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Provider of Services for Urban Air Mobility (PSU) Prototype Simulation (X5) Final Report

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Executive Summary

Urban Air Mobility (UAM) is a new air transportation service concept to carry passengers or cargo in metropolitan areas, leveraged by innovative aircraft and air traffic automation technologies. NASA has conducted a series of simulations, called the X-series simulation, to evaluate the UAM concept of operations and support the development of airspace procedures and services for UAM operations. The simulation called "X5" was conducted in 2023 to test a Provider of Services for UAM (PSU) prototype developed by NASA for UAM flight planning, strategic conflict management support, and data exchange between UAM operators. In this simulation, two strategic conflict management capabilities, Demand-Capacity Balancing and Sequencing and Scheduling, were further investigated. This document describes the UAM system architecture modeled, the X5 simulation environment to be executed (e.g., traffic scenario and UAM airspace construct), and the strategic conflict management processes developed and evaluated in this study. Then, the simulation results are provided using several system performance metrics, such as the number of operations planned and activated, demand-capacity imbalances detected and resolved, and pre-departure delays. Based on these metrics, the test findings and lessons learned from this simulation are discussed.

NASA developed a PSU prototype as part of a reference implementation of UAM system architecture and evolved strategic conflict management capabilities for UAM operations from the previous collaborative simulations with industry partners. Below is the summary of the achievements:

- Aligned NASA's UAM reference architecture with the FAA's UAM ConOps notional architecture
- Extended UAM airspace management capabilities to include 1) Demand-Capacity Balancing (DCB) to ensure operators coordinate planned usage of shared vertiports, and 2) Sequencing and Scheduling (S&S) at UAM corridor entry and exit points to help facilitate an orderly flow of traffic
- Defined the PSU information exchange APIs and requirements towards informing industry standards
- Developed and tested a NASA PSU prototype as reference implementation to validate the requirements and APIs
- Developed a prototype service connecting NASA's PSU and the FAA system for testing future PSU-ATM interface requirements
- Tested NASA-developed assumptions for UAM operations such as airspace design, procedures, vehicle performance, and strategic conflict management methods to inform future Cooperative Operating Practices (COPs) development with industry
- Evaluated system performance metrics such as number of simultaneous operations and ground delays that can help define system-level requirements. The simulation results showed that the UAM traffic demand could be managed to minimize the needs of tactical separation provision with ground delays assigned by DCB and S&S.

These accomplishments and the lessons learned from the PSU Prototype X5 simulation activities will be valuable inputs for the Air Mobility Pathfinders (AMP) project, which is NASA's new project to create and evaluate a reference architecture for safe, secure, and scalable UAM operations.

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1 Background

Urban Air Mobility (UAM) is an emerging concept that envisions highly automated, cooperative, passenger or cargo-carrying air transportation in metropolitan areas, enabled by innovative aircraft, air traffic technologies, and business models [1, 2]. UAM focuses on short flight operations in and around urban areas to reduce door-to-door travel time and uncertainty, compared to ground transportation alternatives.

The Federal Aviation Administration (FAA) released a UAM Concept of Operations (ConOps) document 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 (and the more general term, 'Cooperative Area'), which are performance-based airspaces of defined dimensions in which aircraft abide by UAM-specific rules, procedures, and performance requirements. The FAA UAM ConOps provides details about how the proposed UAM Corridor concept would function and evolve over time. To characterize the evolution of UAM operations, the ConOps document describes a framework defining initial, midterm, and mature state operations based on key indicators, including operational tempo, UAM structure (airspace and procedures), UAM-driven regulatory changes, UAM Cooperative Operating Practices (COPs), aircraft automation level, and location of the pilot in command (PIC). Based on the NASA-developed Unmanned Aircraft System (UAS) Traffic Management (UTM) paradigm, the Provider of Services for UAM (PSU) was introduced for efficient data exchanges and information sharing between multiple UAM operators. The FAA ConOps also emphasizes the need for COPs (formerly Community Based Rules (CBRs)) which are industry-defined, FAA-approved practices that address how operators cooperatively manage their operations within UAM cooperative areas, including conflict management, equity of airspace usage, and Demand-Capacity Balancing (DCB). With these new concepts and the notional system architecture for a UAM ecosystem, more research and development are needed for both effective UAM airspace design and cooperative 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 a series of 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 communications between air traffic controller and pilot using helicopter routes in the Dallas-Fort Worth (DFW) metropolitan 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 UAM operations in the shared airspace [6]. The next simulation called "X3" was 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 DCB of UAM operations at capacity-constrained, shared airspace resources (e.g., vertiports). For the DCB implementation, all participants, including NASA and partners, were required to develop (or procure from an external source) an airspace service that strategically scheduled operations to ensure that the demand at constrained resources did not exceed the given capacity. To conduct collaborative simulations with multiple UAM operators, NASA designed a simulation system implementation of the notional UAM architecture introduced in the FAA UAM ConOps version 1.0 [3]. The simulation system for X4 allowed for integration of software components developed by NASA and partners and established a framework for the necessary foundational research into airspace construct design and air traffic management, considering scalability and extensibility [12].

2 PSU Prototype Simulation Overview

NASA developed a reference architecture of the UAM airspace management system, implemented a PSU prototype for testing and evaluation, and improved existing strategic conflict management capabilities for cooperative midterm UAM operations.

2.1 Objectives

Following the Strategic Conflict Management X4 simulation, NASA continued to enhance the existing airspace services and introduce additional functions. These airspace services were implemented in a PSU prototype and intended for evaluation within NASA's "X5" UAM simulation environment to support evaluation of UAM flight planning, strategic conflict management, and data exchange between UAM operators. The main objectives of the X5 simulation are:

1. To evolve strategic conflict management capabilities for cooperative midterm to mature state operations,
2. To test and validate requirements for PSU / airspace automation, and
3. To develop a reference implementation of the UAM airspace management system for future integration activities based on the UAM notional architecture from the FAA UAM ConOps.

To achieve these objectives, the 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 prototype include Demand-Capacity Balancing (DCB) and Sequencing and Scheduling (S&S). The simulation approach also defined the information exchange between PSU and other services for flight planning (i.e., initial APIs) that may inform developing industry standards (e.g., ASTM). NASA prototypes were developed as reference implementations to test requirements and APIs. An initial connection between NASA and the FAA systems was also set up for testing future PSU-ATM interface requirements.

2.2 Proposed UAM Architecture

The FAA published the UAM ConOps v2.0 [4] in 2023, which described the envisioned operational environment that supports the expected growth of flight operations in and around urban areas. The ConOps v2.0 document served as an initial guideline for this simulation. One of the main objectives of this simulation was to ensure alignment with the FAA's UAM notional architecture (shown in Figure 1). The UAM notional architecture, therefore, was used as a basis for the airspace management system architecture.

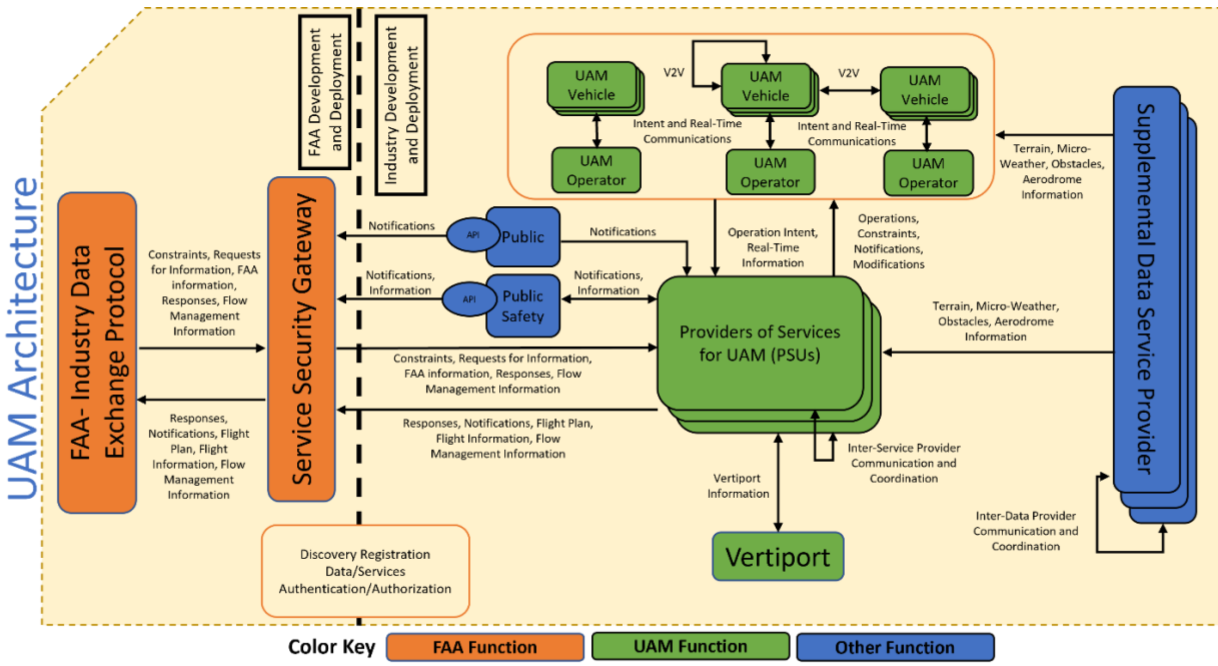

Figure 1 Notional UAM Architecture from FAA UAM ConOps [4]

While the UAM notional architecture served as the starting point for this simulation, the final simulated architecture for X5 included more refined capabilities to define the "Provider of Services for UAM (PSU)," as well as other services and technologies needed to support strategic conflict management (SCM) for UAM operations. Section 3.1 describes the X5 simulation architecture in more detail, including these refined capabilities, that can be used for future collaboration activities with potential industry partners.

2.3 Assumptions for the Simulated Environment

The PSU Prototype (X5) simulations were conducted based on a set of common assumptions on the airspace and vertiport environment, weather conditions, vehicles, and communications related to UAM Operators, PSU, and Air Traffic Control (ATC). These assumptions were the same as the ones used in the Strategic Conflict Management X4 simulation [12], as shown in Figure 2. Note that the interactions between UAM Operator and ATC tower at busy airports were simulated and explored in NASA's separate experiment, called ATM Interoperability Simulation (AIS) [13].

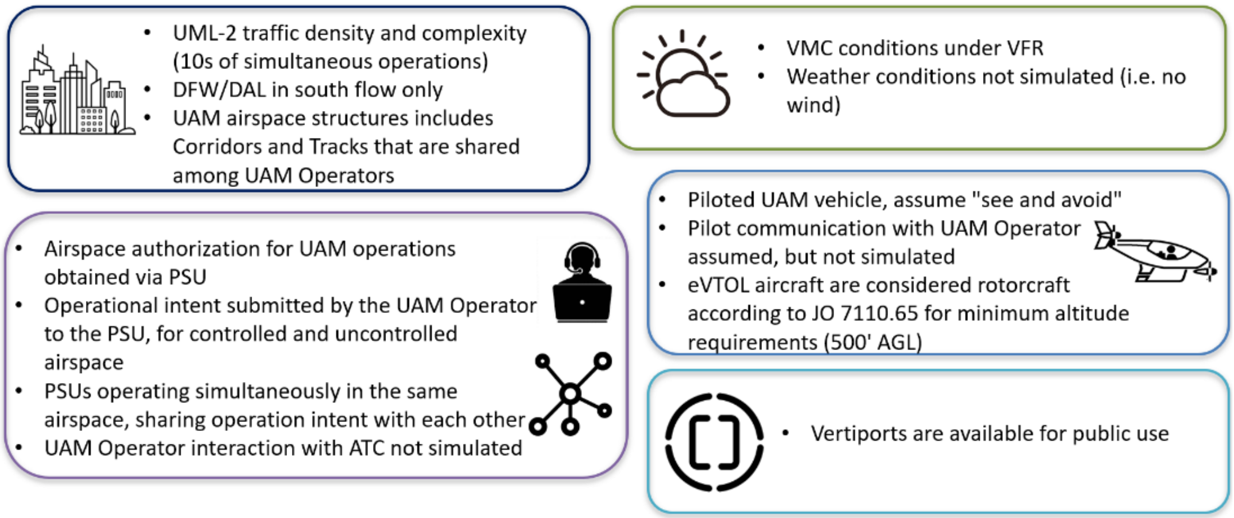

Figure 2 High-Level Assumptions [12]

2.4 Proposed UAM Airspace and Procedures

This section describes specific UAM airspace and procedures in the Dallas-Fort Worth metropolitan area, which were developed during X4 and used for X4 and X5. For a detailed description of the DFW airspace design assumptions and analysis, refer to References [12, 14].

The UAM airspace used in the PSU Prototype (X5) simulation included notional corridors, tracks, vertiport locations, arrival and departure procedures in the Dallas-Fort Worth metropolitan area, including airspace around airports such as Dallas-Fort Worth (DFW), Dallas Love Field (DAL), and Addison (ADS). The simulated airspace assumed traditional traffic around DFW were operating in ‘south flow’ configuration only in which DFW operates predominantly (i.e., DFW arrivals landing to the south). The UAM airspace construct, i.e., corridors and tracks, was designed to minimize impact on air traffic services and to minimize interactions with traditional IFR operations.

Figure 3 shows the airspace constructs and vertiport locations used in this simulation within the DFW Class B airspace. The given airspace constructs included 20 vertiports inside Class B airspace and another 14 vertiports in Class E/G (not shown in the graphic). All corridors included bi-directional tracks that were separated laterally by 1,500 ft, and 750 ft from the edge of the corridor, making the width of the corridor 3,000 ft, as shown in Figure 3. Corridors and tracks were designed for Class B airspace only. For operations within the uncontrolled airspace like Class E and G airspace, a pre-defined UAM airspace construct was not required, but for simplicity of simulation, NASA created potential routings between vertiports for operational planning. Extended corridor around Dallas downtown (shaded in dark brown color) was designed to allow flights to reposition between close-by vertiports without ATC permission. Within the extended corridor, it was assumed that there is one frequency where pilots can announce their arrivals and departures so that they would visually separate from other flights.

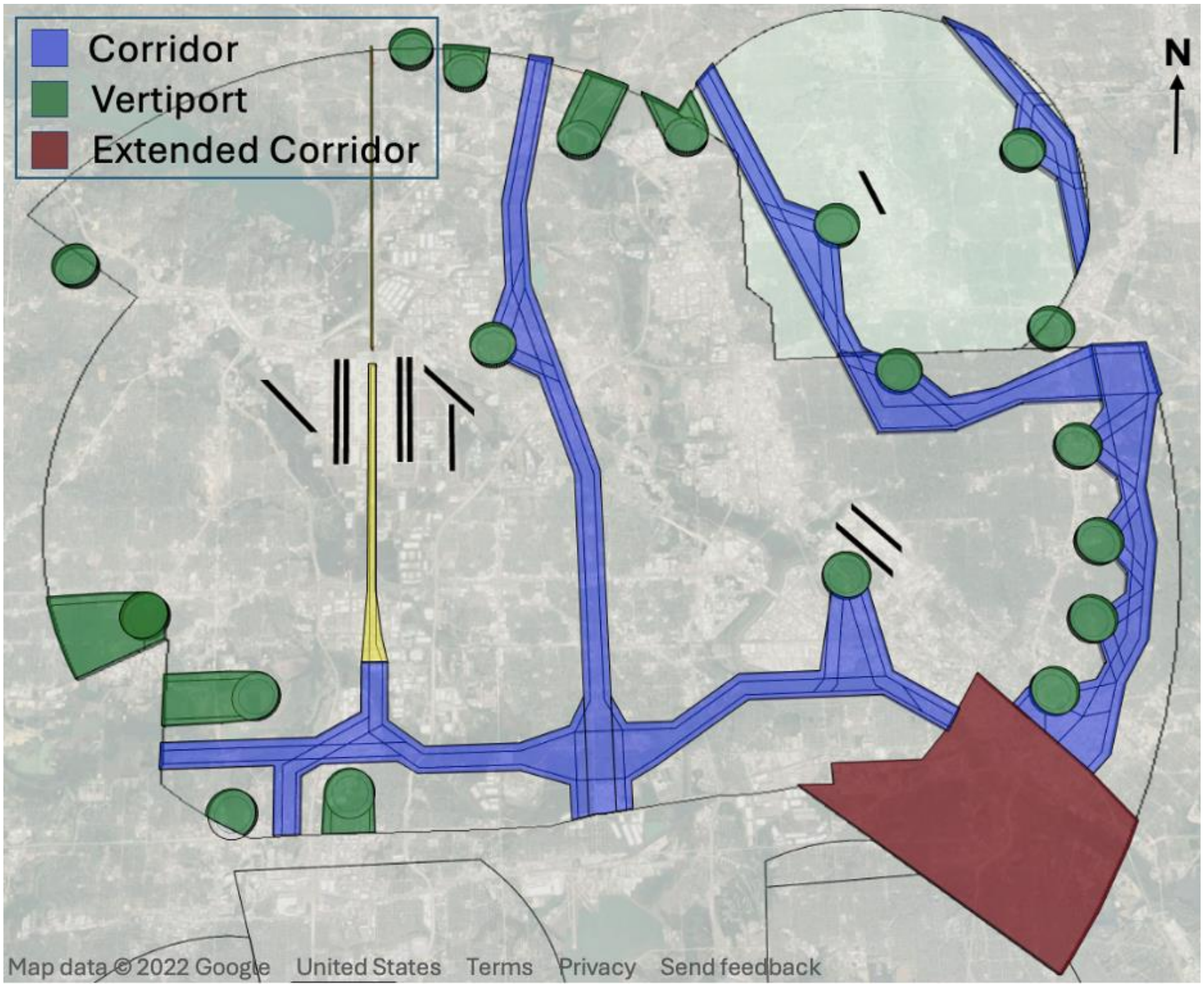

Figure 3 UAM Corridors and Vertiport Locations used in This Simulation

3 PSU Prototype (X5) Simulation Development

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

3.1 UAM System Architecture for PSU Prototype (X5) Simulation

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

The UAM system architecture includes services to represent UAM operators that generate and modify flight plans and monitor the status of planned flights, a prototype service of the FAA-Industry Data Exchange Protocol (FIDXP), a 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.

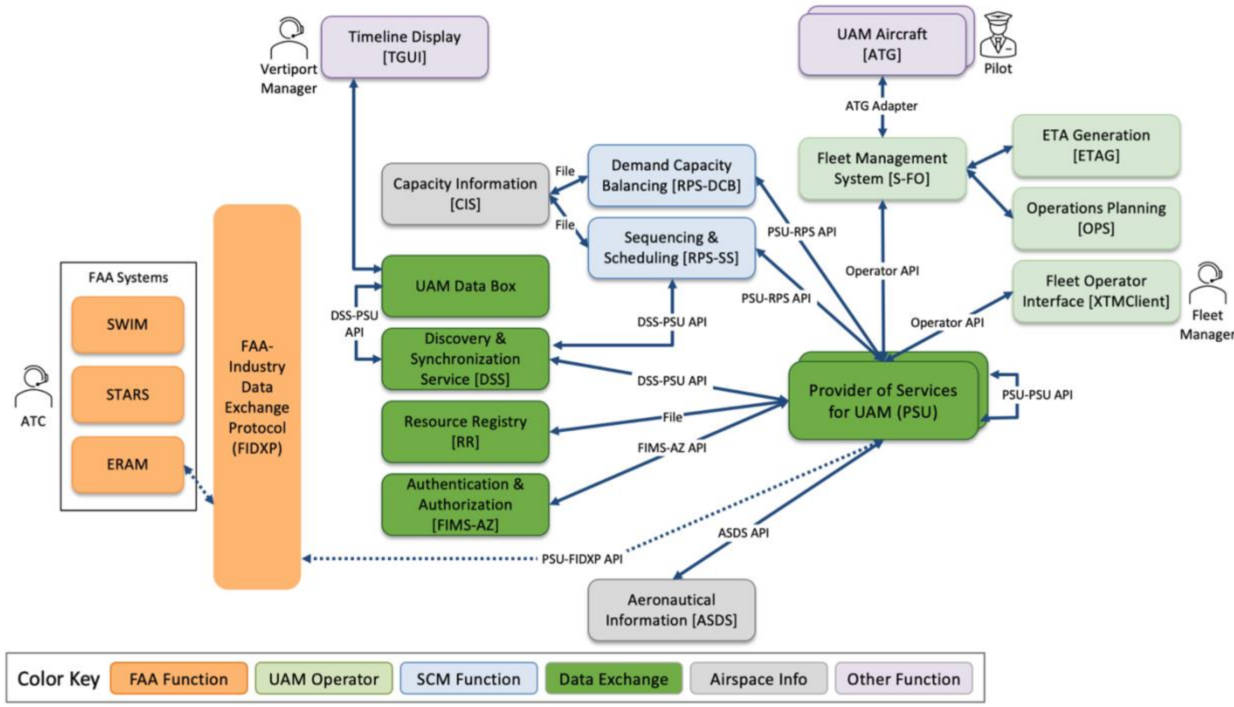

Figure 4 UAM System Architecture for PSU Prototype (X5) Simulations.

To facilitate how 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 [15]. High-level descriptions of the main services are provided in the next subsections.

3.2 Airspace Services and System Components for PSU Prototype Simulations

This subsection introduces various airspace services and system components that are defined in the UAM system architecture and developed by NASA to conduct the PSU Prototype simulations.

3.2.1 Airspace Services for Flight Management

1) Surrogate Fleet Operator (S-FO)

Surrogate Fleet Operator (S-FO) is a simulation tool to emulate the role of the fleet management system/services that Fleet Operator (FO) may use for UAM operations such as flight plan creation, modification, and submission. S-FO connects with various airspace services and runs a traffic scenario in a simulation. S-FO is designed to act as an automatic system component (i.e., a flight plan can be created and submitted without a human actor or a Graphical User Interface (GUI)). While this does not preclude having a user display, such a display (S-FO Map Viewer) could be used to display flight status and set preferences, as the autonomous system expects S-FO to respond to any changes in operational environments (e.g., vertiport capacity reduction) very quickly without any delay due to manual inputs from a human operator, when managing its UAM flights.

2) Operations Planning Service (OPS)

Operations Planning Service (OPS) provides the 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 operational plan. OPS is a trial planning application used to schedule flights on a route, given a set of constraints. This service accounts for 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. 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. Although this tool is not used for interactions between PSU and human fleet manager in this simulation, it can be used for future UAM research and the relevant simulations as a flight monitoring tool or an expanded service to obtain manual inputs from a fleet manager.

3.2.2 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 information and services about resource availability and constraints at resources as part of strategic conflict management capabilities.

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.

3.2.3 Services for Data Exchanges

1) Provider of Services for UAM (PSU)

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 a 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)

Discovery and Synchronization Service (DSS) is an open-source implementation to meet certain ASTM standards for UTM [16] that has been built and maintained by industry. For UTM, the DSS allows UAS Service Supplier (USS) to identify relevant information that may be owned by another USS ("Discovery"), ensures that information was consistent across each USS ("Synchronization"), and supports strategic deconfliction detection by identifying operational volumes that intersect each other. The same version of DSS is used in this UAM simulation.

3) Resource Registry (RR)

Upon request, the Resource Registry (RR) provides basic information about airspace resources such as origin and destination vertiports, UAM Corridor Entry/Exit Points (CEPs), and waypoints for merging or crossing. Registered resources only are used for scheduling by RPS-DCB and RPS-SS.

4) Flight Information Management System - Authentication and Authorization (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 via the PSU prior to operating within the UAM Corridors inside controlled airspace like Class B/C/D airspace.

3.2.4 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 such as latitude, longitude, and altitude of waypoints and vertiports and performance requirements in the UAM Corridors. The simplifying assumption for this simulation was such information would be made available digitally to UAM Operators over a federated service network (PSU network) to support operations planning via the ASDS hosted by NASA.

2) Constraint Information Service (CIS)

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

3.2.5 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 FAA systems and data. The FIDXS prototype is used to submit a VFR flight plan of the UAM flight to the FAA systems (e.g., System Wide Information Management (SWIM), 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 such as Estimated Time of Arrival (ETA) and Scheduled Time of Arrival (STA) at a scheduling point of interest. This tool can be used for a vertiport manager to monitor and manage the usage of vertiport resources.

3.3 Sequence Diagram

A high-level sequence diagram for initial flight planning in the PSU Prototype (X5) simulation is provided in Figure 5. During the pre-departure scheduling phase, two main capabilities for strategic conflict management are considered sequentially, which are DCB and S&S.

When a traveler requests an UAM service (e.g., a flight from one vertiport to another), the Fleet Operator (FO), simulated by S-FO, starts flight planning for this new trip. Given the trip request information, including departure and arrival vertiports, and desired departure time, the FO attempts to find a feasible flight schedule through the PSU network, considering other flights that have already been scheduled or are currently flying. 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 constrained waypoints like entry/exit points at the controlled airspace boundary to maintain sufficient spacing between aircraft for safety, as well as for the acceptable level of air traffic controller workload. It is assumed that there is a sufficient UAM fleet in this simulation, so that an aircraft is already available at the departure vertiport.

3.3.1 Demand-Capacity Balancing (DCB)

For a new flight, the FO first requests the available time windows at its origin and destination vertiports to the associated PSU. The PSU looks for a service registry in the RR (i.e., DSS_RR in the figure) to identify which services the PSU needs to contact. Once it receives the contact information for the associated 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(s) check which time windows are available by comparing the existing demand with the capacity provided by Constraint Information Service (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 ETAs at waypoints along the given route from the 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; not implemented in this simulation), in which it is always possible to select the closest departure time to the desired departure time, if any solution is available. FO's Trial Planner (FO_TP in Figure 5 or OPS in Section 3.2.1) 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 the PSU and shares its operational intent with other operators through the federated service network, after acceptance by the DSS.

3.3.2 Sequencing and Scheduling (S&S)

After obtaining an approved operational intent that complies with all DCB constraints, the FO requests sequencing and scheduling a few minutes before the departure time determined during the DCB process. Once again, the PSU identifies the contact information about the associated S&S service(s) for this flight by looking them up in the RR. The PSU then asks the S&S service (i.e., SS_X) to compute the STAs at control waypoints. The S&S service assigns additional pre-departure delays to the flight until finding the feasible STAs that satisfy all the sequencing and spacing constraints for avoiding any overtaking and 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 for demand-capacity imbalances again after passing through the S&S in this study. As a result, additional delay due to sequencing and spacing can cause DCB violation issues. 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).

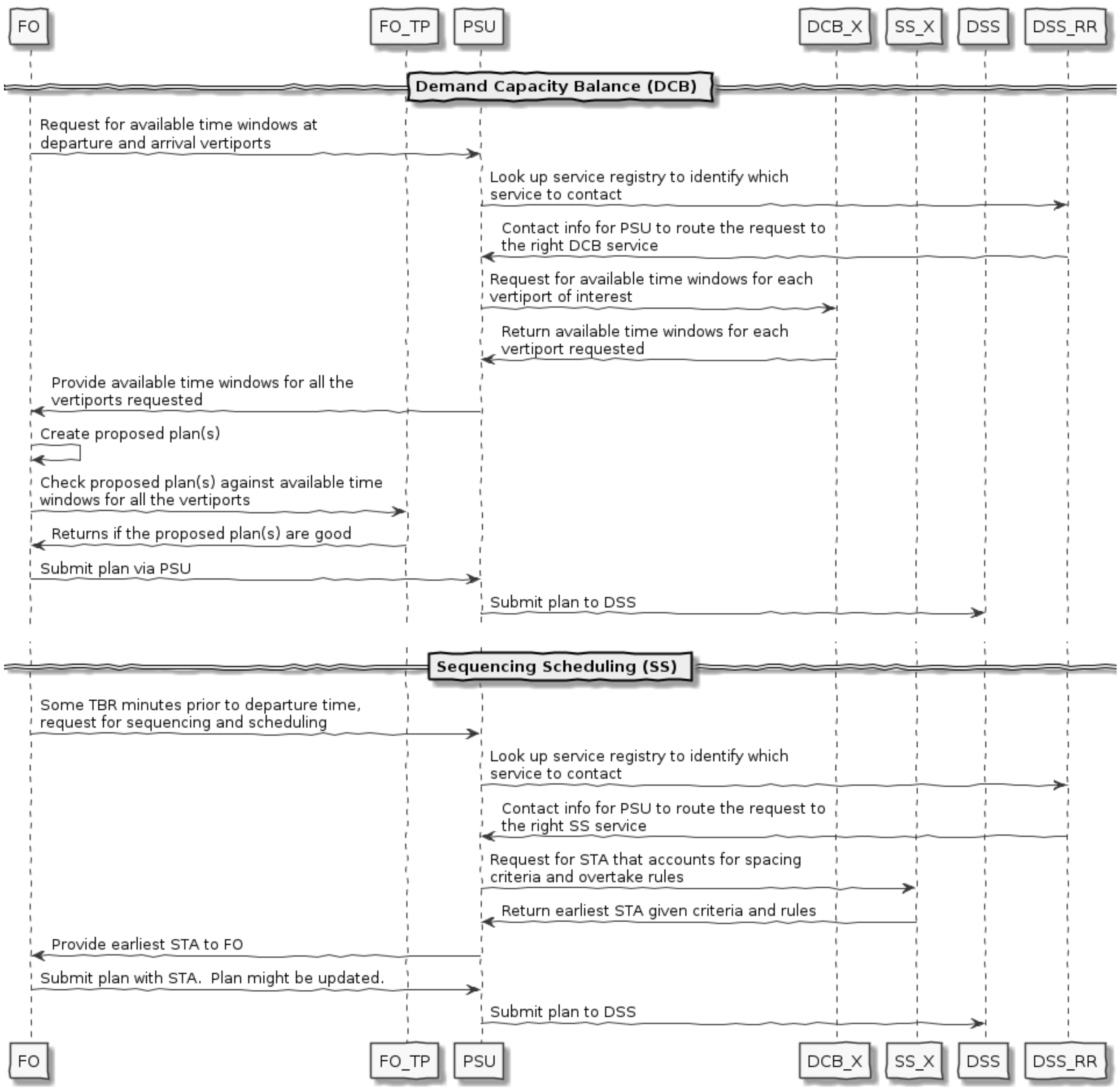

Figure 5 Sequence Diagram for PSU Prototype (X5) Simulations

4 PSU Prototype (X5) Simulation Execution

This section describes the process of implementing simulations to run and test a PSU prototype and other airspace services developed by NASA to validate the PSU requirements and evaluate strategic conflict management capabilities for UAM operations. It includes the target airspace, traffic scenarios, and simulation configurations used in this simulation.

4.1 UAM airspace

As in the X4 simulations, this simulation used 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 [14]. 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) was designed to deconflict UAM flights from traditional IFR operations and minimize the impact on ATC services. Note that there is no traditional air traffic simulated in this simulation because it focuses on the UAM flight planning.

A set of vertiports and Origin-Destination (OD) pair routes connecting those vertiports in the given UAM airspace over the DFW metropolitan area were selected to explore both DCB and S&S functionalities for this simulation. Figure 6 shows the selected 10 OD pair routes with 7 vertiports whose names start with “DF” used in the simulation. A series of orange or magenta balloons show the waypoints defining a route where a flight would go through them. Table 1 shows the list of these routes, with the 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 minutes, as a starting point. 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 waypoints at the boundary of Class B controlled airspace (shaded in light green color in Figure 6), which are EB002, EB003, TF024, and TF027. The other waypoints, EB011 and EB012, were excluded because they would be excessive constraint points. All the simulated flights are based on a single aircraft model, flying at the same speed given in each flight phase. In addition, sequencing constraints at key waypoints for merging and/or crossing were carefully defined and applied to prevent flights with different OD pairs from overtaking each other on 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, 14].

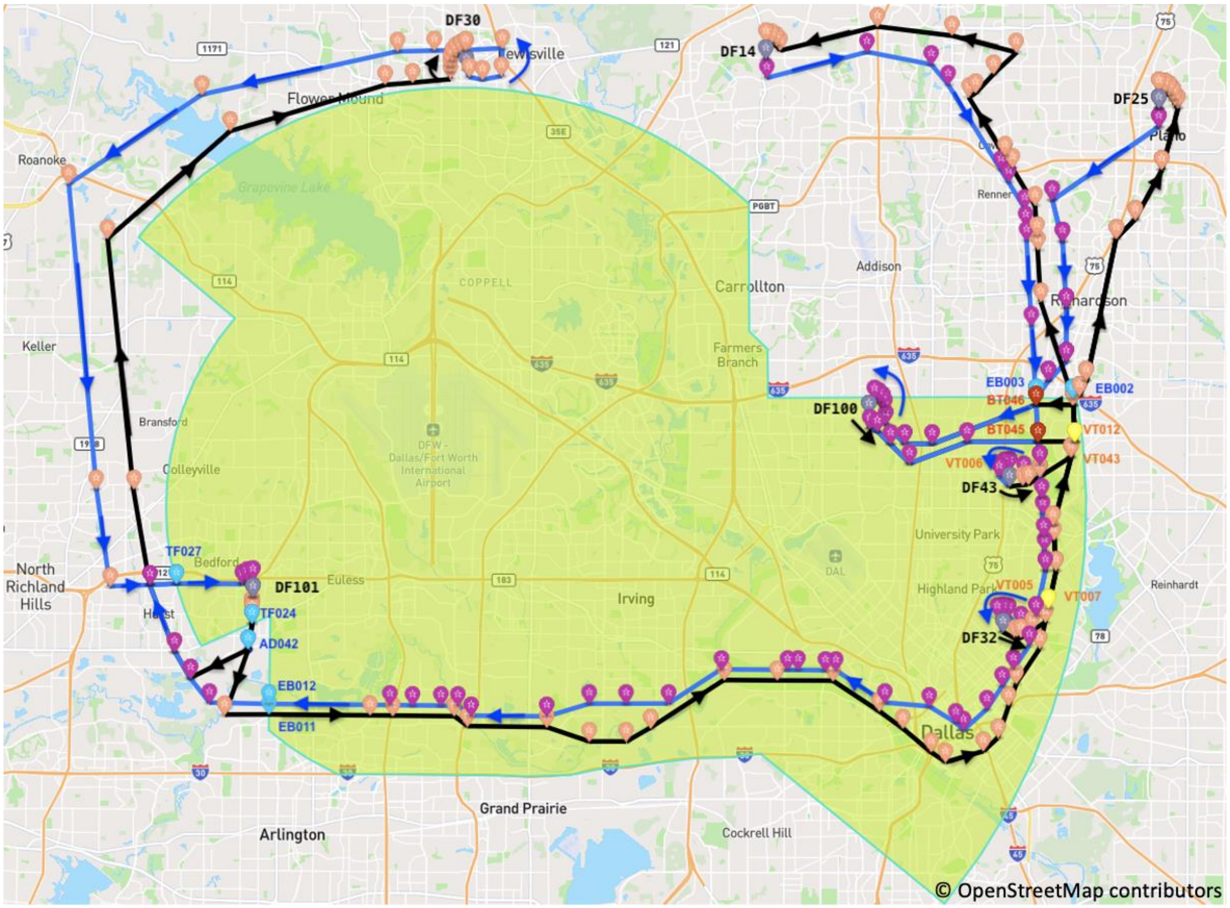

Figure 6 Route Network in DFW Airspace for PSU Prototype (X5) Simulations

Table 1: Origin-destination pair routes used in PSU Prototype (X5) simulations.

No	Origin	Destination	Waypoint for Spacing	Flight Time [minutes]
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

4.2 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 was assumed that two UAM operators shared the airspace resources such as vertiports and spacing waypoints, while their flights operated on the given 10 OD pair routes covering the DFW metropolitan area. The traffic demand was designed to cause demand-capacity imbalances at vertiports, which can be resolved by assigning pre-departure delay. It also may have potential losses of separation at spacing waypoints, expecting additional pre-departure delay due to sequencing and spacing. To represent the midterm traffic density, the traffic scenario had tens of simultaneous operations in the air at the peak.

A single traffic scenario was generated to meet the above considerations, which had 40 flights in total over a 1.5-hour simulation. Each operator was assigned 20 operations, which were evenly distributed among the 10 routes connecting seven vertiports (i.e., two operations per route for each operator), with different desired departure times.

4.3 Simulation configurations

For the PSU Prototype (X5) simulations, the airspace services introduced in Section 3.2 were configured 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-FO) were run, with an associated OPS and ETAG for each operator. A single RPS-DCB was activated to provide DCB service for the seven control points (i.e., vertiports), and one RPS-SS to schedule the flights at four control points (i.e., spacing waypoints), while meeting the minimum separation requirements and sequencing criteria. The simulation included a RR with the updated control point addresses and a CIS with all vertiport capacity definitions in static file format. To support UAM flight planning, ASDS, FIMS-AZ, and DSS were run. xTMClient, S-FO Map Viewer, and Timeline GUI (TGUI) at waypoints of interest were used for flight monitoring during the simulation.

In the baseline case, DCB was performed six minutes before the desired departure time. Then, S&S function was applied one minute before the scheduled departure time in which DCB was already applied. If the assigned delay to resolve both DCB and S&S issues was greater than one hour, the flight is canceled as the 1-hour threshold is assumed to meet the customer's transportation needs (i.e., if the delay is too long, the customer may use the other transportation mode like a ground taxi). If the temporal spacing value in the RPS-SS is set to zero, that could be equivalent to running the system with only the RPS-DCB turned on. Similarly, setting a large capacity in RPS-DCB would in essence skip DCB and apply S&S only. Furthermore, the lead times for DCB and S&S, as well as the maximum delay, can be varied by changing the parameters in the services. This document focuses on the baseline case described above to validate the PSU prototype proposed in the X5 system architecture for strategic conflict management capabilities. The impact of various simulation configuration setups was also investigated (see Ref [18]).

5 PSU Prototype (X5) Simulation Results

This section presents the data analysis results and discussion from this simulation. The metrics employed for data analysis are first described, followed by presentation of results for each metric, lessons learned and, finally, topics for future research.

5.1 System Performance Metrics

Four metrics were used to evaluate UAM system performance in this simulation. The metrics used for evaluating the proposed strategic conflict management approaches for UAM operations include:

- Number of operations,
- Number of demand-capacity imbalances detected and resolved,
- Number of violations in sequencing and spacing constraints, and
- Pre-departure delays assigned to aircraft by DCB and S&S.

5.1.1 Number of Operations

For the simulated flights, there are four flight states: planned, accepted, activated, and closed. Table 2 shows the number of operations in each flight state. Among the 40 flights in total (20 flights each for two operators) in the given traffic scenario, one flight was cancelled during the simulation due to 1-hour maximum delay limit by operator.

Table 2: Number of operations in each flight state.

Planned	Accepted	Activated	Closed
40	39	39	39

Figure 7 shows the number of simultaneous operations over the simulation time. It is observed that 13 flights were flying simultaneously at peak on 10 OD pair routes in the given route network. In this traffic scenario, Operator 1 and Operator 2 had at most 8 and 7 concurrent flights, respectively.

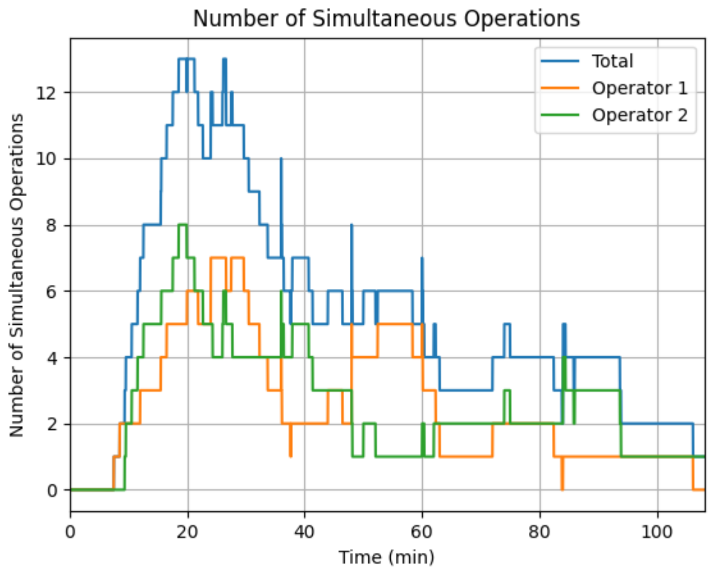

Figure 7 Number of Simultaneous Operations over Simulation Time

5.1.2 Demand Capacity Imbalance Detections and Resolutions

With respect to the traffic scenario tested in this simulation, flights were intentionally scheduled to have a demand peak (exceeding capacity) within the first 30 minutes of simulation initiation so that the proposed strategic conflict management capabilities can be assessed. The simulation results show that the traffic demand was properly distributed by DCB and S&S by assigning the necessary pre-departure delay. Figure 8 shows heatmaps for the original and modified flight schedules where the number in each cell indicates the number of operations, including both departures and arrivals, assigned to the 12-minute time bin at a specific vertiport. As seen in the X4 simulation results [12], the demand-capacity imbalances were resolved by the DCB. However, variation in flight times depending on the routes can cause unoccupied slots (indicated in Figure 8 by ‘bins’ with fewer than 2 operations), which may be resolved by improving DCB algorithms for more efficient resource utilization (e.g., introducing speed adjustments in a feasible range).

After DCB, one minute before takeoff, 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. Due to the scheduling gap between DCB and S&S, additional delay applied by S&S can place the operation in a different time bin and cause a DCB violation. In Figure 8, for example, one DCB violation is found in time bin #7 at DF101 because two other flights had already occupied this time bin by DCB when S&S applied additional delay to a flight that was assigned to time bin #6 by DCB.

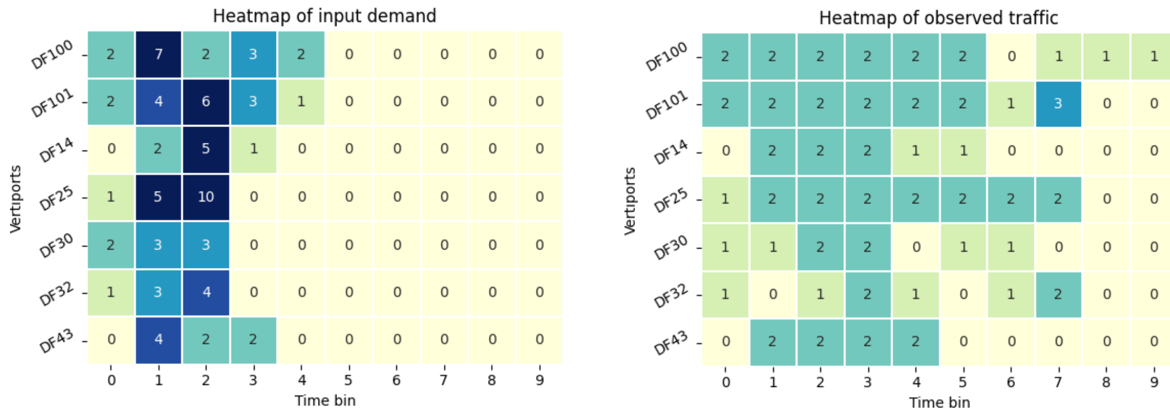

Figure 8 Traffic Demand Heatmaps for Original Schedule (left) and Modified Schedule (right)

5.1.3 Sequencing and Spacing

As expected, no overtaking situations were observed during the simulation because all aircraft fly at the same airspeed along the same routes. Also, there were no violations of the prescribed spacing requirements at the designated waypoints in the airspace.

5.1.4 Ground Delays

In this simulation, pre-departure ground delays were assigned, first by DCB and then by S&S, to resolve demand-capacity imbalances and satisfy sequencing and spacing criteria, respectively. Table 3 shows the sum of delays, the number of delayed flights, and average delay of these flights due to DCB and S&S. Although considerable delays occurred due to the dense demand in the given traffic scenario and the low vertiport capacity, most delays (98.2%) came from DCB and were applied to 25 out of 39 (64.1%) activated flights. On the other hand, compliance with S&S constraints resulted in additional delays for only 9 flights, including 6 flights that had already incurred delay due to DCB.

Table 3: Ground delay due to DCB and S&S.

	DCB	S&S	Total
Total Delay (minutes)	705.7	13.0	718.6
Number of Delayed Flights	25	9	28
Average Delay (minutes/flight)	28.2	1.4	25.7

Fairness between operators in scheduling is not the focus in this simulation, but it is observed that Operators 1 and 2 had an equal number of flights delayed (14 flights of each operator) with comparable delay assignment (i.e., 23.7 minutes/flight and 27.6 minutes/flight of average delay for Operators 1 and 2, respectively). 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 an interesting future research topic for efficient and equitable UAM operations.

5.2 Lessons Learned and Future Research

The PSU Prototype X5 simulation accomplished NASA's objectives for PSU prototype development and evaluation through simulations, which included enhancements of strategic conflict management capabilities such as Demand-Capacity Balancing and Sequencing and Spacing for cooperative midterm UAM operations, the validation of potential requirements for PSU and airspace automation, and the implementation of a reference architecture of the UAM airspace system for future integration activities. This section captures lessons learned from this simulation through internal discussions at NASA during architecture development and simulation implementation, as well as post-sim data analysis, and offers a set of questions for future research.

5.2.1 Lessons Learned

***PSU prototype as reference implementation* –** Through the X4 and X5 simulation activities, NASA developed a reference architecture for the UAM airspace system based on the UAM notional architecture illustrated in the FAA's ConOps and implemented PSU prototype simulations to test and validate the requirements for PSU and airspace automation. As an outcome of iterative processes and discussions, a sequence diagram for flight planning among system actors was also developed, accounting for strategic conflict management. In addition, PSU API specifications and requirements for information exchange between airspace services and system components in a federated service network were defined that may inform industry standards. NASA's PSU prototype is one example of a UAM airspace system, but it still needs to reflect more operational needs and constraints through collaborations with industry partners. Based on the lessons learned from X4 and X5 simulations, NASA is actively participating in the development of ASTM PSU Interoperability standard document and API specifications to reach common understanding and agreement on the UAM system architecture and data flow.

***Strategic conflict management* –** This simulation addressed how two types of strategic conflict management approaches, DCB and S&S, can be combined in the flight planning phase through the federated service network, but there is a lot of room for improvements. In this initial effort, DCB was only applied to vertiports, and S&S only included a small set of waypoints of interest. However, DCB can be extended to other airspace resources like UAM corridor entry/exit points and crossing/merging points. Furthermore, the UAM system architecture may have multiple DCB services for different airspace resources. For S&S, the route network can have more complicated sequencing problems, especially when UAM aircraft fly at different speeds. Usage of passing zones may be investigated to address this challenge and allow overtakes where practical and beneficial (e.g., a priority flight). In addition, spacing requirements at departure fixes around vertiports (e.g., 2-minute separation) may override a departure interval for consecutive takeoffs (e.g., 1-minute interval), if flights follow the same route with the same speed, resulting in additional ground delay. Lastly, for the vertiports having multiple vertipads, independent paths for climb and approach may need to be designed to support higher tempo operations.

***Traffic scenario* –** The traffic scenario used in this simulation likely does not represent a realistic demand profile or route utilization for midterm UAM phase. Based on the routes for DFW metropolitan area that had been developed for X4, the traffic scenario was developed with the aim of assessing both DCB and S&S functions so that most flights were initially scheduled in the first 30 minutes of the scenario, resulting in large delay assigned by DCB. The OD pair routes were also selected among the existing routes defined in the X4 simulation. These aspects of the scenario served the need of evaluating DCB and S&S functions, rather than modeling a realistic demand that does not exist yet. In future simulation activities, more realistic traffic scenarios and more reasonable route network structure with promising vertiport sites should be used to reflect actual demand patterns from UAM service customers. Furthermore, although this simulation only focused on a nominal scenario, off-nominal scenarios (e.g., re-route due to a temporary flight restriction, go-around situation) and contingency scenarios (e.g., emergency landing, lost Command and Control (C2) link) should be explored as well.

Vertiport operator – The vertiport operator roles should be integrated in the next simulations to account for the interactions with vertiport operators in flight scheduling and evaluate a vertiport management system. This simulation did not include vertiport operators or vertiport management services in its system architecture because it was based on the FAA UAM ConOps v1.0 and vertiport operator was not the focus of this simulation. Hence, the roles and responsibilities of Vertiport Operator, as well as the relevant requirements, were not investigated in this simulation. However, Vertiport Operator is one of main stakeholders in UAM ecosystem, which can affect the flight planning and strategic conflict management of UAM operations. Since the new ConOps added "vertiport" to its notional architecture, it is necessary to incorporate vertiport management and coordination services representing vertiport operators into the next system architecture. These services will provide the vertiport capacity and situational constraint information to UAM operators through the federated service network to facilitate situational awareness and communication of resourcing information at vertiports.

Air Traffic simulator – The air traffic simulator should represent actual flight vehicle behaviors as much as possible, but there are limited data for UAM flights based on electric Vertical Take-Off and Landing (eVTOL) aircraft under development. So, this simulation used a simulated aircraft model developed by NASA's Revolutionary Vertical Lift Technology (RVLT) project. It is expected that the air traffic simulator can be improved when the actual telemetry data is obtained from flight tests using eVTOL vehicles. Those data would be helpful to enhance the accuracy of trajectory predictions (e.g., estimated time of arrival at destination), especially when a flight performs a drastic maneuver like climbing/descending near vertiports and turning.

Trajectory prediction – Future simulations should incorporate weather impacts to trajectory and ETA predictions such as wind magnitude and direction at low altitude. Some efforts to ensure consistency in the units of aircraft speed (e.g., Ground speed, True Airspeed (TAS), Calibrated Airspeed (CAS), Indicated Airspeed (IAS)) and altitude among the services developed and provided by different companies are also needed.

DSS for UAM – A new or modified DSS for UAM is needed because the current UTM-based DSS is not suitable for UAM operational intent scheduling. This simulation used the existing DSS based on the UTM paradigm as in the X4 simulation. Therefore, the lessons learned from X4 with respect to DSS, such as handling of past operations, sizing of operational volumes, synchronization issues in a federated architecture, and distribution of airspace constraint information, are still valid. In addition, this simulation identified other issues when the UTM-based DSS is used for UAM flight planning. Table 4 shows the list of proposed DSS enhancements to support UAM.

Table 4: Proposed DSS enhancements for UAM.

Item	Description
New operational states	The current DSS handles four operational states: Accepted, Activated, Nonconforming, and Contingent. However, there is a need to add new operational states for DCB and S&S. For initial flight scheduling, a "Proposed" state should be added, in which a flight would check the DCB with the latest airspace information before getting accepted. In addition, "Completed" and "Canceled" states are needed for correct counting of demand in DCB. A flight

	in either state should be deleted from DSS and relevant PSUs in a timely manner.
Conflict evaluation based on 4D volumes	In this simulation, PSU submits operational intents with disjoint, small 4-D operational volumes surrounding vertiports and scheduling waypoints. DSS uses those volumes with only one time window for strategic deconfliction checks, which may lead to inefficient airspace usage and scalability issues. To determine potential conflicts between UAM flights more effectively, it would be better to use a continuous volume surrounding all the waypoints in the 4D trajectory. Alternatively, it needs, at least, check the conflicts of individual volumes around each resource with different time windows associated to the volume.
Operational data storage	The current DSS only checks the relevant operations in a subscribing area, but it doesn't store and share the detailed data. Since multiple system actors like PSUs and vertiport operators get access to the DSS, it would be useful to store the operational data history and provide an integrated operating picture.
Access to NAS traffic data and non-PSU system actors	This simulation did not include non-UAM traffic, but it is necessary to share the UAM flight data with other airspace users since UAM and non-UAM flights use the shared airspace resources (e.g., airport transfer use case). For this reason, the DSS may need access to NAS traffic data and non-PSU system actors (e.g., USS) in the future, leveraging FAA systems like SWIM for a common operating picture.
Grid size adjustment for UAM	DSS may sometimes make false alerts about potential conflicts between operations due to the proximity or overlapping of operational volumes based on DSS's common cell size used in the DSS Airspace Representation (DAR). DSS's grid size may need to be adjusted appropriately for UAM applications since some scheduling waypoints can be close and located within the same grid cell (e.g., origin vertiport and departure fix).

VFR flight plan submission to the FAA system – As part of the PSU Prototype (X5) simulation activities, the FAA-Industry Data Exchange Protocol Service (FIDXS) to submit a VFR flight plan for a UAM flight to the FAA system and receive the associated beacon code was developed and tested internally, although it was not actually connected to the FAA system and tested yet. This service will be useful for the FAA to track UAM flights and communicate with them once the actual connection is made between NASA's UAM airspace system and the FAA's air traffic management system like ERAM. Figure 9 illustrates a test result of the FIDXS to submit a flight plan (simplified to include gufi and route info only) and receive its beacon code.

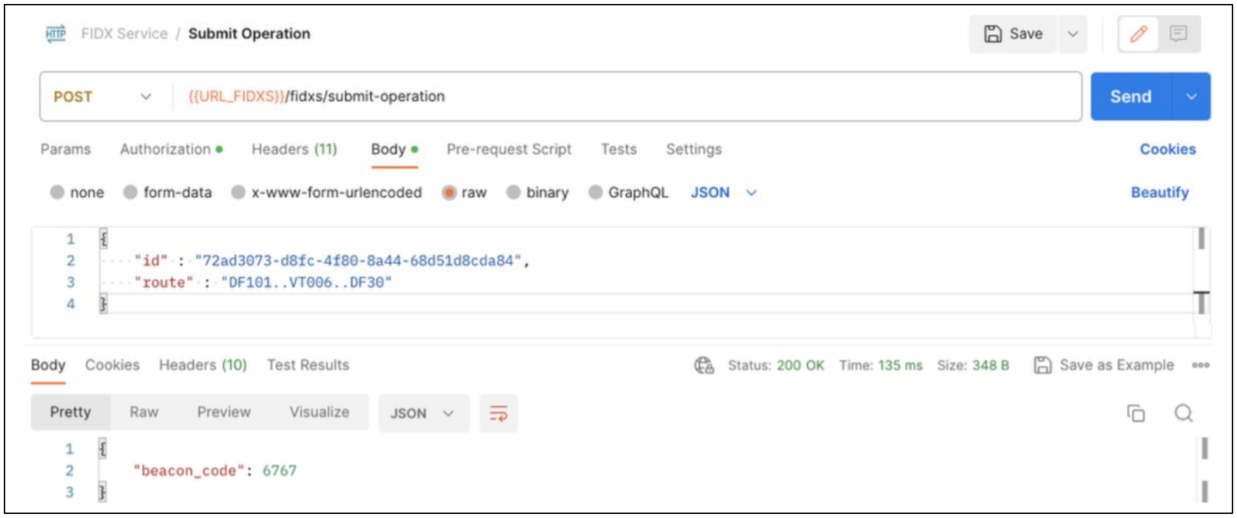

Figure 9 FIDXS Sample Test Result

Metrics – Various metrics have been developed for the performance evaluation of the reference UAM airspace system from the X4 and X5 simulations [10]. Those system performance metrics will be used to define system-level requirements for the future UAM airspace system development and evaluation.

5.2.2 Future Research

The PSU Prototype (X5) simulations assumed that only UAM flights operated in the given airspace using UAM corridors in a good weather condition / Visual Meteorological Conditions (VMC) and tested SCM capabilities for a nominal scenario with no uncertainty. While developing the UAM system architecture and the sequence diagram and implementing the simulations, other research questions have been identified and discussed, which are expected to be answered in future work, including:

- What kinds of SCM approaches should be applied to effectively manage various level of traffic density/tempo covering initial, midterm, and mature state UAM operations?
- How should the SCM capabilities be improved to make the flight plan robust against operational uncertainties like winds and human actors? How can those uncertainties be implemented in the simulation system?
- How can the SCM approaches handle off-nominal and contingency scenarios, such as irregular situations (e.g., go-around), airspace constraint changes, and emergency flights causing a vertiport closure? Those scenarios may be mainly handled by the tactical separation provision (e.g., Detect-and-Avoid (DAA)) and collision avoidance layers. Then, how can those layers be integrated with the SCM layer?
- For DCB, what is the appropriate capacity at various airspace resources (e.g., vertiports) to accommodate demand growth as UAM industry evolves?
- For sequencing and spacing, what is the best approach to considering sequencing constraints at merging/crossing waypoints? How can the passing zones to allow overtaking (e.g., emergency response flights) be introduced in airspace design and procedures? How can S&S accommodate varying aircraft performance models (i.e., mixed equipage)? What mechanisms and processes will be employed to establish the separation minima for UAM operations?

- What is the best scheduling discipline for system performance (e.g., maximizing throughput), efficiency (e.g., minimizing delay), and/or fairness, in case that UAM flights have different lead times to the desired departure time (scheduled vs. on-demand UAM services)? Is the First-Come, First-Served (FCFS) scheduling the best? How should priority flights be managed?
- In the federated service network for UAM, communication latency between system actors may impact scheduling. How can this latency issue be overcome?

The research questions listed above can be investigated and answered by fast-time simulations on a desktop computer, Human-in-the-Loop (HITL) simulations with air traffic controllers and pseudo pilots, or Live, Virtual, Constructive (LVC) simulations with live aircraft. NASA and its collaborators have a variety of capabilities to answer some of these questions, and prioritization of these questions and determination of which capabilities could be utilized to best answer each question is a key.

6 Conclusions

Through the PSU Prototype Simulation activities (called X5 simulation), NASA developed a PSU prototype as the reference implementation of UAM system architecture and evolved strategic conflict management capabilities for UAM operations from the previous X4 simulations. This PSU prototype was successfully tested and validated with a traffic scenario in Dallas-Fort Worth airspace in NASA's simulation environment. The simulation results showed that the UAM traffic demand could be managed to minimize the needs of tactical separation provision with ground delays assigned by DCB and S&S services.

Below is a summary of the achievements.

- Aligned NASA's UAM reference architecture with the FAA's UAM ConOps notional architecture
- Extended UAM airspace management capabilities to include 1) DCB to ensure operators coordinate planned usage of shared airspace resources like vertiports, and 2) S&S at UAM corridor entry and exit points to help facilitate an orderly flow of UAM traffic
- Defined the PSU information exchange APIs and requirements that may inform industry standards (e.g., ASTM PSU Interoperability standard)
- Developed and tested NASA PSU prototypes as reference implementation to validate the relevant requirements and APIs
- Completed stand-alone tests of a prototype NASA-FAA data exchange service (FIDXS) for testing future PSU-ATM interface requirements
- Tested NASA-developed assumptions for UAM operations such as airspace design, procedures, vehicle performance, and strategic conflict management methods to inform future Cooperative Operating Practices (COPs; formerly CBRs) development with industry
- Evaluated system performance metrics such as number of simultaneous operations and ground delays that can help define system-level requirements

NASA plans to share the findings and lessons learned from the PSU Prototype (X5) simulation activities with industry to facilitate the UAM traffic management technology research and development. NASA will continue to develop and enhance the UAM reference architecture and airspace services to validate the integrated requirements for the UAM ecosystem through supporting data from research, development, and testing of a subset of UAM automation prototypes.

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B. Acronyms/Abbreviations

Acronym	Description
ADS	Addison Airport
AGL	Above Ground Level
AIS	ATM Interoperability Simulation
AMP	Air Mobility Pathfinders
API	Application Programming Interface
ASDS	Airspace Structure Definition Service
ASTM	American Society for Testing and Materials
ATC	Air Traffic Control
ATG	Airspace Traffic Generator
ATM	Air Traffic Management
CAS	Calibrated Airspeed
CBR	Community Based Rule
CEP	UAM Corridor Entry/Exit Point
CIS	Constraint Information Service
ConOps	Concept of Operations
COP	Cooperative Operating Practice
DAA	Detect-and-Avoid
DAL	Dallas Love Field Airport
DAR	DSS Airspace Representation
DCB	Demand-Capacity Balancing
DFW	Dallas-Fort Worth International Airport
DSS	Discovery and Synchronization Service
ERAM	En Route Automation Modernization
ETA	Estimated Time of Arrival
ETAG	ETA Generation service
eVTOL	electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FCFS	First-Come, First-Served
FIDXP	FAA-Industry Data Exchange Protocol
FIDXS	FAA-Industry Data Exchange protocol Service
FIMS	Flight Information Management System
FO	Fleet Operator

Acronym	Description
GUI	Graphical User Interface
HITL	Human-in-the-Loop
IAS	Indicated Airspeed
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
LVC	Live, Virtual, Constructive
NASA	National Aeronautics and Space Administration
NAS	National Airspace System
NC	National Campaign
OD	Origin-Destination
OPS	Operations Planning Service
PIC	Pilot in Command
PSU	Providers of Service for UAM
RPS	Resource Planning Service
RR	Resource Registry
RVLT	Revolutionary Vertical Lift Technology
SCM	Strategic Conflict Management
STA	Scheduled Time of Arrival
SWIM	System Wide Information Management
S&S	Sequencing and Scheduling
S-FO	Surrogate Fleet Operator
TAS	True Airspeed
TGUI	Timeline Graphic User Interface
TP	Trial Planner
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UML	UAM Maturity Level
USS	UAS Service Supplier
UTM	Unmanned Aircraft Systems (UAS) Traffic Management
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
xTMClient	Extensible Traffic Management Client