospace Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, heather.arneson@nasa.gov. AIAA Member.

[4] Aerospace Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, annie.cheng@nasa.gov. AIAA Member.

[5] Senior Software Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, chin.h.seah@nasa.gov. AIAA Member.

[6] Aerospace Engineer, NASA Ames Research Center, Mail Stop 210-6, Moffett Field, CA 94035, levin.m.guillermo@nasa.gov. AIAA Member.

I. Nomenclature

ASDS	=	Airspace Structure Definition Service
ATM-X	=	Air Traffic Management – eXploration
DCB	=	Demand-Capacity Balancing
DSS	=	Discovery and Synchronization Service
FIMS-AZ	=	Flight Information Management System Authorization
NC	=	National Campaign
PSU	=	Provider of Services for UAM
SCM	=	Strategic Conflict Management
UAM	=	Urban Air Mobility
UDC	=	Universal Data Collector
UML	=	UAM Maturity Level
UTM	=	Unmanned Aircraft System (UAS) Traffic Management
UVR	=	UAS Volume Reservation

II. Introduction

Urban Air Mobility (UAM) is a new aviation market that extends the scope of traditional aviation from national and global air transportation services to local and regional levels, specifically to the provision of air transportation services to passengers and cargo transport within and around large metropolitan areas. A future, mature state of UAM operations involves high levels of autonomy and operational tempo in and around urban and suburban areas [1]. NASA has defined six UAM Maturity Levels (UML) which describe different stages of increasingly more complex and operationally dense UAM operations for gradually increasing levels of system autonomy [2].

NASA has been conducting a series of simulation experiments to support the gradual progression of the UAM market towards higher UMLs. These test activities, conducted under the "Advanced Air Mobility (AAM) National Campaign (NC)" banner and involving collaboration between government and industry, are intended to provide insights into the evolving regulatory, operational, and safety environment of emerging aviation markets, including UAM. In turn, the insights generated by these tests are necessary to enable the envisioned FAA UAM concept of operations while promoting public confidence in safety.

The latest of these simulation experiments, concluded in June 2022, were called the "X4" simulations and focused on the development of a strategic conflict management service for UAM. In this paper, we briefly describe the X4 simulations followed by detailed analysis of data collected during these simulation runs. The primary objective of this data analysis is to assess the performance of current system architecture and, especially, describe the performance of the strategic conflict management services in a low-density operational environment. The insights gained from this analysis will guide future design decisions on development and integration of airspace services.

In the following sections, we present an overview of NASA's series of simulation activities, especially the X4 simulations, in Sec. III. In Sec. IV, we provide additional details of the experiment design of X4 simulations. Next, in Sec. V, we present analysis results of simulation data. Finally, we will discuss the lessons learned from these analysis results and conclude this paper in Sec. VI and VII.

III. X4 Simulation Overview

The UAM simulation events being conducted by NASA, collectively called the X-series simulations, started with "X1" simulations during 2017-18 with the goal to explore and evaluate the roles and responsibilities and information exchange requirements of UAM stakeholders during both nominal and off-nominal conditions [3]. Following these, during 2018-19, the "X2" simulations investigated the application of the information exchange architecture developed for Unmanned Aircraft System (UAS) Traffic Management (UTM) to UAM operations in shared airspace [4]. The "X3" simulation followed in 2020 and provided the initial opportunity to assess the NC airspace system developed by the UAM Sub-Project under NASA's Air Traffic Management – eXploration (ATM-X) project and the capabilities provided by airspace partners [5, 6].

The latest in the X-series of simulation activities are the "X4" simulations which had two primary objectives – to research and develop a strategic conflict management service for UAM operations and to work along with industry airspace service partners to prepare them for National Campaign-1 (NC-1) flight tests. The National Campaign is a series of NASA-hosted activities focused on identifying and addressing the key challenges to the realization of new aviation markets such as UAM; the goal of the first of these, NC-1, is to promote public confidence in UAM safety and facilitate community-wide learning. X4's focus on the strategic conflict management for UAM operations [7] involves an initial implementation and testing of Demand-Capacity Balancing (DCB) of UAM operations. In this implementation, all partners were required to develop (or procure from an external source) a service that strategically schedules operations to ensure that the total demand at each of the constrained resources remains at or below its capacity. Since collaboration with industry partners was an important aspect of the X4 simulations, the simulation system architecture was designed with a view to integrate the software components developed by airspace service provider partners and establish a framework for the necessary foundational research into airspace structure design and air traffic management. The overall architecture of the simulation system was based on the notional UAM architecture defined within the FAA's UAM Concept of Operations (ConOps) version 1.0 [1].

A. UAM System Architecture for X4 Simulation

Figure 1 shows the architecture of the X4 system. This architecture includes the UAM subsystems, including the Providers of Services for UAM (PSU), an Airspace Structure Definition Service (ASDS), which provides the adaptation data such as airspace structure and performance requirements, a Discovery and Synchronization Service (DSS), which allows PSUs to discover other PSUs operating in the shared airspace, and a Flight Information Management System Authorization (FIMS-AZ) service, which provides authentication and authorization services to the PSUs. These subsystems provide the software components developed to demonstrate the capabilities defined in the X4 simulation scenarios.

Data generated from simulations were collected and stored for later analysis. The components of the data collection environment include components for collecting PSU exchange data during simulations and storing these data for post-sim data analysis. All simulation data are collected by a Universal Data Collector via the endpoints defined in the PSU Application Programming Interfaces (API). These data are forwarded to the Data Pipeline, which validates all messages received for conformance to the baselined X4 APIs and further forwards them to data storage, which are secure repositories-of-record utilized to store and recall both real-time and post-operations data.

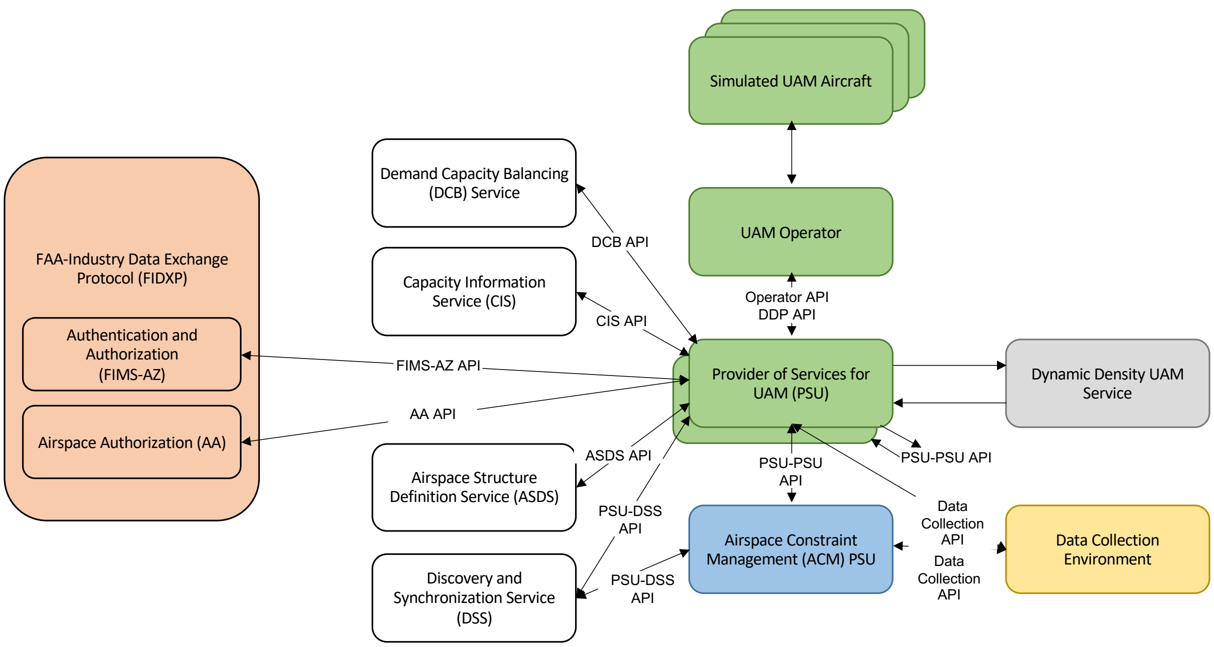


Fig. 1 Notional UTM-inspired UAM system architecture for X4 [11].

B. Demand-Capacity Balancing (DCB) for UAM

As noted above, the strategic conflict management capability developed for UAM operations in X4 focused on the development of a Demand-Capacity Balancing (DCB) service. In the National Airspace System, the DCB service provides strategic evaluation of system-wide traffic flows and aerodrome capacities to allow airspace users to determine when, where, and how they operate, while mitigating conflicting needs for airspace and aerodrome capacity [8]. Similarly, UAM operators need to coordinate on use of shared resources (e.g., vertiports, airspace routes) as these resources have capacity limits. For UAM operations under VFR, strategic plans should be coordinated among UAM operators to avoid overloading the shared resources, and with enough buffer built in so that pilots can handle some expected level of uncertainty. For UAM operations under IFR, strategic plans may still be the responsibility of the UAM operator, but ATC may play a role.

In X4, the providers of this service were responsible for ensuring submitted operational plans met all applicable capacity constraints. NASA's implementation of the DCB service proceeds in four steps. Step 1 identifies capacity at constrained resources. In X4, capacity constraints were imposed only at the vertiports by an authoritative source, which was available to all operators and PSUs via a defined API. Step 2 identifies the air traffic demand at those resources. For all proposed operations, the DCB service identifies the current demand at both the origin and destination vertiports. Step 3 determines if there is an imbalance between the demand and capacity at any of the constrained resources (vertiports). This implies identifying those vertiports where the demand is more than the given capacity within a specified time interval. Finally, Step 4 resolves the identified imbalances by assigning pre-departure delays. For each operation that has an imbalance at any or both of its vertiports, the PSU updates the operational plan to resolve the imbalance. Reference [9] presents additional details on NASA's DCB algorithm along with analysis of effects of imbalance resolution on system performance.

IV. X4 Simulation Setup

This section presents the setup of X4 collaborative simulations, including descriptions of the assumptions made regarding the route network, traffic density, and vehicle performance.

To test DCB capabilities developed by NASA and by seven NC-1 airspace partners, NASA developed traffic scenarios for multiple hypothetical UAM operators and shared them with the airspace partners prior to each simulation. These traffic demand scenarios were designed to create sufficient demand-capacity imbalances at vertiports and assess how PSUs would update their operational plans to resolve the imbalances. Two traffic scenarios were defined: Scenario 1, which included flight and operation planning for nominal operations, and Scenario 2, which included enroute operation re-planning in response to an announced airspace constraint area (i.e., a UAS Volume Reservation, or UVR). These simulations focused on the traffic density at levels 2 and 3 of the UML framework [2]; Table 1 shows the first five operations defined in Scenario 1 of X4. In this table, the column "Operation" is a unique numeric key that identifies the sequence of proposed operations and has a one-to-one mapping with the column "Callsign." The owner of each operation is identified by the participant number – P1, P2, or P3 – in column "Operator," and the origin and destination of each operation are shown in the following two columns. The final column, "Departure Time," is the time in seconds since start of simulation when the operation is initially proposed to depart. As noted, the initial departure times are intentionally specified so as to create demand-capacity imbalances in the traffic scenario.

Table 1: Example of a traffic scenario definition.

Operation	Callsign	Operator	Origin	Destination	Departure Time
0	UAM201	P2	DF32	DF30	420
1	UAM202	P2	DF14	DF43	480
2	UAM101	P1	DF43	DF28	480
3	UAM301	P3	DF30	DF32	480
4	UAM302	P3	DF32	DF30	540

For X4 simulations, NASA defined a route network over the Dallas/Fort Worth metropolitan area [11]. A subset of the vertiports were selected as Origin-Destination (OD) pairs to support various objectives for X4 simulations, including exercising DCB, exploring operators' routing choices through Class B/D and in Class E/G airspace, and interacting with the airspace constraints in Scenario 2. Figure 2 shows the twelve routes connecting the selected OD pairs used for Scenario 1 Collaborative Simulation. The traffic demand of each operator was distributed equally over these routes but had a peak in planned simultaneous operations during the 1.5-hour long simulation run, ensuring sufficient demand-capacity imbalances for each participant to evaluate its DCB capability. No uncertainties were modeled in X4 simulations.

Each collaborative simulation run had three groups, with each group comprised of three participants from among NASA and seven industry partners. For Scenario 1, each participant was assigned 32 operations for a total of 96 operations, which were evenly distributed to 12 routes connecting 7 vertiports. For Scenario 2, certain routes were removed from the previous Scenario 1 to simplify the traffic interaction with the UVR. As a result, participants 1, 2, and 3 were assigned 28, 29, and 30 operations, respectively, with a total of 87 operations.

As noted above, capacity constraints were imposed only at the vertiports equal to four operations in each time bin. A time bin was defined as a fixed period of 12-minute duration starting from the beginning of the hour, i.e., the time bins were defined as blocks of time [0:00, 11:59], [12:00, 23:59], etc. in minutes. Thus, the DCB algorithms compared the total traffic proposed in each time bin and, if the traffic exceeded four operations in any bin, proposed a resolution. In X4, all participants chose to resolve all demand-capacity imbalances solely by assigning pre-departure delays.

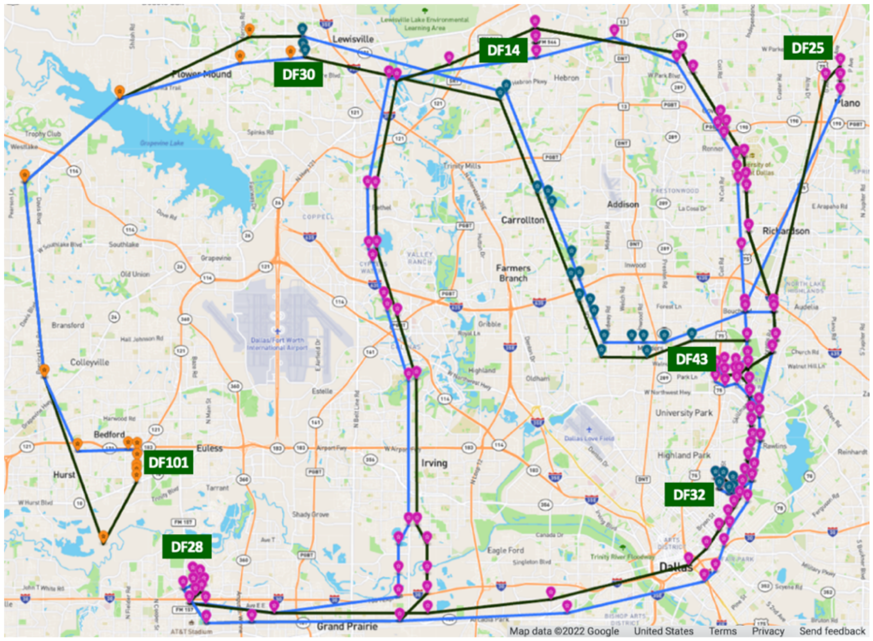


Fig. 2 Route network in Dallas/Fort Worth urban area for Scenario 1 Collaborative Simulation.

V. Simulation Data Analysis Results

This section presents the analysis results of the data collected during X4 simulations. The metrics presented include evaluation of the throughput at vertiports, the conformance of operations to their intents, performance evaluation of a proposed DCB algorithm, and the delays assigned to aircraft. The primary purpose of this analysis is to identify the simulation artifacts that can be fed to future UAM simulations and lessons learned regarding system performance that can guide future advancements in airspace services. The authors previously presented an approach for data analysis of simulation results from X4 in [10]; additionally, some of the results and lessons learned from X4 are also documented in a NASA Technical Memorandum [11].

A. Traffic Throughput at Vertiports

To assess traffic throughput in the route network, we calculated metrics such as the number of flights that were planned, the number of flights that were accepted and completed their missions, and the running count of number of operations that were airborne at any given time during the simulation. The objectives of calculating these metrics were to show the traffic level represents the UML-2/3 traffic density and to check if most flights are operated in simulation as planned.

Figure 3 shows the total number of operations that were accepted, activated, and ended in simulation runs of all three groups in each of the two Collaborative Simulations. Here, “Accepted” means that the submitted operational intent was accepted to operate over its route. “Activated” means that the flight took off and flew the route, while “Ended” means that the operation landed at its destination and concluded the flight. Additional data from all simulations are available and have been analyzed to obtain more granular performance data. For example, from Fig. 3, we can see that Group 3 had the least number of operations flown during both Collaborative Simulations. By analyzing data for each participant separately, we identified that only one of the three participants had fewer number of operations than those specified by the scenario. While we expected most operations to get activated (i.e., take off) and complete their missions, the reasons for an operation not activating included technical issues with PSU, some operations not getting submitted or activated, indicating issues with implementation of DSS, or even failure of data collection for some operations.

Figure 4 shows a running count of simultaneously airborne operations during the same simulations as above. In both scenarios, the peak value of the total number of simultaneously airborne aircraft was 23. At the participant level, we expected each participant to reach 10s of simultaneous operations at their peak; all but one participant in each of Scenario 1 and Scenario 2 individually achieved the level of at least 10 simultaneous operations at some point during the experiment.

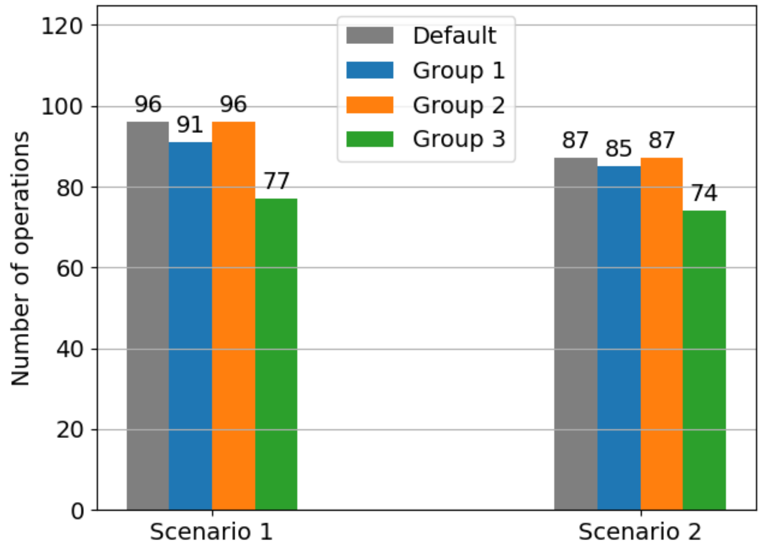


Fig. 3 Number of operations that completed their missions (Ended) in Collaborative Simulations [11].

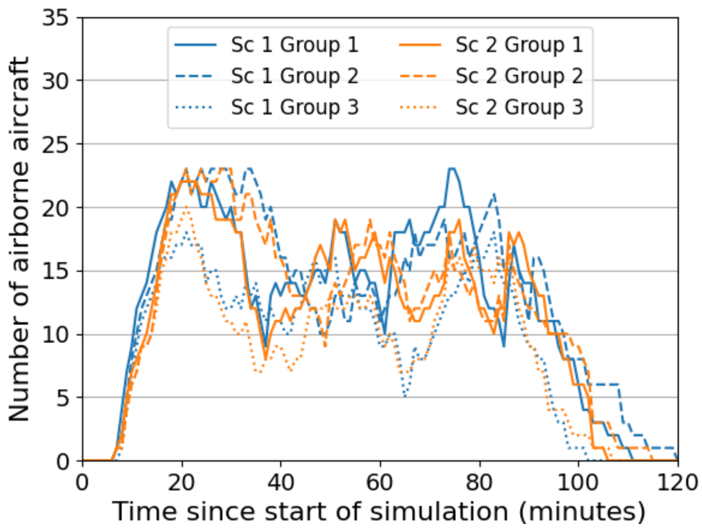
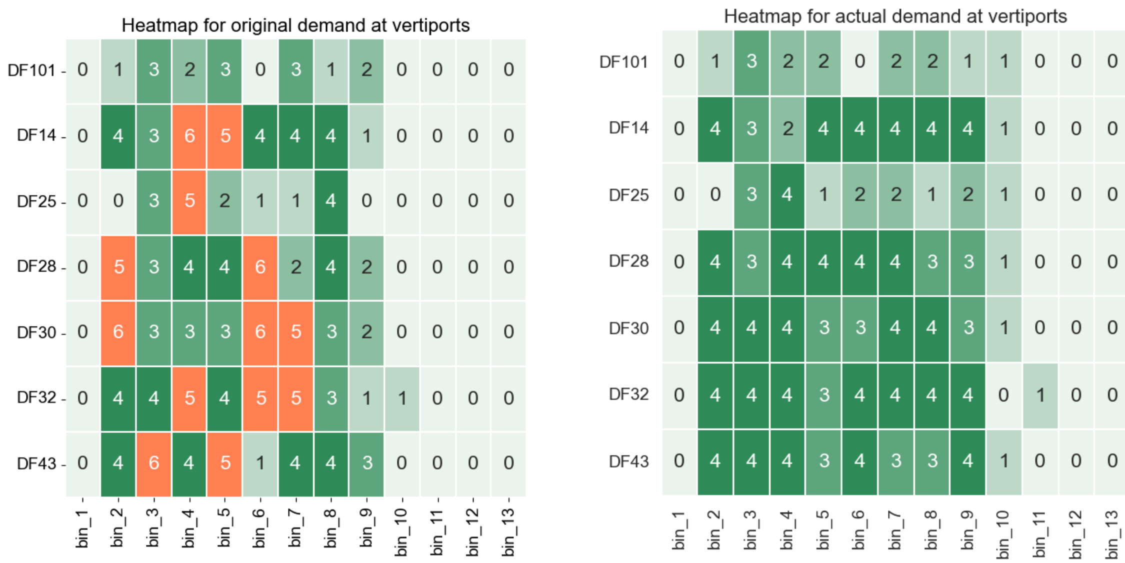


Fig. 4 Number of simultaneously airborne operations during Collaborative Simulations.

B. Demand-Capacity Imbalance Detection and Resolution

Since the focus of X4 simulations was on the strategic conflict management, specifically the Demand-Capacity Balancing (DCB) of UAM operations, it was expected that the DCB algorithms would resolve all instances of excess demand over capacity. To assess if all instances of demand-capacity imbalance were indeed detected and resolved, we counted the number of operations in each time bin at each vertiport; this information is presented both for the input scenario and the actual number of operations as heatmaps in Fig. 5. Each flight is represented twice in the heatmaps, once at the origin vertiport and once at the destination vertiport. To demonstrate the results and guide discussion, we show the results from simulation of Group 1 in Scenario 1. For this group, only 93 out of 96 operations were accepted and 91 of those operations completed their missions (Fig. 3).

Figure 5(a) shows the demand distribution specified in the input scenario. The figure highlights, in orange, the 13 time bins where the demand was intentionally specified to exceed the capacity to test the participants' DCB algorithms. Figure 5(b) shows the demand distribution that was observed during the simulation as a result of the participants running their respective DCB services. In this case, all detected imbalances were successfully resolved. However, as described in Reference [11], in some other runs, there were instances of unresolved imbalances. These were attributed to either issues with the PSUs' demand-capacity balancing algorithms or issues with timing and synchronization between the Discovery and Synchronization Service (DSS), the PSUs, and DCB services; see Ref. [11] for additional information.



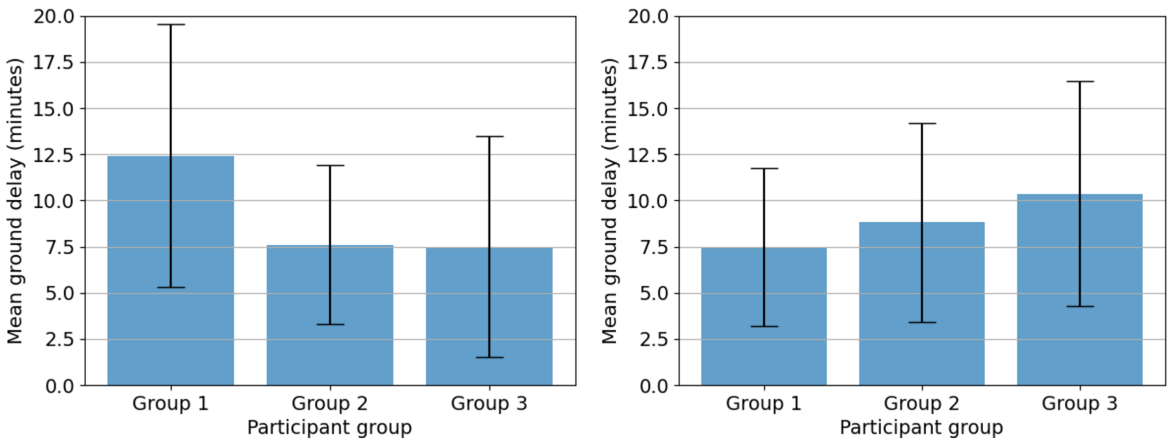
(a) (b)

Fig. 5 Heatmap for the number of operations (a) before demand-capacity imbalance resolution and (b) after resolution in each time bin for Group 1 in Scenario 1 Collaborative Simulation.

Although all imbalances were resolved in the simulation depicted in Fig. 5, we can identify a few unused slots. For example, the time bin "bin_4" at DF14 has only two operations post-DCB while the input scenario specified six operations. Thus, this time bin is underutilized, which is an indicator of inefficiency. Similarly, time bin "bin_5" at DF32 has three operations post-DCB whereas the input scenario had four – demand was reduced in this time bin at DF32 even though it was at capacity. This underutilization can be explained by the fact that, for each operation, demand was required to remain at or below capacity at both the origin and destination vertiports. Thus, post-DCB demand in a time bin at a vertiport can be different even if input demand does not exceed capacity, such as in case of "bin_5" at DF32, if some of the flights are moved to different time bins due to imbalance resolution at their other terminals. Moreover, if the DCB algorithms are restricted to using only pre-departure delay as a resolution mechanism, the DCB services will delay a flight if it exceeds capacity at either of the two vertiports with the result that some operations will be delayed more than would be required if other resolution mechanisms are available (e.g., airborne delay). An enroute conflict management service could allow a flight to take off even if its estimated arrival were predicted to cause excess demand over capacity at the destination, because it could resolve the imbalance using enroute maneuvers.

C. Pre-departure Delay Distribution

Although there was no requirement on how each participant should resolve a demand-capacity imbalance, all participants chose to resolve imbalances by assigning pre-departure delays to operations. The metrics calculated in this subsection check if the assigned delays for DCB are reasonable and fair between participants. To check that delays were reasonable relative to the length of the flights, we calculated the mean delay for all delayed aircraft in each simulation run. Thus, Fig. 6(a) and 6(b) show the mean delay of all delayed aircraft in each of the three participant groups in Scenario 1 and Scenario 2, respectively. In Scenario 1, while Group 2 and Group 3 had nearly the same amount of mean delay, Group 1 had a larger value. In Scenario 2, we see differences in mean delay values for all three groups. These differences arise because of the differences in their DCB algorithms. For example, some participants assign additional pre-departure delay with buffers over the minimum required to resolve an imbalance. The minimum required delay is achieved if an aircraft is pushed back to the beginning of a time bin with available capacity, which was the mechanism that NASA's DCB algorithm used. On the other hand, some participants assigned departure times in the middle of the next available time bin. Because there is variance in the initially proposed departure time, this introduced variability in the amount of assigned delay.



(a) (b)

Fig. 6 Mean pre-departure delay in (a) Scenario 1 and (b) Scenario 2 Collaborative Simulation.

Figure 7 gives additional detail by showing the distribution of delay over all flights for each participant in Group 1 of Scenario 1 Collaborative Simulation; Table 2 breaks down details of the mean, median, minimum, and maximum pre-departure delays assigned. Note that Participant 2 had five fewer activated flights than the other two participants. This participant also had higher mean and median delay values, which is also evident in Fig. 7. This result led to a higher mean total delay for the entire group. Although details of the partners' delay assignment algorithms are unavailable, based on calculation of observed delays, we can evaluate the tradeoff between fairness and efficiency of operations in the UAM route network. In Group 1, while the pre-departure delays for one participant are higher than the other two, the total number of delayed operations were nearly evenly divided among the three participants. The observed delays, therefore, are a function of the delay mechanism employed by each participant.

Table 2: Details of pre-departure delays assigned in Group 1 of Scenario 1 Collaborative Simulation.

	Total Group 1	Participant 1	Participant 2	Participant 3
Delayed / Total flights	33 / 91	10 / 32	12 / 27	11 / 32
Mean (minutes)	12.42	6.96	18.50	10.76
Median (minutes)	13.15	8.46	19.50	12.15
Min (minutes)	0.3	0.96	8.0	0.3
Max (minutes)	25.0	13.96	25.0	19.1

D. Flight Speed Profile Comparison

All participants submitted operational intents that specified the intended flight plans for each of the participants' flights. The operational intents included such information as the intended departure time, flight speed, and the sequence of trajectory waypoints along with planned arrival times at each waypoint. For the safety and efficiency of all, it is desirable that all operations conform to their filed and approved operational intents. To evaluate whether this was indeed the case, we calculated the number of operations that conformed to both their filed intents and airspace requirements. The X4 Simulations Final Report [11] presents some results on the trajectory conformance of operations. Here, we compare the flight speed profiles of the participants against one another on a specific route. The flight speed, in turn, correlates with the conformance to desired speed ranges. Note that the airspeed range, i.e., the lower and upper bounds on flight airspeeds, are specified by the Airspace Structure and Definition Service (ASDS) and is one of the performance requirements that the participants will have to meet to fly in the UAM corridors. For X4, the performance requirements specified maximum and minimum airspeeds of 130 knots and 70 knots, respectively.

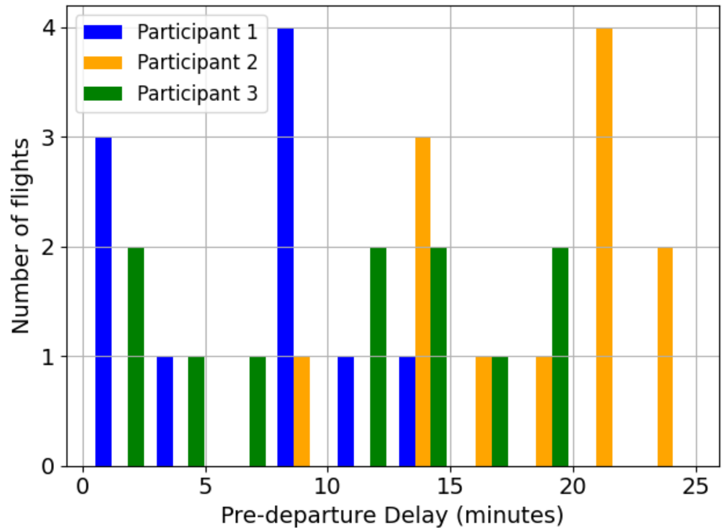


Fig. 7 Histogram of delay distribution for Group 1 in Scenario 1 Collaborative Simulation.

Figure 8 shows the flight speed profiles for all operations on the route from DF30 to DF32; the flights shown are data from Group 1 of Collaborative Simulation 1. Flights operated by Participant 1 are shown in shades of blue, flights operated by Participant 2 are shown in shades of orange, flights operated by Participant 3 are shown in shades of green. Clearly, Participants 2 and 3 both flew at higher speed than Participant 1, which chose to fly at a lower speed: Participant 1 flew the route at an average speed of 52 knots and completed the flights in an average of 29 minutes; Participant 2 flew at an average speed of 77 knots and took an average of 16 minutes, and Participant 3 flew at an average speed of 91 knots and took an average of 15.5 minutes to complete the flights. Due to the different flight speed settings among operators, we observed overtakes during the simulation. For example, the flight with callsign "UAM120" operated by Participant 1 took off 36 minutes into the start of the simulation and landed at 64 minutes into the simulation, while the flight 'UAM213' operated by Participant 2 took off later, at 45 minutes into the simulation, but still managed to land earlier at 62 minutes. Overtakes were not prohibited in X4 simulations and future advancements to strategic conflict management services or the inclusion of enroute conflict management services could prevent them.

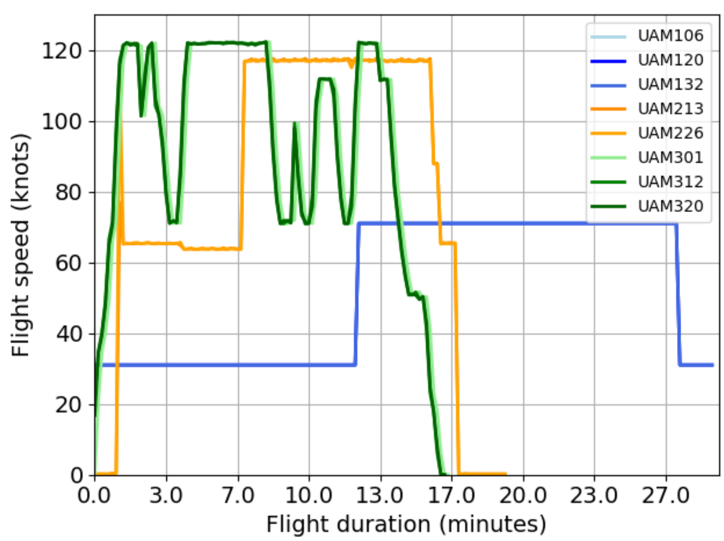


Fig. 8 Flight speed profiles for all operations on the DF30..DF32 route.

E. Rerouting in Response to UAM Volume Reservation (UVR)

Scenario 2 of the X4 simulations involved a UAS Volume Reservation (UVR) or a Temporary Flight Restriction (TFR) that restricted access to a part of the airspace to all operations. Only one route of the network had a UVR, and six operations, two of each participant, were impacted. The participants were required to re-route each of their two impacted operations, of which one was impacted while airborne and the other was impacted pre-departure. Thus, whereas in Scenario 1 all participants used pre-departure delay to resolve demand-capacity imbalances, in Scenario 2, it was expected that one of the two flights impacted by a UVR would require replanning while airborne. After simulations, we evaluated to check if participants were able to reroute properly and timely when encountering the UVR restriction.

Table 3, also shown in Ref. [11], shows that two of the three groups re-routed all operations, while in Group 3, one airborne operation and one pre-departure operation were not successfully re-routed. Of the two failed re-routes, one operation used a recommended pre-departure re-route instead of an airborne re-route, which was considered a failure. The other operation was expected to re-route pre-departure, but its start time was proposed after UVR expiration and hence the operator did not need to re-route. However, this operation was expected to be proposed for departure at a time such that it would encounter a UVR, and, therefore, this too was considered a re-routing failure.

Table 3: Re-routing to avoid UVR in Scenario 2 Collaborative Simulations.

Group	Airborne re-routes	Pre-departure re-routes	Total percentage of operations replanned
Group 1	3 / 3	3 / 3	100%
Group 2	3 / 3	3 / 3	100%
Group 3	2 / 3	2 / 3	66.67%

Similar to demand-capacity imbalance resolution, each participant was free to choose its own approach to re-routing to avoid the UVR. However, although we observed few instances of re-routing failures, the participants had the advantage of knowing beforehand the route that would be impacted by the UVR and could plan their resolutions in advance. Further, no uncertainties were modeled, which made it easier to find acceptable and successful resolution maneuvers. The takeaway from these observations is that more tests are needed to fully evaluate the rerouting capability. For example, we need to test operators' responses to abrupt UVR pop-ups (with little lead time), uncertain UVR expiration time which will impact their strategic planning, the interaction among airborne flights near a UVR, etc.

VI. Discussion and Lessons Learned

From the above analysis of results, we have identified some lessons learned that will guide future developments in airspace services and the system architecture. Since the focus in X4 was on DCB, many of these lessons learned relate to enhancement of the DCB service.

1) During the simulation, not all planned operations could activate. While some failed activations were traced to technical issues with the PSU implementation, some other operations were impacted by limitations of message exchange. In X4, the DSS facilitated automated message exchange among the PSUs and the DCB services. However, we identified that in some cases the DSS itself became a bottleneck that inhibited higher operational tempo [11]. Thus, to support higher operational densities and higher message throughput, the operational intent submission process through DSS should be improved to avoid skipped flights.
2) One of the shortcomings of the current DCB algorithms is that they are limited to resolve imbalances by pre-departure delays alone. Lacking any enroute resolution or optimization capabilities, the penalty incurred in form of pre-departure delays can be large, especially for aircraft that take off later during the simulation. The more advanced DCB algorithms will be able to optimize capacity usage by moving the scheduled departure time earlier and resolving demand-capacity imbalances at all enroute waypoints in addition to vertiports. Further, any strategic deconfliction service will need to ensure that delay assignment remains reasonable and fair in a federated operational environment.
3) Yet another shortcoming is that the current DCB algorithms do not account for uncertainties that could result from weather or operational effects. A more mature airspace services system of systems will also include additional services that work alongside DCB to improve efficiency without compromising on safety. Thus, DCB could interact with additional services such as weather services to handle uncertainties, for example, by recommending enroute maneuvers, reducing the amount of assigned pre-departure delays.

VII. Conclusions

A series of simulation experiments conducted by NASA in collaboration with seven industry partners during 2021-22 have been described and analysis of data collected during those simulations presented. Each of NASA and the seven industry partners developed their own PSU and developed or procured an external DCB service which were then integrated into a common simulation environment for testing. The experiments involved simulations of urban air mobility flights in the Dallas/Fort Worth Metropolitan area at a traffic density of up to tens of flights airborne simultaneously. The simulation platform developed by NASA was designed to enable integration of industry-developed airspace services so that the proposed federated architecture of the UAM airspace services system could be tested. The simulations focused on strategic conflict management, specifically the Demand-Capacity Balancing (DCB) service that ensures that the traffic at constrained resources remains at or below their capacities. In X4, constraints were only enforced at vertiports, and demand-capacity imbalances were resolved by assigning pre-departure delays.

The Collaborative Simulations were an opportunity to demonstrate how multiple PSUs could work together in a federated environment. Issues related to different DCB implementations, system performance, data collection, etc. that were encountered during these simulations were identified and, from evaluation of these issues together with post-simulation data analysis of data, lessons learned were documented.

While all participants were able to successfully complete all experiments and resolve demand-capacity imbalances as expected, we observed inefficiencies in the system due to the limitations of the DCB services. Specifically, the limitation of using only pre-departure delay as a mechanism for resolving imbalances led to large delays that quickly became unacceptable for later flights. An absence of an enroute conflict management service requires resolving imbalances even before an aircraft takes off, which will only work so long as there are no uncertainties. From these observations, we recognized that we may need to improve the strategic conflict management service and/or integrate it with an enroute separation provision service to avoid situations such as one aircraft overtaking another mid-flight.

The X4 simulations successfully demonstrated the feasibility of integrating airspace services from multiple industry service providers and autonomously providing air traffic management services to UAM operations. Analysis of collected data has provided insights into the shortcomings of the current system architecture and firmly lent support to the need for additional services such as an enroute conflict management service. Further, more advanced airspace services will be able to improve efficiencies thereby improving flights throughput without compromising on safety.

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