Simulated Evaluation of Strategic Conflict Management Capabilities for Urban Air Mobility Operations

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Urban Air Mobility (UAM) is a new air transportation service concept to carry passengers or cargo in metropolitan areas, leveraged by innovative aircraft and automation technologies. NASA has conducted a series of simulations to evaluate the UAM concept of operations and inform the development of airspace procedures and services for UAM operations. The latest set of simulations called "X5" were conducted to test a Provider of Services for UAM (PSU) prototype that NASA developed for UAM flight planning, strategic conflict management support, and data exchange between UAM operators. In these simulations, two strategic conflict management capabilities, Demand-Capacity Balancing (DCB) and Sequencing and Scheduling (S&S), were further investigated. This paper describes the system architecture designed for the X5 simulation activities, the sequence diagram for strategic conflict management, and the simulation environment in the Dallas/Fort Worth urban area. The simulation results based on several system performance metrics for evaluation show that a sequential application of DCB and S&S effectively works to distribute traffic demand and meet sequencing and spacing criteria by assigning ground delays, compared to the DCB only and S&S only cases.

I. Introduction

Urban Air Mobility (UAM) is an emerging concept that enables highly automated, cooperative, passengers or cargo-carrying air transportation services in metropolitan areas, leveraged by innovative aircraft, technologies, and business models [1, 2]. As a subset of the Advanced Air Mobility (AAM) that envisions a safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions, UAM focuses on short flight operations in and around urban areas to significantly reduce door-to-door travel time and uncertainty.

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The Federal Aviation Administration (FAA) released the Concept of Operations (ConOps) document for UAM to describe the envisioned operational environment that supports the expected growth of UAM operations and provide guidance to the UAM industry [3, 4]. In this document, the FAA proposed UAM Corridors, which are a performance-based airspace of defined dimensions in which aircraft abide by UAM specific rules, procedures, and performance requirements. It provided details about how the designated UAM Corridors would function and evolve over time. To characterize the evolution of UAM operations, the ConOps document described a framework defining initial, midterm, and mature state operations based on key indicators, including operational tempo, UAM structure (airspace and procedure), UAM-driven regulatory changes, UAM Cooperative Operating Practices (COPs), aircraft automation level, and location of the pilot in command (PIC). Based on the Unmanned Aircraft System (UAS) Traffic Management (UTM) paradigm, the Provider of Services for UAM (PSU) was also introduced for efficient data exchanges and information sharing between multiple UAM operators. In addition, the FAA emphasized the needs of the COPs (formerly known as Community Based Rules) which are industry-defined, FAA-approved practices that address how operators cooperatively manage their operations within the cooperative area for UAM, including conflict management, equity of airspace usage, and demand-capacity balancing. With these new concepts and the notional system architecture for a UAM ecosystem, more research and development are needed for both airspace design and airspace management services.

To support the development of airspace procedures and services for UAM operations and assess the FAA's UAM ConOps, NASA has conducted various simulations, called the X-series simulations. First, the "X1" simulations conducted in 2017-18 explored the roles and responsibilities of UAM stakeholders and investigated their information exchange requirements for the ATC-pilot communications using helicopter routes in Dallas/Fort Worth (DFW) urban area for initial UAM operations [5]. Following these simulations, NASA conducted the "X2" simulations with an industry partner in 2019 to see if the airspace operational volumes and data exchange protocols developed for UTM can be applied to the UAM operations in the shared airspace [6]. The next simulation called "X3" was virtually conducted in 2020 to assess airspace systems like PSUs developed by NASA and National Campaign (NC) partners [7, 8].

In 2021-22, NASA completed the "X4" simulations with industry airspace service partners to develop a strategic conflict management service for UAM operations and prepare for the NC-1 flight test [9-13]. In the X4 simulation, the strategic conflict management capabilities focused on the Demand-Capacity Balancing (DCB) of UAM operations at the shared airspace resources. For the DCB implementation, all participants, including NASA and partners, were required to develop or procure an airspace service that strategically scheduled operations to ensure that the demand at constrained resources did not exceed the given capacity. To conduct the collaborative simulations with multiple UAM operators, NASA designed a simulation system architecture for UAM operations that can integrate the software components developed by partners and establish a framework for the necessary foundational research into airspace construct design and air traffic management (ATM), considering the scalability and extensibility [12]. The overall architecture of the X4 simulation system was based on the notional UAM architecture defined in the FAA's UAM ConOps version 1.0 [3].

Following the X4 simulations, NASA continued to enhance the airspace services with more features and conducted independent simulations, called "X5", to test a PSU prototype that NASA developed for UAM flight planning, strategic conflict management support, and data exchange between UAM operators. The main objectives of the X5 simulation are:

- to evolve strategic conflict management capabilities for cooperative midterm to mature state operations,
- to test and validate requirements for PSU / airspace automation, and
- to develop a reference implementation of the UAM airspace system for future integration activities.

To achieve these objectives, the X5 simulation architecture and services were built upon the initial industry-vetted capabilities and testing environment from the X4 simulation. The airspace management capabilities embedded in the PSU include Demand-Capacity Balancing (DCB), as well as Sequencing and Scheduling (S&S). The X5 simulation approach also defined the information exchange between PSU and any other services for flight planning (i.e., initial Application Programmer Interfaces (APIs)) that may inform industry standards bodies such as ASTM International and EUROCAE. As part of X5 simulation activities, NASA prototypes were developed as a reference implementation to test the relevant requirements and APIs. Initial connection work between NASA and the FAA systems was also performed for testing future PSU-ATM interface requirements.

This paper will describe the system architecture designed for the X5 simulation activities, including brief descriptions about the airspace services developed for this simulation and the sequence diagram for the data flow between those services, in Section II. Then, Section III describes the X5 simulation environment, including airspace construct, traffic scenario, and configurations for simulation runs. The simulation results for evaluating the prototype

PSU will be provided in Section IV. Section V will summarize the achievements and lessons learned from this simulation activity.

II. System Architecture for X5 Simulation

This section describes a system architecture developed to support the X5 simulations, introduces various airspace services included in the system architecture, and explains a sequence diagram to exchange data between those services for strategic conflict management of UAM operations.

A. System architecture

As shown in Fig. 1, the system architecture for the X5 simulation is based on the UAM notional architecture in the FAA UAM ConOps v2.0 [4]. The X5 system architecture includes additional services needed to support strategic conflict management capabilities for UAM operations.

The X5 simulation architecture includes various services to represent UAM operators which generate and modify flight plans and monitor the status of planned flights, a prototype service of the FAA-Industry Data Exchange Protocol (FIDXP), prototype of a service providing UAM airspace structure and capacity information to UAM operators, third-party services for data exchange and flight/resource identification, other services to facilitate UAM strategic conflict management such as DCB and S&S, services for data collection and visualization, and UAM aircraft simulator.

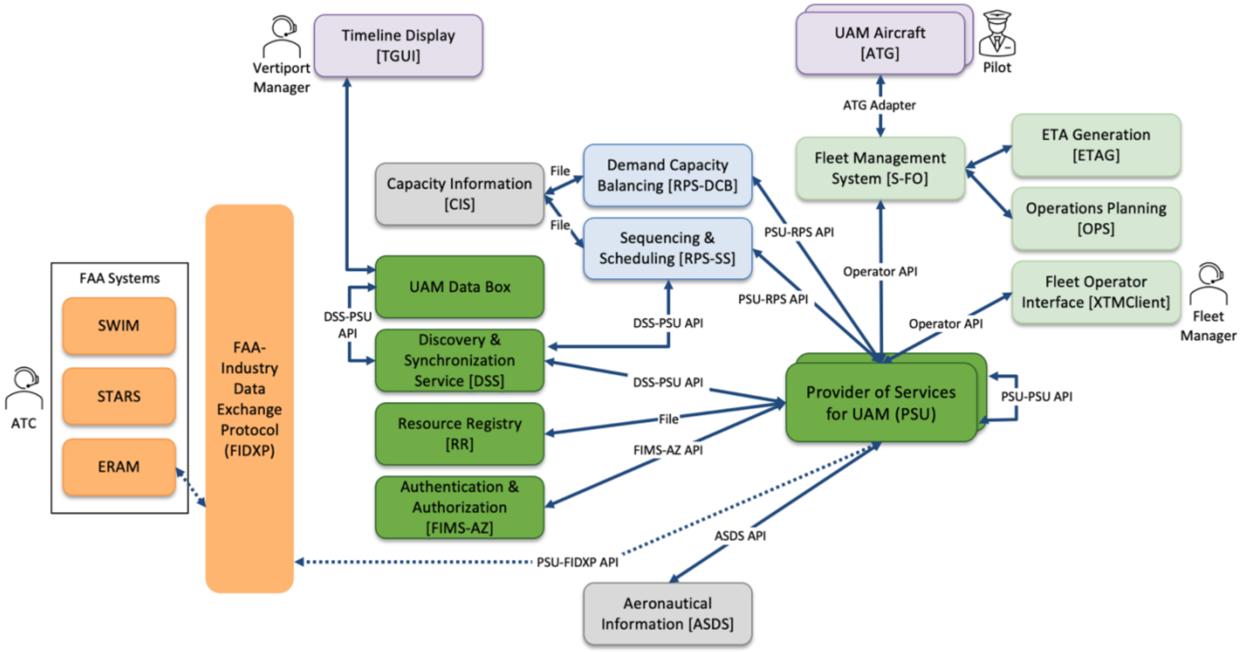

Fig. 1 System architecture for X5 simulations.

To facilitate how the information would be exchanged among PSUs and with other services, NASA developed and provided data model definitions and Application Programming Interfaces (APIs) that were made publicly available [14]. High-level descriptions of the main services are provided in the next subsections.

B. Airspace Services for flight management

1) Surrogate Fleet Operator (S-FO)

Surrogate Fleet Operator (S-FO) is a simulation tool for representing a Fleet Operator, which is intended to emulate the role of the flight management system/services for UAM operations. S-FO is meant to integrate various airspace services and traffic scenarios for UAM simulation and demonstration. S-FO is intended to act as an automatic system component, i.e., without a human actor and no Graphical User Interface (GUI) display. While this does not preclude having a GUI display, such display (S-FO Map Viewer) likely would be used to display flight status and set preferences, as the autonomous system expects S-FO to respond very quickly when managing its UAM flights.

2) Operations Planning Service (OPS)

Operations Planning Service (OPS) provides Fleet Operator with a feature to generate multiple operational plans for evaluation based on metrics (e.g., expected delay) due to constraints and availability of resources needed by an operation plan. OPS is a trial planning application used to schedule flights on a route, given a set of constraints. This service takes the availability windows at resources that a given flight is planning to use as its constraints and iterates on each scheduling point with delay assigned, until a given route sits within these windows.

3) ETA Generation service (ETAG)

ETA Generation service (ETAG) generates the Estimated Times of Arrival (ETA) at waypoints along the given route in the flight plan based on a UAM vehicle behavior model, considering aircraft performance (e.g., cruise speed, climb/descent rate), airspace construct design and procedure, and environmental conditions like wind. The current ETAG service assumes good weather conditions with no wind, using a standard atmosphere model.

4) Extensible Traffic Management Client (XTMClient)

Extensible Traffic Management Client (XTMClient) is a prototype flight management service for fleet operators that NASA developed for UTM research. It can be used for UAM research and the relevant simulations as a flight monitoring tool.

C. Strategic conflict management services

1) Resource Planning Service for Demand-Capacity Balancing (RPS-DCB)

Resource Planning Service for Demand-Capacity Balancing (RPS-DCB) provides a UAM Operator with the information and services for demand-capacity imbalance detection and resolution such as resource availability, constraints at resources, and pre-departure delay for resolving DCB issues as part of strategic conflict management capabilities. This service is based on the DCB algorithm proposed in [11].

2) Resource Planning Service for Sequencing and Scheduling (RPS-SS)

Resource Planning Service for Sequencing and Scheduling (RPS-SS) provides a UAM Operator with advisory services such as adjusted timings and speeds for an operation to meet sequencing criteria and spatial/temporal spacing constraints at airspace resources as part of strategic conflict management capabilities. In X5, this service provides the Scheduled Times of Arrival (STAs) at control waypoints and the destination vertiport, with the modified departure time for ground delay.

D. Services for data exchanges

1) Provider of Services for UAM (PSU)

Provider of Services for UAM (PSU) is an entity that provides services to the UAM Operator which help meet UAM operational requirements that enable safe, efficient, and secure use of the airspace [3, 4]. Multiple PSUs employed by different operators will be part of a network and subject to interoperability requirements. Within the UAM notional architecture, the PSU is a key component that serves several functions such as communication bridge in federated service network, analysis and confirmation of submitted operational intent, distribution of confirmed operational intent, support of cooperative separation management services, and operational data archiving.

2) Discovery and Synchronization Service (DSS)

For X5, a Discovery and Synchronization Service (DSS) built for UTM was used [15]. For UTM, the DSS allowed the UAS Service Supplier (USS) to identify relevant information that may be owned by another USS (“Discovery”), ensured that information was consistent across each USS (“Synchronization”), and supported strategic deconfliction by identifying operational volumes that intersect each other [16]. The same DSS functionalities were used in this UAM simulation.

3) Resource Registry (RR)

Resource Registry (RR) provides information about the registered identification of airspace resources such as origin/destination vertiports and waypoints for UAM Corridor entry/exit, merging, or crossing, upon request.

4) Flight Information Management System - Authentication and Authorization Service (FIMS-AZ)

Flight Information Management System - Authentication and Authorization Service (FIMS-AZ) ensures that access is provisioned to those permitted to obtain it. Leveraging the FIMS-AZ developed by NASA for UTM, it provides the method of authentication for all PSUs and other airspace services that are used by PSU (e.g., DSS, ASDS). It also allows UAM Operators to obtain an authorization prior to operating within the UAM Corridors inside controlled airspace like Class B/C/D airspace via the PSU.

E. Airspace information services

1) Airspace Structure Definition Service (ASDS)

Airspace Structure Definition Service (ASDS) is a simulation component that provides the information about airspace structures and vertiports in the target urban area, including information such as latitude, longitude, and altitude of waypoints and vertiports and performance requirements in the UAM Corridors. For X5, the simplified assumption was that such information would be made available to PSUs digitally to support UAM Operators on their operation planning, via the ASDS hosted by NASA.

2) Constraint Information Service (CIS)

Constraint Information Service (CIS) is a service responsible for providing constraint information such as vertiport capacity and sequencing dependencies on waypoints along the routes and supporting resource planning services for strategic deconfliction such as RPS-DCB and RPS-SS.

F. Other services and system components

1) Airspace Traffic Generator (ATG)

Airspace Traffic Generator (ATG) is NASA's simulation tool to generate the flying trajectories of aircraft used in various air traffic simulations at NASA [17]. These trajectories are used to virtually fly UAM aircraft from their origin to destination during a simulation. ATG runs as a separate software process and has its own set of API functions through which it communicates with other services.

2) FAA-Industry Data Exchange protocol Service (FIDXS)

The FAA-Industry Data Exchange Protocol (FIDXP) is part of the UAM Notional Architecture and is an interface for data exchange between FAA systems and UAM participants, managed by the FAA. This interface between the FAA and UAM stakeholders is a gateway such that external entities do not have direct access to the FAA systems and data. The FIDXS is used to file the flight plans for Visual Flight Rules (VFR) operations of the UAM flights to the FAA systems (e.g., System Wide Information Management (SWIM), Standard Terminal Automation Replacement System (STARS), and En Route Automation Modernization (ERAM)) and obtain a beacon code for the planned flight.

3) Timeline Graphic User Interface (TGUI)

Timeline Graphic User Interface (TGUI) is a web application that displays the relevant times of aircraft at a concerned scheduling point such as Estimated Time of Arrival (ETA) and Scheduled Time of Arrival (STA), which can be useful for vertiport manager.

G. Sequence Diagram

A high-level sequence diagram for initial flight planning in the X5 simulation is provided in Fig. 2. During the pre-departure scheduling phase, two main capabilities for strategic conflict management are considered sequentially, which are Demand-Capacity Balancing (DCB) and Sequencing & Scheduling (S&S). Note that the airspace services for fleet management described in Section II.B cover what Fleet Operator (FO) and FO Trial Planner (FO_TP) do in Fig. 2, while RPS-DCB and RPS-SS play the roles of DCB_X and SS_X, respectively.

When a customer requests a UAM service, Fleet Operator (FO), whose role is performed by the S-FO software in the X5 architecture, starts flight planning for this new trip. Given the trip request information, including departure and arrival vertiports, and desired departure time, FO tries to find a feasible flight schedule through PSU network, considering other flights that have already been scheduled or flying in the air. In this simulation environment, the flight planning includes 1) DCB at vertiports for takeoff and landing to ensure the traffic demand is at or below the given capacity and 2) S&S at control waypoints, such as entry/exit points at the controlled airspace boundary and cross/merging waypoints, to ensure sufficient spacing between aircraft for safety and to maintain air traffic controller workload at an acceptable level.

1) Demand-Capacity Balancing (DCB)

For a new flight, the FO first sends a request for available time windows at its origin and destination vertiports to the associated PSU. The PSU looks for a service registry in the Resource Registry (RR) to identify which services the PSU needs to contact. Once it receives the right contact information for DCB, the PSU makes a request for the available time windows to the DCB services for each vertiport of interest (i.e., DCB_X). The DCB service checks which time windows are available by comparing the existing demand for other flights with the capacity provided by CIS. When obtaining the available time windows at departure and arrival vertiport resources from DCB_X, the PSU passes the information to the FO. Based on the Estimated Times of Arrival (ETAs) at waypoints along the given route from ETA Generation service (ETAG), the FO calculates the estimated landing time at the destination and creates a proposed flight plan (or plans, if multiple scheduling and/or routing options are available), in which it usually selects the closest departure time to the desired departure time, if possible. FO's Trial Planner (FO_TP in Fig. 2 or Operations Planning Service (OPS) in Section II.B) checks whether the proposed plan(s) are feasible against the available time windows at the vertiports. If everything looks good, the FO submits its flight plan to the DSS via PSU and shares its operational intent with other operators through PSU network, after accepted by DSS.

2) Sequencing and Scheduling (S&S)

After going through the DCB process, the FO requests for sequencing and scheduling a few minutes before the departure time determined during the DCB. Once again, the PSU identifies the contact information for the appropriate S&S service(s) for this flight by looking them up in the RR. The PSU then asks the S&S service to compute the Scheduled Times of Arrival (STAs) at control waypoints. The S&S service assigns additional pre-departure delays to the flight until finding feasible STAs that satisfy all the sequencing and spacing constraints for avoiding any overtaking and the minimum separation violations with other flights. The PSU delivers the earliest STAs from the S&S service to the FO. Then, the FO updates its flight plan with the suggested STAs and submits it to the DSS for approval.

Note that the FO does not check the demand-capacity imbalances again after passing through the S&S in this study. In some cases, additional delay due to sequencing and spacing can cause DCB violation issues already set in the previous step. However, those violations would be allowed for efficient resource usage and scheduling, instead of undergoing too many iterations to meet all the constraints. As the first step of strategic conflict management, the DCB only functions to distribute demand into a wide range of time bins at the controllable level before applying the next strategic conflict management method (i.e., S&S).

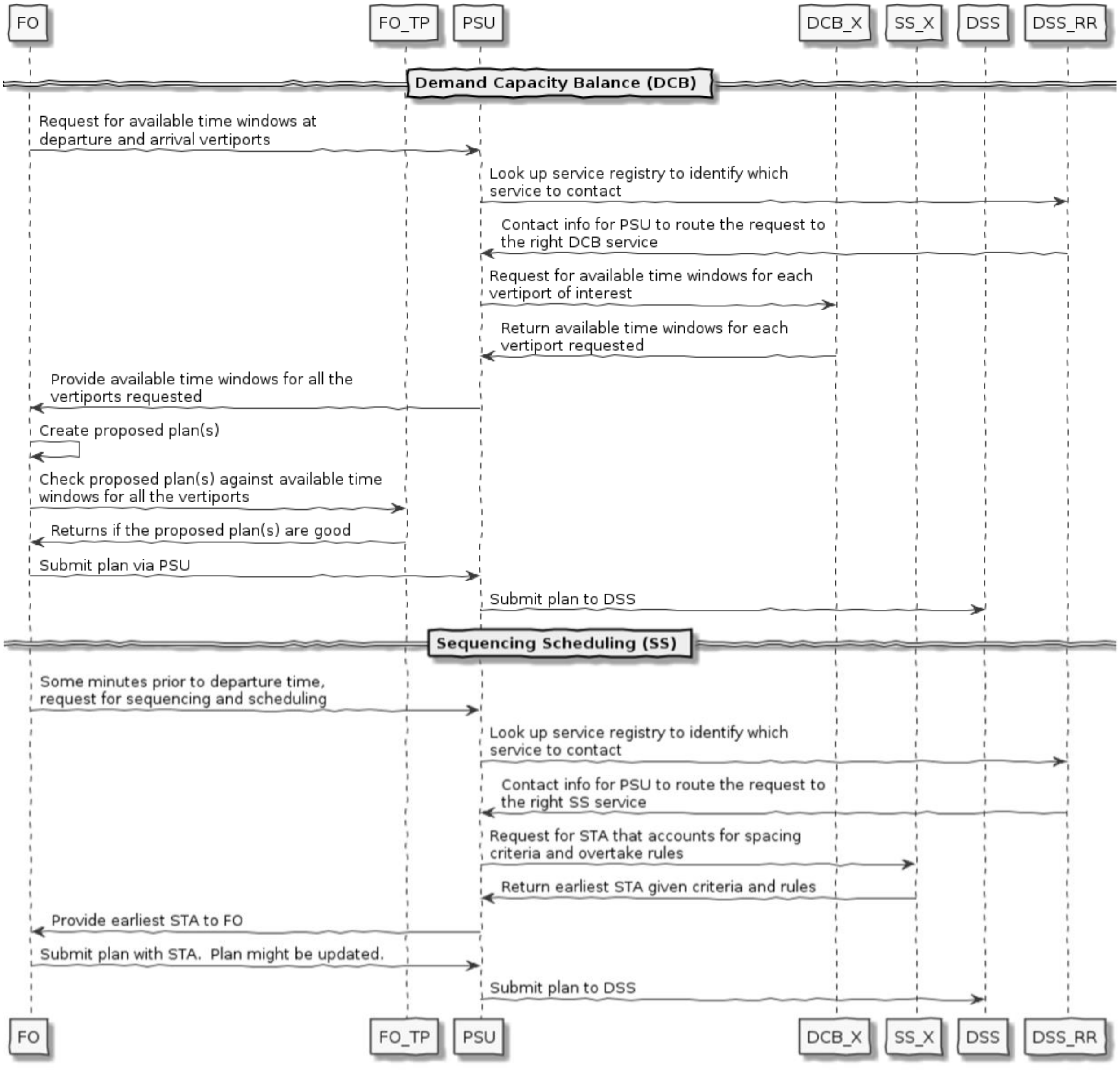

Fig. 2 Sequence diagram for X5 simulations.

III. X5 Simulation Setup

A. UAM airspace

As in the X4 simulations, the X5 simulations also look at a route network over the Dallas/Fort Worth (DFW) metropolitan area. The UAM airspace used in the X4 and X5 simulations includes notional corridors, tracks, vertiport locations, and arrival/departure procedures in DFW airspace. The airspace assumes conventional air traffic around DFW are operated in south flow only, which is a dominant configuration. The UAM airspace construct, i.e., corridors and tracks, were designed to deconflict UAM flights from traditional Instrument Flight Rules (IFR) operations and minimize the impact on Air Traffic Control (ATC) services.

A subset of vertiports and Origin-Destination (OD) pair routes connecting those vertiports in the given UAM airspace over DFW urban area were selected to explore both DCB and S&S functionalities for X5 simulations. Fig. 3 shows the selected 10 OD pair routes with 7 vertiports whose names start with "DF" used in the simulation. The blue and black directed lines in the figure show the predefined routes to connect vertiports, with the waypoints shown in orange or magenta balloons. Table 1 shows the list of these routes, with the control waypoint for spacing and the flight time from origin to destination along the pre-defined route, assuming a cruise speed of 120 knots.

The capacity at vertiports for DCB is assumed to be 2 operations per 12-minute time bin. At each vertiport, simultaneous operations for takeoff and/or landing are also allowed in the flight planning phase. For the sequencing and spacing, a 2-minute temporal spacing constraint is applied at 4 control waypoints at the boundary of Class B controlled airspace (shaded in light green color in Fig. 3), which are EB002, EB003, TF024, and TF027. The other waypoints, EB011 and EB012, were excluded because they would be excessive constraint points. Note that these 4 control waypoints do not have a capacity constraint for DCB. All the simulated flights are based on a single aircraft model, flying at the same speed in each flight phase. In addition, sequencing constraints at key waypoints for merging and/or crossing were carefully defined and applied to prevent the flights having different OD pairs from overtaking each other on the common route segments. The detailed descriptions about the UAM airspace design assumptions, procedures, and analyses for the DFW urban area can be found in [12, 18].

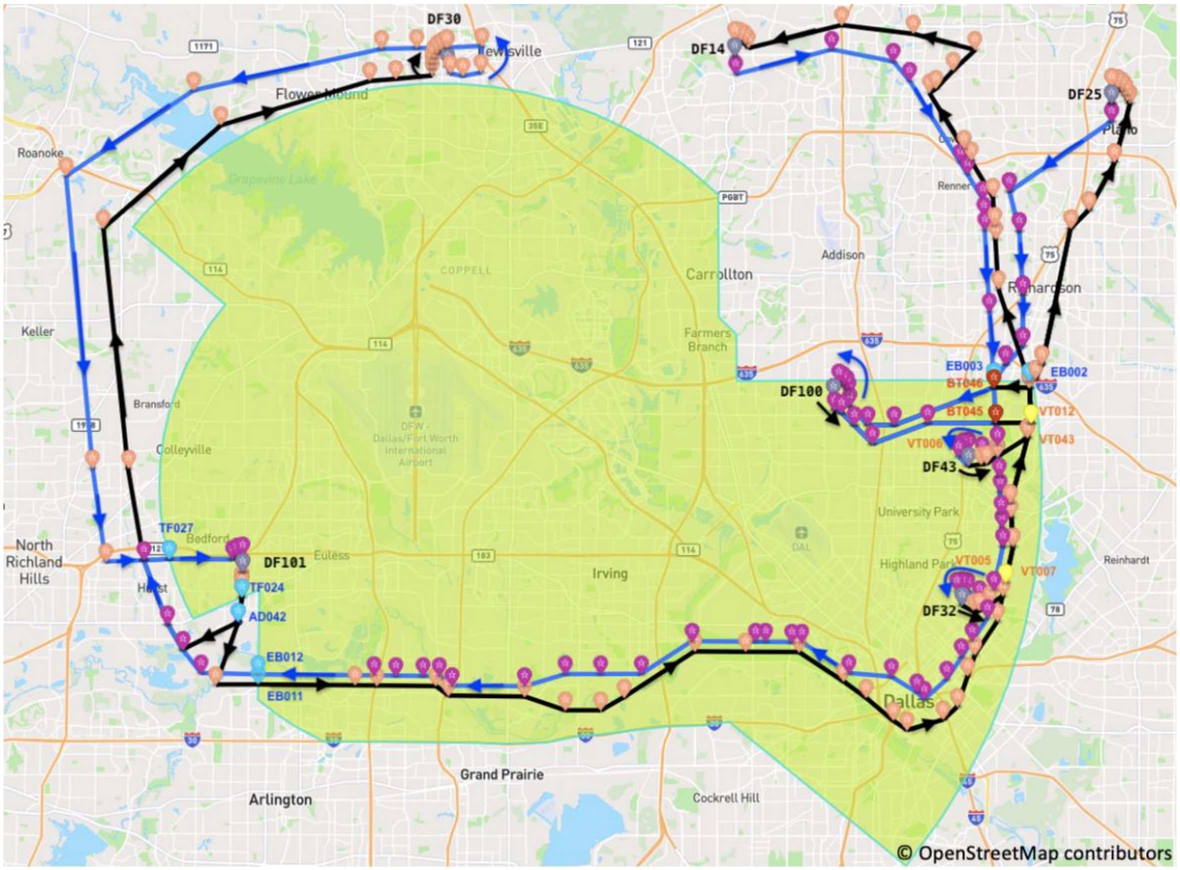

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Fig. 3 Route network in DFW airspace for X5 simulations.

Table 1: Origin-destination pair routes used in X5 simulations.

No	Origin	Destination	Waypoint for Spacing	Flight Time [min]
1	DF14	DF43	EB003	10.1
2	DF25	DF32	EB003	10.7
3	DF25	DF100	EB003	10.5
4	DF30	DF101	TF027	17.8
5	DF32	DF25	EB002	11.2
6	DF43	DF14	EB002	12.6
7	DF100	DF25	EB002	11.2
8	DF100	DF101	TF027	24.7
9	DF101	DF30	TF024	15.7
10	DF101	DF100	TF024	25.4

B. Traffic scenario

The traffic scenario for this simulation was designed to test both DCB and S&S capabilities for midterm UAM operations defined in [4]. It is assumed that two UAM operators share the airspace resources such as vertiports and control waypoints for S&S while their flights are operated in the given 10 OD pair routes covering the DFW urban area. The traffic demand should have sufficient flights to cause demand-capacity imbalances at vertiports, which can be resolved by assigning pre-departure delay. The number of flights should also be high enough to cause potential loss of separation at control waypoints for S&S, expecting additional pre-departure delay due to sequencing and spacing. To represent the midterm traffic density, the traffic scenario should have tens of simultaneous operations in the air during a peak.

While meeting all the considerations mentioned above, the traffic scenario was generated to have 40 flights in total for 1.5-hour long simulation. Each operator was assigned 20 operations, which were evenly distributed among 10 routes connecting 7 vertiports (i.e., 2 operations per route for each operator), with different desired departure times.

C. Simulation configurations

For the X5 simulations, various airspace services introduced in Section II were set up and run on multiple machines, while exchanging the necessary data through APIs. To model a federated operational environment, two NASA PSUs and Fleet Operators (S-FOs) were run, with the associated OPS and ETAG for each operator. A single RPS-DCB was activated to cover the demand-capacity balancing at 7 endpoints (i.e., vertiports), and one RPS-SS to schedule the flights at 4 endpoints (i.e., control waypoints for S&S), while meeting the 2-minute minimum separation requirements and sequencing criteria. The X5 simulation system had the RR with the updated endpoint addresses and the CIS with all vertiport capacity definitions in static file format. To support UAM flight planning, ASDS, FIMS-AZ, and DSS were also run. XTMClient, S-FO Map Viewer, and Timeline GUI (TGUI) at waypoints of interest were used for flight monitoring during the simulation.

The X5 simulation was conducted to test both DCB and S&S capabilities for strategic conflict management under various configurations of parameters controlling the airspace services on a microscopic level. There are 3 parameters tested in this simulation, which are 'DCB Lead Time', 'S&S Lead Time', and 'Max Delay' causing a flight cancellation. In the baseline case (Case #3), DCB is implemented 6 minutes before the desired departure time, as defined with industry partners during the X4 simulation. Then, S&S function is applied 1 minute before the scheduled departure time in which DCB was already considered. In this case, S&S is considered pre-tactical, accounting for the latest operational conditions before requesting a takeoff clearance. If the assigned delay to resolve both DCB and S&S issues is greater than 1 hour, the flight is cancelled with the assumption it would no longer meet the customer's needs. By adjusting the parameter values, DCB and S&S functions can be turned on or off. Setting the temporal spacing value in the RPS-SS to be zero, for example, could be equivalent to running the system with only RPS-DCB turned on (Case #1). Similarly, setting a large capacity in RPS-DCB would appear to skip DCB and apply S&S only (Case #2). In addition, the scheduling gap between DCB and S&S can be removed, which means that the S&S function can be performed right after DCB is run (Case #4). The parameters set in the four different test cases are summarized in Table 2.

Table 2: Description of test cases in X5 simulations.

No	Configuration	DCB Lead Time	S&S Lead Time	Max Delay
Case 1	DCB only	6min before departure time	Off (0sec spacing)	1 hour
Case 2	S&S only	Off (large capacity)	1min before departure time	1 hour
Case 3	DCB, then S&S	6min before departure time	1min before new departure time modified by DCB	1 hour
Case 4	DCB, then S&S without gap	6min before departure time	Immediately after DCB	1 hour

IV. Simulation Results

This section will present the data analysis results from the X5 simulations. The metrics used for evaluating the proposed strategic conflict management approaches for UAM operations include the number of operations (submitted, activated, and operated), the number of demand-capacity imbalances detected and resolved, the pre-departure delays assigned to aircraft due to DCB and S&S (e.g., number of delayed flights, total delay, and average delay), and the airspace throughput (i.e., number of simultaneous operations in the air over simulation time).

A. Number of operations

In the given traffic scenario, there are 40 flights in total, which are equally distributed between two operators (i.e., 20 flights for each operator). Depending on the status in scheduling process, there are 4 flight states: Planned, Accepted, Activated, and Closed. A flight initially created is in 'Planned' state. After it is validated by DCB and S&S and accepted by DSS, its state changes to 'Accepted'. Once the flight takes off from its origin vertiport, the state becomes 'Activated'. Then, it changes to 'Closed' state after landing at its destination vertiport. Table 3 shows the number of operations in each flight state by test cases. Among 40 flights in the scenario, only one flight is cancelled during the simulation due to 1-hour maximum delay limit by operator. The large delay for this flight comes from DCB. So, the Case 2 where DCB is not applied doesn't have any cancelled flights. When the 'Max Delay' parameter was increased to 2 hours, we could see that all the flights were accepted and activated without any cancellation, with the maximum delay of 67.65min.

Table 3: Number of operations by test cases in X5 simulations.

No	Configuration	Planned	Accepted	Activated	Closed
Case 1	DCB only	40	39	39	39
Case 2	S&S only	40	40	40	40
Case 3	DCB, then S&S	40	39	39	39
Case 4	DCB, then S&S without gap	40	39	39	39

B. Number of demand-capacity imbalances detected and resolved

When developing the traffic scenario tested in this simulation, flights were intentionally scheduled to have a peak within 30 minutes so that the proposed strategic conflict management capabilities can be assessed. Fig. 4 shows the heatmaps of the observed traffic for the different test cases. In the heatmaps, the horizontal axis shows 10 time bins where each bin represents a 12-minute interval, and the vertical axis shows 7 vertiports. The value in each cell indicates the number of operations assigned to the 12-min time bin at a specific vertiport, including both departures and arrivals. The simulation results show that the traffic demand was properly distributed and met the given capacity constraints by assigning the associated pre-departure delay, in case that DCB is applied (Cases 1, 3, and 4). When the S&S is only applied (Case 2), the resultant heatmap in Fig. 4(b) shows many DCB violations where the demand exceeds the given capacity. This heatmap is similar to the original flight schedule's heatmap because of small pre-departure delays assigned, but the modified schedule satisfies the minimum separation requirements and the sequencing constraints.

In Case 3, S&S follows DCB with a scheduling gap. S&S slightly adjusts the flight schedule modified by DCB once again to consider sequencing constraints at merging/crossing waypoints and meet the minimum separation requirements 1 minute before takeoff. Due to this time gap between DCB and S&S, additional delay applied by S&S can cause a DCB violation. In Fig. 4(c), such a DCB violation is found in time bin #7 at DF101 because other two flights have already occupied this time bin by DCB when S&S applies additional delay to a flight that was assigned in time bin #6 by DCB. In Case 4, on the other hand, S&S is applied right after DCB, with no scheduling gap. That is, the departure time is adjusted to meet the sequencing and spacing constraints and fixed earlier than in Case 3. Then, the following flights would fill in the remaining time slots for DCB one by one, resulting in no DCB violations as shown in Fig. 4(d). However, this case may not address the uncertainties in actual operational environment accordingly since the departure schedule is determined too early.

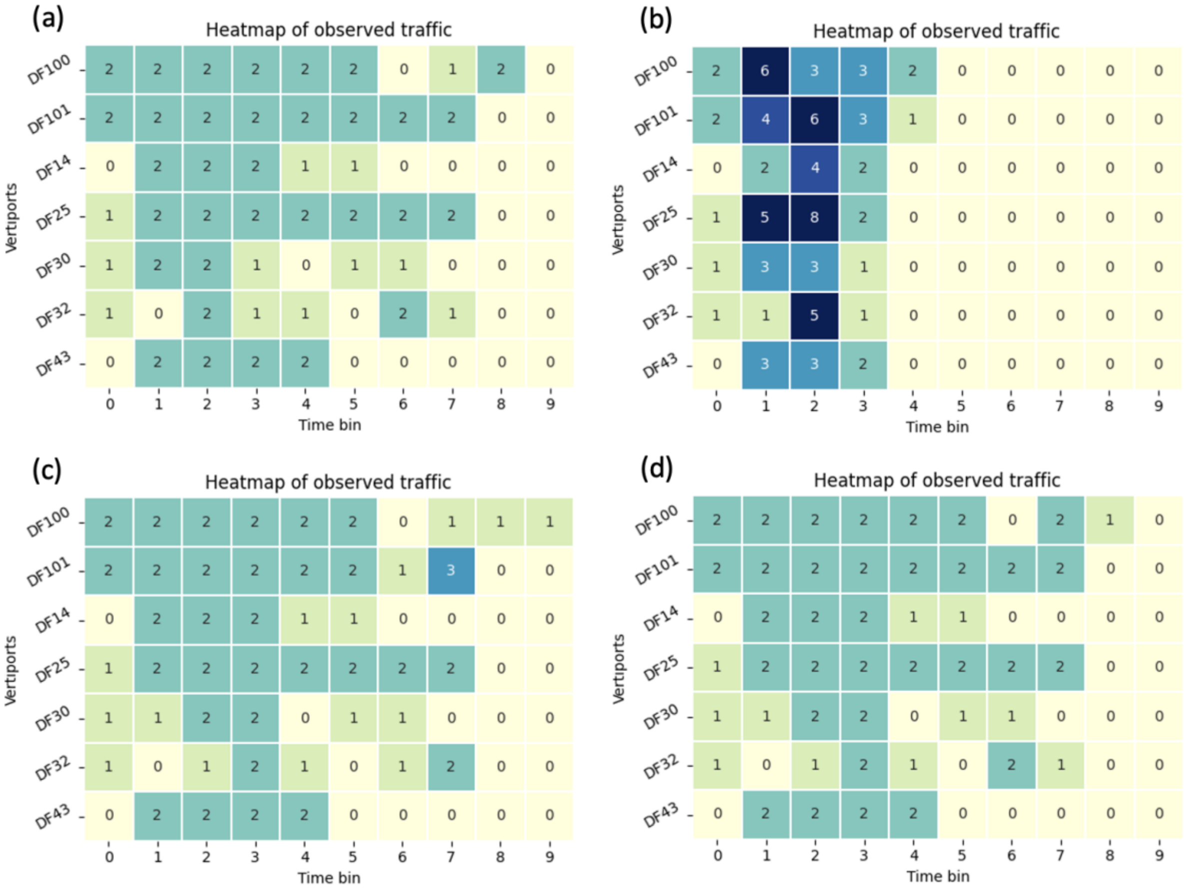

Fig. 4 Traffic demand heatmaps for Demand-Capacity Balancing. (a) Case 1 (DCB only), (b) Case 2 (S&S only), (c) Case 3 (DCB, then S&S), (d) Case 4 (DCB, then S&S without a scheduling gap).

C. Ground delay

In this simulation, pre-departure ground delays are assigned by DCB and S&S sequentially to resolve demand-capacity imbalances and satisfy sequencing and spacing criteria. Table 4 shows the sum of delays due to DCB and S&S, the number of delayed flights, and the average delay of these flights in four different test cases. When DCB is activated (Cases 1, 3, and 4), considerable delays are observed due to the packed demand in the given traffic scenario and the low vertiport capacity. When S&S only is active (Case 2), a relatively small amount of delay is allocated per flight. When DCB and S&S are sequentially applied with a scheduling gap (Case 3), most ground delays are assigned, compared to other cases. In this case, most delays (98.2%) come from DCB and are applied to 25 flights (64.1%) out of 39 activated flights. On the other hand, S&S adds a small amount of ground delay for 9 flights to meet the minimum separation requirements 1 minute before takeoff at pre-tactical level. If the S&S is applied right after DCB (Case 4), the total delay is reduced because flights would fix their departure times on a First-Come, First-Served basis, preventing later flights from occupying the earlier slots for DCB and changing departure sequences for S&S.

Fairness between operators in scheduling is not the focus in this simulation, but it is observed that in Case 3, for example, Operators 1 and 2 have an equal number of delayed flights (14 flights in each operator) with a similar level of delay assignment (i.e., 23.7 min/flight and 27.6 min/flight of average delay for Operator 1 and 2, respectively). Similar trends were observed in other cases. However, the amount of delay assigned by scheduling algorithms may depend upon the initial flight schedule, flight plan submission time, and delay allocation method, which would be one of the interesting future research topics for efficient and equitable UAM operations.

Table 4: Pre-departure ground delay by test cases in X5 simulations.

No	Configuration	DCB delay	S&S delay	Total delay	Average delay
Case 1	DCB only	704.3 min for 25 flights	N/A	704.3 min for 25 flights	28.2 min
Case 2	S&S only	N/A	61.6 min for 26 flights	61.6 min for 26 flights	2.4 min
Case 3	DCB, then S&S	705.7 min for 25 flights	13.0 min for 9 flights	718.6 min for 28 flights	25.7 min
Case 4	DCB, then S&S without gap	687.5 min for 25 flights	11.0 min for 8 flights	698.5 min for 28 flights	24.9 min

D. Number of simultaneous operations

Fig. 5 shows the number of simultaneous operations over the simulation time for each test case. When DCB is applied (Cases 1, 3, and 4), it is observed that 13 flights are flying simultaneously at peak over the given route network. In this traffic scenario, Operator 1 and Operator 2 have at most 8 and 7 concurrent flights, respectively. There are no significant differences between these cases. However, when only S&S is applied (Case 2), the traffic pattern is totally different. This case has much higher number of concurrent flights in the air (up to 24 operations) within the half simulation time to complete all the operations because of the even shorter ground delay as shown in Table 4.

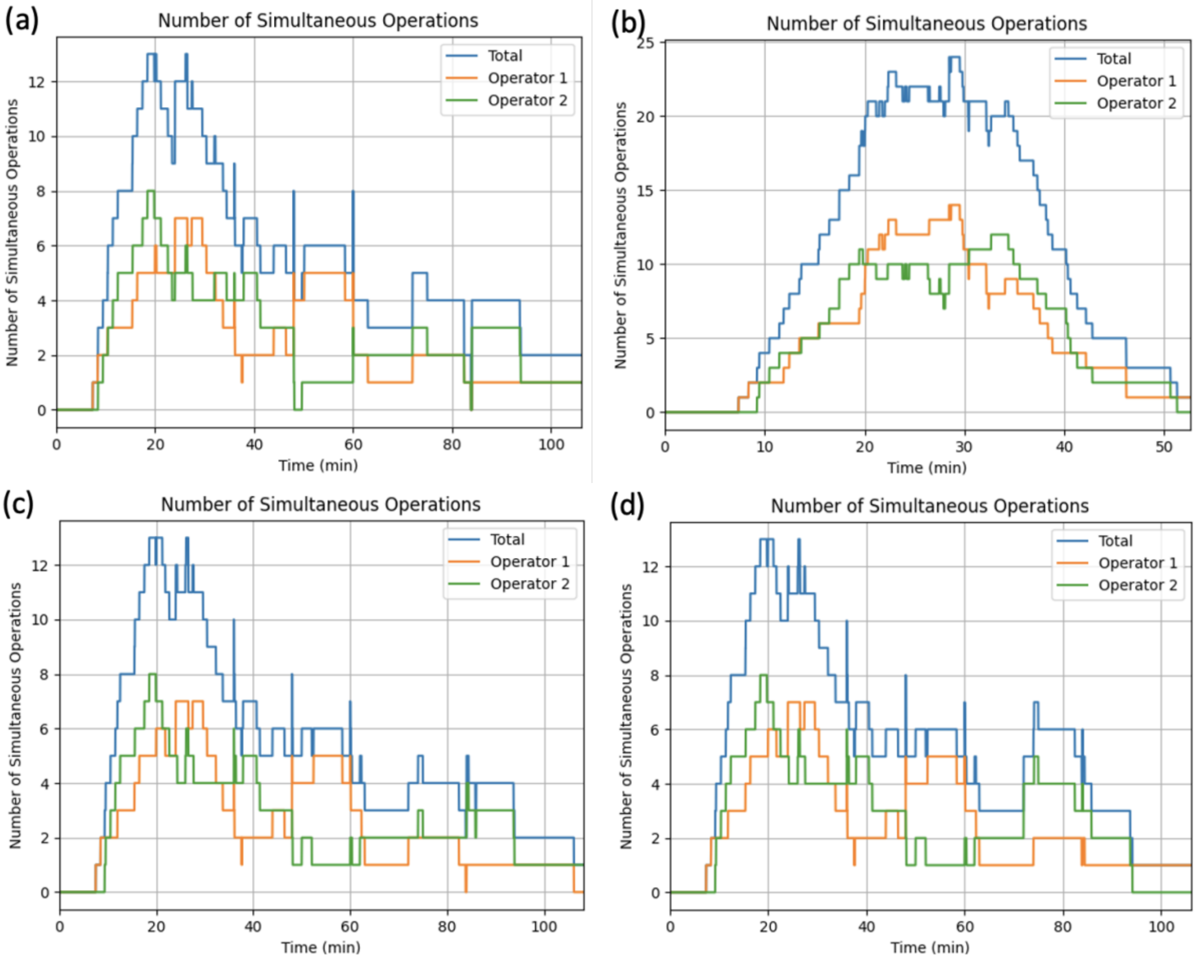

Fig. 5 Number of simultaneous operations in the air over simulation time. (a) Case 1 (DCB only), (b) Case 2 (S&S only), (c) Case 3 (DCB, then S&S), (d) Case 4 (DCB, then S&S without a scheduling gap).

V. Conclusions and Future Work

To evaluate the UAM concept of operations and support the development of UAM airspace procedures and services, NASA developed the PSU prototype and conducted simulations to test it. For this simulation, NASA developed a reference architecture for the UAM airspace system aligned with the FAA's notional architecture and evaluated two types of strategic conflict management methods, Demand-Capacity Balancing (DCB) and Sequencing & Scheduling (S&S), in a simulation environment to represent UAM operations in Dallas/Fort Worth urban area.

In this simulation, four different configurations, DCB only, S&S only, DCB followed by S&S with and without a scheduling gap, were simulated and compared to evaluate the interoperability of DCB and S&S functions for strategic conflict management of UAM operations. The simulation results verified that DCB and S&S functions worked well as expected to resolve imbalances of demand and capacity at shared resources by multiple UAM operators and to satisfy sequencing and spacing criteria at enroute control waypoints. However, the current DCB algorithm assigned large ground delay, leading to the inefficient use of airspace resources. Therefore, advanced DCB algorithms, including aircraft speed control and schedule optimization over the whole network, need to be explored. Also, the result of the S&S only showed shorter ground delays and higher throughput, but caused many DCB violations, which may lead to more tactical separation provisions in the air.

While combining DCB and S&S sequentially, there was an issue about when the S&S should be applied within the scheduling time horizon. Further studies are required to obtain answers about how different strategic conflict management approaches can work effectively and how the strategic conflict management for UAM operations can be integrated with tactical separation provisions such as handoff timing, decision point for replanning in case of non-conforming, and conflict resolution methods (e.g., speed control) when the increasing traffic demand cannot be managed by the strategic conflict management approach only.

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