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# National Campaign (NC)-1 Strategic Conflict Management Simulation (X4) Final Report

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**December 2022**

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# Executive Summary

Urban Air Mobility (UAM) enables highly automated, cooperative, passenger or cargo-carrying air transportation services in and around urban areas. UAM is a subset of the Advanced Air Mobility (AAM) concept under development by the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and industry.

The Strategic Conflict Management (SCM) Simulation, dubbed “X4”, was conducted between July 2021 and June 2022 by NASA with the FAA and industry to evolve the Provider of Services for UAM (PSU) that will be needed to ensure initial UAM operations can scale in the National Airspace System (NAS). The FAA UAM Concept of Operations (ConOps) v1 [1] served as an initial guiding document for the X4 airspace management system design to ensure the architecture supports testing of services provided by third-party service providers. To that end, the X4 architecture leveraged concepts and technologies developed for Unmanned Aircraft System (UAS) Traffic Management (UTM) while also developing and testing new capabilities and services needed for UAM. The architecture included an initial prototype of the FAA-Industry Exchange Protocol (FIDXP), third-party services such as the PSUs, and Discovery and Synchronization Service (DSS), and other new services such as Demand-Capacity Balancing (DCB) to facilitate UAM strategic conflict management.

During X4, NASA led discussions and collaborated with seven industry airspace partners to develop initial airspace management concepts for UAM that drove what would be tested and evaluated during the simulations. The initial capabilities defined for PSU leveraged UTM UAS Service Supplier (USS) as a starting point and evolved to meet UAM requirements. These discussions were also an opportunity for NASA to collaborate with industry to develop a set of initial Community-Based Rules (CBRs). These CBRs enabled how UAM traffic would be cooperatively managed among UAM operators. The collaborative, iterative process of developing CBRs with industry during X4 provided insight into the challenges involved and identified the need for a suitable and effective forum for future CBR development.

In parallel with these discussions, NASA conducted a series of seven software sprints and two collaborative simulations with the airspace partners that built up in complexity. Over the course of the year, all seven partners successfully completed all the sprints by demonstrating the required capabilities. They also participated in the two collaborative simulations to demonstrate how multiple PSUs could work together in a collaborative, more complex environment with higher traffic density.

The X4 simulation accomplished NASA's objectives and helped advance the development of the seven participating PSUs. The lessons learned provided insight into key elements of the UAM Notional Architecture from the FAA ConOps v1 [1] and UTM technologies when applied to UAM:

- Having a Concept of Use (ConUse) defined prior to the activity would accelerate the time and effort from concept development to testing.
- While the UAM Notional Architecture provided a starting point for a federated architecture that support services provided by third-party providers, the USS and PSU differed in their capability definitions for operational intent submission and sharing, conformance monitoring, airspace authorization, strategic conflict management, airspace constraints and dynamic replanning.
- While existing DSS developed for UTM provided a way for PSU and other UAM services (such as DCB) to discover relevant operations from each other, additional complexity and challenges were found during X4 testing and illuminated the need for a more suitable solution for UAM.

Industry can leverage the results of this demonstration to accelerate UAM requirements, CBRs, and standards development. The FAA and other government municipalities and agencies will be able to leverage results to inform future policies and identify additional gaps that require further analysis, moving toward operationalization of UAM.

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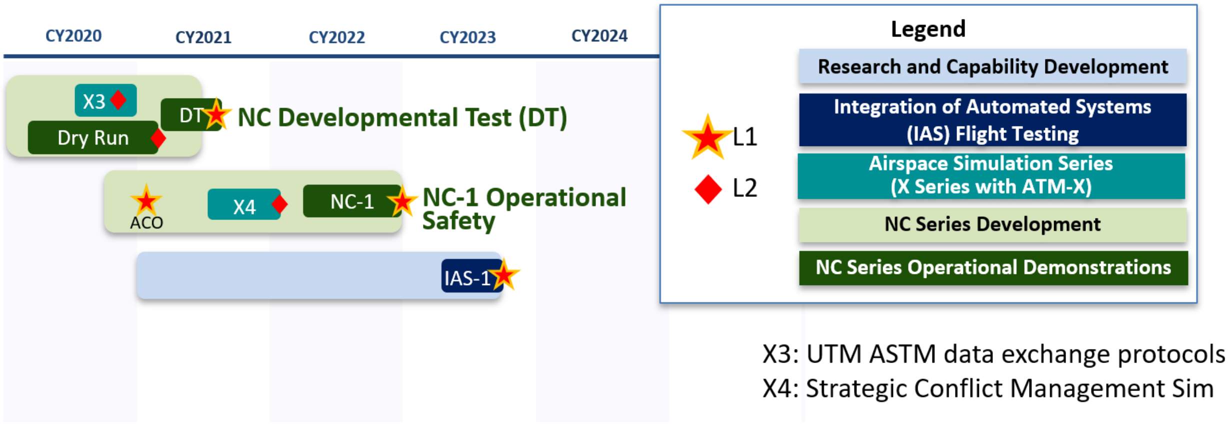
# 1 Background

NASA’s vision for Advanced Air Mobility (AAM) is to help emerging aviation markets develop a safe air transportation system that would allow moving people and cargo between places previously not served or underserved by aviation [2]. Advanced Air Mobility (AAM) encompasses a range of innovative aviation technologies (small drones, electric aircraft, automated air traffic management, etc.) that are transforming aviation’s role in everyday life, including the movement of goods and people. Urban Air Mobility (UAM) represents one of the AAM concepts with highly automated aircraft, providing commercial services to the public over densely populated cities to improve mobility. The improvement of UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air travel as an integral mode of transportation in metropolitan areas. This includes flying to local, regional, intra-regional, and urban locations using revolutionary new electric Vertical Takeoff and Landing (eVTOL) aircraft that are only just now becoming possible.



X3: UTM ASTM data exchange protocols
X4: Strategic Conflict Management Sim

*Figure 1. Strategic Conflict Management X4 Simulation in Relation to National Campaign (NC)*

In support of NASA’s vision for AAM to accelerate the integration of UAM operations in the NAS, the National Campaign (NC) planned a series of test activities focused on flight and simulation. The NC flight test series will guide the collective community and stakeholders through scenario-based test activities that involve vehicles and airspace management services operating in a live test environment over the next several years. The Air Traffic Management eXploration (ATM-X) UAM Airspace Sub-Project (UAM SP), under the Airspace Operations and Safety Program (AOSP) within NASA’s Aeronautics Research Mission Directorate, supports the NC flight test activities by conducting simulation test activities with NC Airspace partners where they can demonstrate their capabilities and components prior to NC flight activities.

By leveraging technologies developed for NASA's innovative Unmanned Aircraft Systems Traffic Management (UTM) system and partnering with a group of airspace service providers and the FAA, the team collaboratively developed, tested, and evaluated the UAM airspace architecture to ensure they are ready for flight tests. The first of such activity, called X3 [3] which began in August 2020 and completed in December 2020, allowed the team to evaluate how well partners perform NC scenarios 1–3 [4] in simulated environments. X3 was a foundational step in establishing the technology, infrastructure, and information on how the UTM federated architecture would work within the UAM environment.

# 2 X4 Overview

The Strategic Conflict Management (SCM) X4 Simulation advanced the technology and test new information sharing requirements – amongst providers, as well as between providers and the FAA – to enable safe, efficient urban air mobility operations while staying aware of increasing demands on the airspace. The SCM X4 simulation was an opportunity to work with industry and FAA to continue evolve the Provider of Services for UAM (PSU) and to identify additional information exchanges for strategic conflict management that will be needed to support initial UAM operation in the NAS. The technologies were aimed at supporting initial operations at UAM Maturity Level (UML)-2 that could be extended for UML-3 [5], [16]. X4 was a series of progressive simulation activities aimed to collaborate with the industry in developing and testing a set of initial UAM airspace capabilities, so that the results and findings can help inform future ConOps and standards development.

As part of the SCM X4 Simulation, seven NC-1 airspace partners – ANRA Technologies, Avision, ARINC, Metron Aviation, OneSky Systems, SkyGrid, and Unmanned Experts – [6] as well as NASA, worked towards developing their PSUs and completed all testing by exercising and demonstrating capabilities of increasing complexity. Five of these partners partnered with Wisk for subsequent National Campaign-1 (NC-1) flight tests.

## 2.1 Proposed UAM Architecture

In 2020, the FAA published its v1 of the UAM ConOps [1] which described the envisioned operational environment that supports the expected growth of flight operations in and around urban areas. The ConOps v1 serves as an initial guiding document for the X4 design. One of the objectives for X4 design is to ensure alignment with FAA's UAM Notional Architecture (shown in Figure 2) and hence the Notional Architecture was used as a basis for the X4 airspace management system architecture.

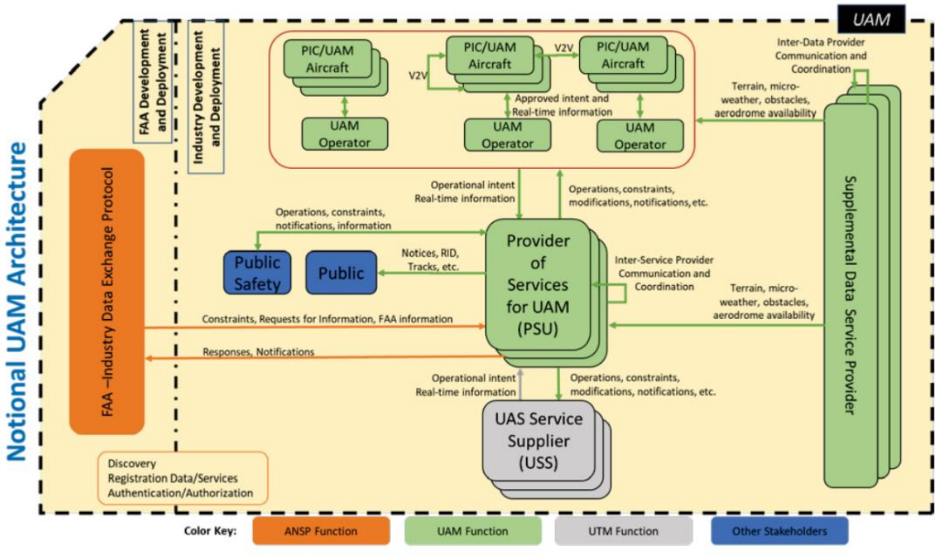
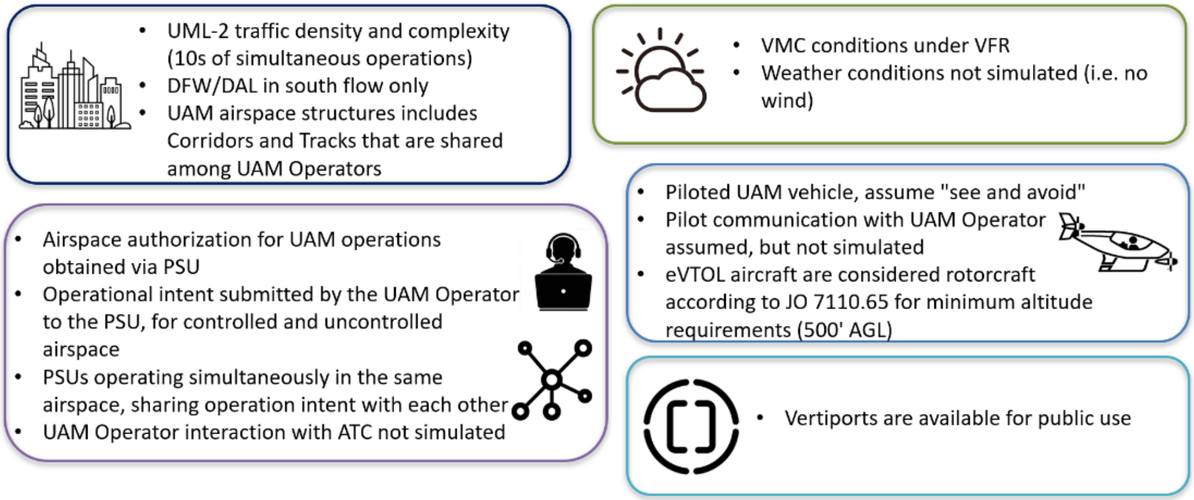


*Figure 2. Notional UAM Architecture from FAA UAM ConOps*

While the UAM Notional Architecture was served as the starting point for X4, the final simulated architecture for X4 included more refined capabilities definition of the "Provider of Services for UAM" (PSU) as well as other services and technologies needed to support strategic conflict management. The simulation architecture will be described in Section 4.3.

## 2.2 Assumptions for the Simulated Environment

The SCM X4 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).



- UML-2 traffic density and complexity (10s of simultaneous operations)
- DFW/DAL in south flow only
- UAM airspace structures includes Corridors and Tracks that are shared among UAM Operators

- VMC conditions under VFR
- Weather conditions not simulated (i.e. no wind)

- Airspace authorization for UAM operations obtained via PSU
- Operational intent submitted by the UAM Operator to the PSU, for controlled and uncontrolled airspace
- PSUs operating simultaneously in the same airspace, sharing operation intent with each other
- UAM Operator interaction with ATC not simulated

- Piloted UAM vehicle, assume "see and avoid"
- Pilot communication with UAM Operator assumed, but not simulated
- eVTOL aircraft are considered rotorcraft according to JO 7110.65 for minimum altitude requirements (500' AGL)

- Vertiports are available for public use

*Figure 3. High-Level Assumptions*

## 2.3 Proposed UAM Airspace and Procedures

This section describes specific UAM airspace and procedures in the Dallas-Fort Worth metropolitan area developed and used for X4. For a detailed description of the DFW airspace design assumptions and analysis, refer to the paper in Reference [4].

The UAM airspace used in the X4 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 airspace assumed traditional traffic around DFW were operating in south flow only, as DFW operates predominantly in such configuration. The UAM airspace construct, i.e., corridors and tracks, were designed to minimize impact on ATC services and to deconflict from traditional IFR operations.

Figure 4 shows the airspace constructs and vertiport locations used in X4 within Class B airspace. The X4 vertiports included 20 vertiports inside Class B airspace and another 14 vertiports in Class E/G (not shown in the graphic). All corridors in X4 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 5 below. Corridors and tracks were designed for Class B airspace only. For operations within Class E and G airspace, pre-defined UAM airspace construct was not required, but for simplicity of simulation, NASA created potential routings between vertiports and provided them to NC-1 airspace partners so they can be used for operational planning.

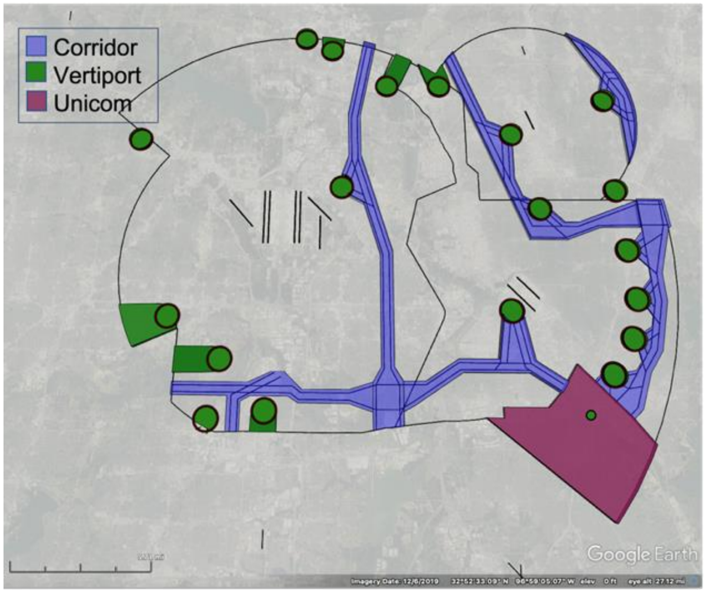


*Figure 4. UAM Corridors and Vertiport Locations in X4*

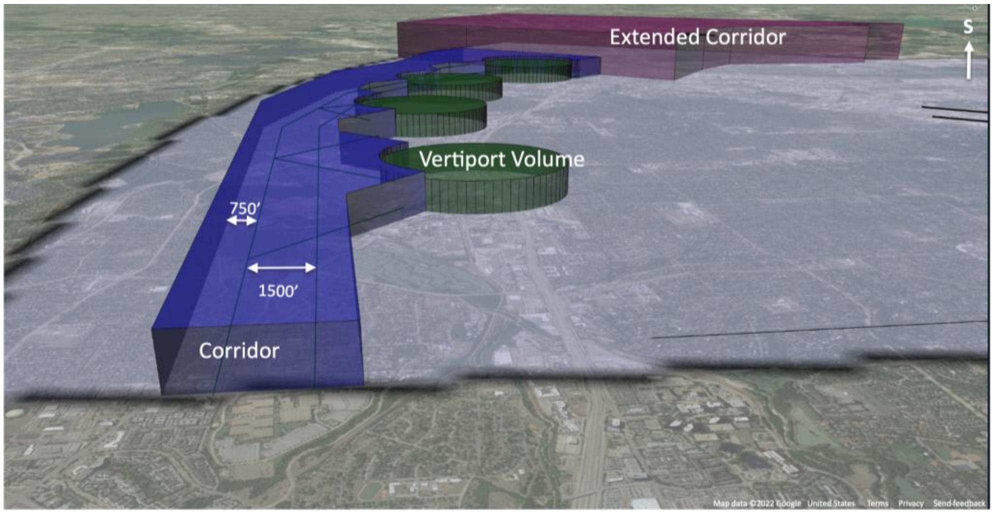


*Figure 5. Closeup of Corridors, Tracks, and Vertiports in the DFW Area*

Within the Class B airspace, UAM corridors and tracks were designed to procedurally deconflict from standard instrument departures (SIDS) and instrument approach procedures (IAP) used by traditional aircraft flying into and out of DFW during south flow. The DFW airspace was evaluated using historical track data to identify altitudes for UAM corridors and tracks to ensure that most of the UAM flights can maintain 2,500 ft lateral or 1,000 ft vertical separation based on existing wake turbulence advisory requirements [7]. Figure 6 shows the departure procedures from Runway 18L would be at 2,166 ft and UAM operations would be flying at 1,100 ft MSL to maintain 1,000 ft vertical separation between legacy and UAM traffic. For simplicity, all X4 tracks were planned at 1,100 ft MSL.

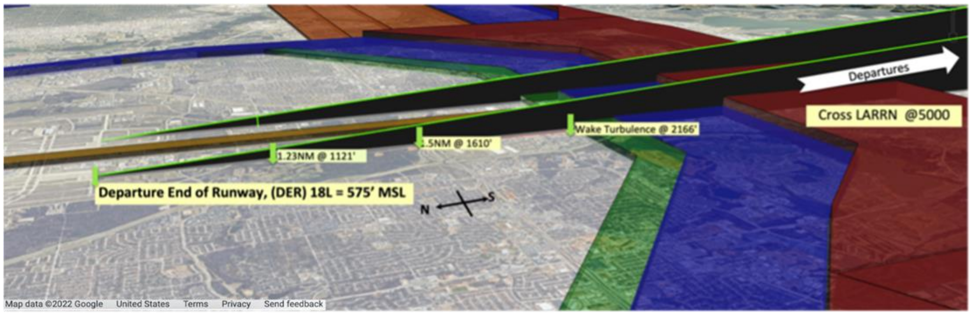


*Figure 6. Analysis on Runway 18L DARTZ Departure Path for Designing UAM Airspace*

The arrival and departure procedures were designed such that the entry and exit paths for a vertiport were separated for the direction of the traffic. This allowed for the aircraft to turn into or out of the vertiports with ease and avoid sharp turns as shown in Figure 7. The vertiport volumes (in yellow) were defined as a cylindrical volume with a circle with 2,750 ft radius.

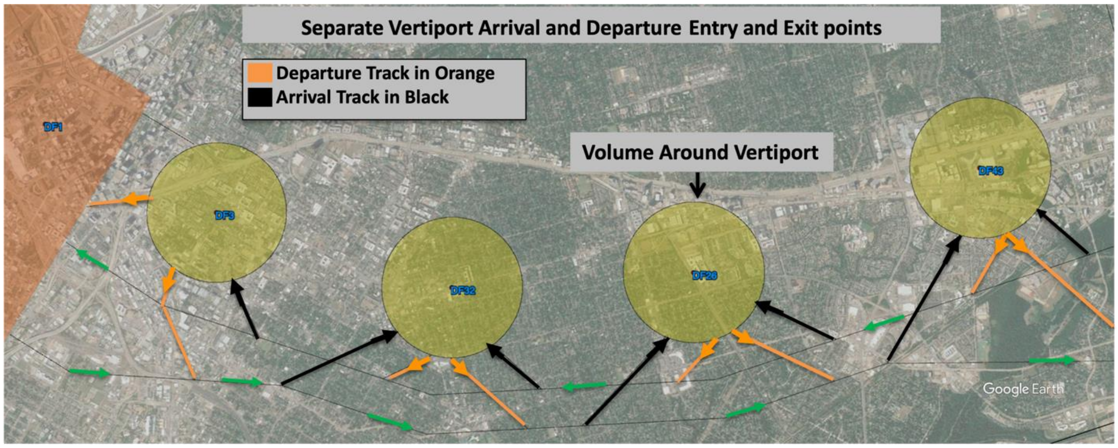


*Figure 7. Entry and Exit Tracks for the Vertiport*

Figure 8 shows the approach procedures into the vertiport volume based on initial UAM aircraft performance [8]. The approach procedures were designed for the UAM aircraft to fly at or below 70 knots, at a 9-degree descent angle, fly at about 3,000 ft prior to landing.

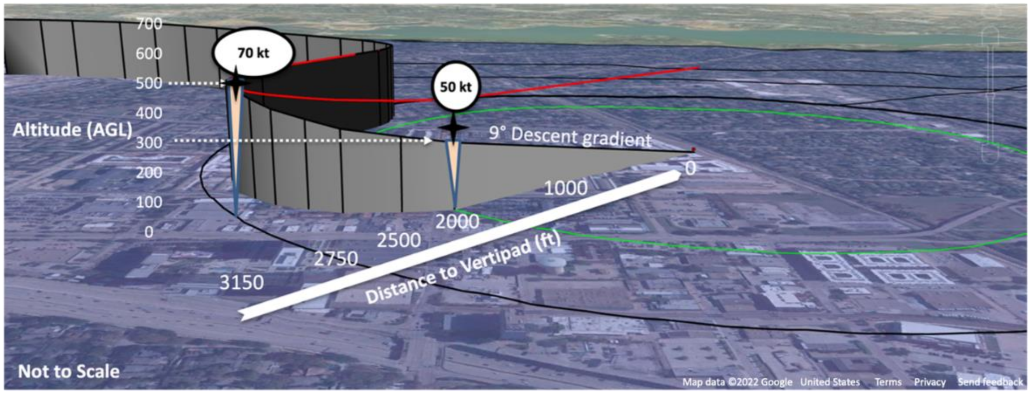


*Figure 8. Approach Procedure into the Vertiport Volume*

Similarly, the departure procedures were designed for UAM aircraft to climb at 500 ft per nm at an 8 degree climb angle when in forward flight, as shown in Figure 9. The total distance traveled prior to joining the tracks inside the corridor was approximately 5,500 ft with a cruise speed of 110–130 kt and cruise altitude of 1,100 ft MSL.

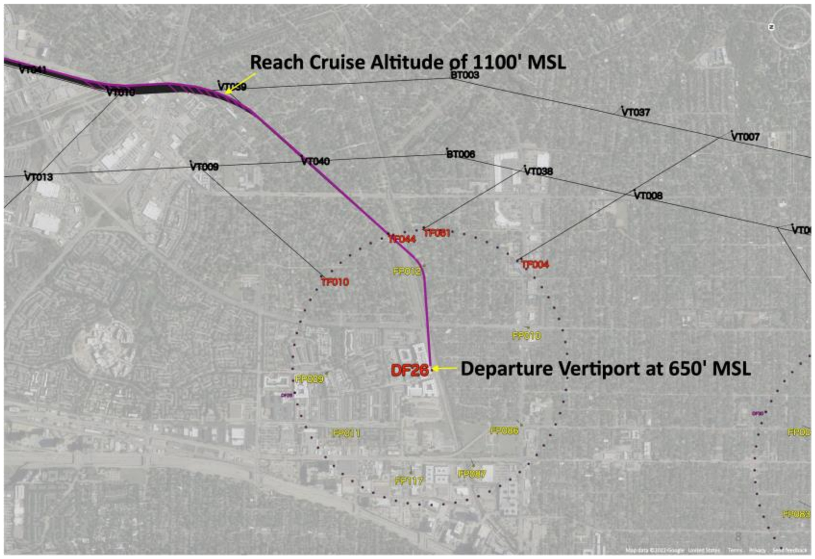


*Figure 9. Departure Procedure from the Vertiport Volume*

## 2.4 Objectives

The X4 simulation had multiple established objectives:

1. Collaborate with industry to establish, develop, and test the Minimum Viable Product (MVP) for the PSU needed to ensure scalable UAM operations through testing in simulation and testing in NC-1 flight demonstrations with vehicle developers where applicable
2. Identify required PSU capabilities versus value-added UAM services
3. Advance the prototype interface to expected FAA data (e.g., FAA industry data exchange protocol)
4. Identify, implement, and test Community-Based Rules (CBRs) for strategic conflict management
5. NASA to develop a PSU reference implementation to stand-in for airspace in NC-1 flights for vehicle developers without an industry airspace provider
6. NASA to implement and test a prototype In-Time Aviation Safety Management Service provided by the SWS Project
7. Assess and inform key elements of current and future FAA ConOps and Use Cases such as airspace constructs (e.g., corridors)
8. Use results to inform standards bodies

The MVP for PSU, described in the first objective, included the following list of capabilities leveraging those required for UAS Service Supplier (USS) in UTM as a starting point. These capabilities formed the basis for how the scope for X4 sprint testing were developed, however, the definition of each capability was further refined during X4. The refined capability definitions will be discussed in Section 3.2.

1. **Access to Airspace Structure Definition.** PSU will support UAM Operators in conducting UAM operations within the UAM airspace constructs defined and shared via the Airspace Structure Definition Service (ASDS). The ASDS provided definitions of airspace construct within Class B/C/D airspace, vertiport locations, and arrival and departure procedures into and out of vertiports.

2. **Operational Intent Submission and Sharing.** PSU will submit 4-dimensional (4D) trajectory-based operational intent and share with other UAM Operators via the PSU Network.
3. **Conformance Monitoring.** PSU will monitor for conformance against filed 4D operational intent. Each PSU will monitor the conformance of its managed operations by checking telemetry information against the approved operational intent while the vehicle is active.
4. **Airspace Authorization.** PSU will obtain an Airspace Authorization for the UAM Operator via the prototyped FIDXP service developed for X4. All UAM Operators conducting UAM operations must obtain FAA authorization when operating within Class B/C/D airspace. The PSU will support this authorization process by checking the UAM Operator's operational plan against performance requirements for operating within a corridor, and coordinate with FAA systems (e.g., NASA prototype FIDXP) on the UAM Operator's behalf.
5. **Strategic Conflict Management.** PSU will detect and resolve strategic conflicts based on the development of requirements and Community Based Rules (CBRs) with Industry partners. Implementation of the PSU will reflect demand-capacity balance at vertiports. PSU may coordinate operations with other PSUs through CBRs for strategic deconfliction. Some services may not be architected to reside within the PSU.
6. **Airspace Constraints and Operational Plan Modifications.** UAM Operators will modify their operational plans to avoid an active airspace constraint and share their modified plans with the other UAM Operators via the PSU.

## 2.5 Development and Test Schedule

To meet the established objectives, the SCM X4 Simulations progressed through two parallel series of activities, shown in in Figure 10 below.

- Partner-informed research and development (R&D)
- NASA-partner software sprints and collaborative simulations

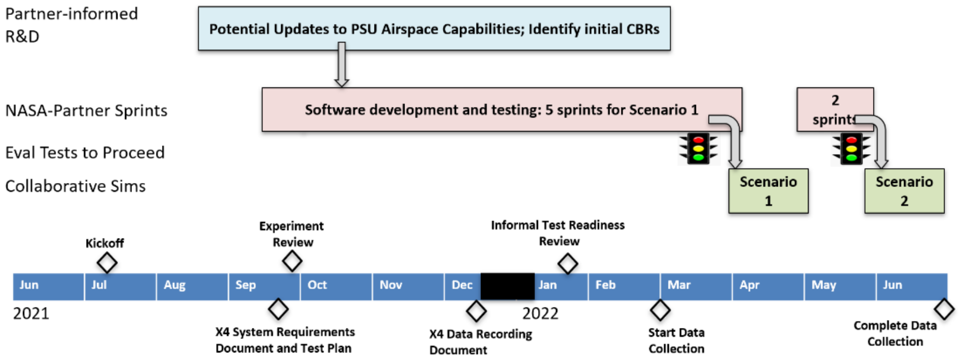


*Figure 10. X4 R&D and Testing Schedule*

Since the start of X4, a series of weekly technical meetings was scheduled for NASA to engage and collaborate with the seven industry partners on developing initial UAM airspace concepts that drive what would be tested and evaluated for X4. These discussions were targeted to focus on initial concepts related to UAM airspace structures, operational intent sharing, conformance monitoring, airspace authorization, and strategic conflict management. As a result of these discussions, requirements were refined, and a subset of those requirements were tested during the seven software sprints. These meetings also served as forum to discuss and develop initial Community-Based Rules (CBRs) with the industry to enable how UAM traffic would be cooperatively managed among UAM operators.

Throughout the duration of X4 simulations, NASA executed a series of software sprints with seven airspace partners and validated their PSU capabilities. As shown Table 1, the X4 testing included a total of seven software sprints and two collaborative simulations. Each software sprint was conducted with one partner at a time, for each of the seven partners. Each collaborative simulation was conducted with a group of three partners at a time, for each of the three groups. NASA stood in as a partner in certain groups, whenever necessary, to form the groups of three.

*Table 1. Sprints and Features Tested in X4*

| Scenario | Sprint # | Sprint | Features Tested |
|---|---|---|---|
| **1** | #1 | Connectivity | Flight Information Management System - Authentication and Authorization Service (FIMS-AZ) Connectivity, ASDS Connectivity for accessing UAM airspace structure data |
| | #2 | Operational Intent | DSS Connectivity, PSU Network Connectivity and Distribution |
| | #3 | Nominal Flight | Vehicle simulation, Telemetry updates, Conformance monitoring |
| | #4 | Airspace Authorization | Airspace Authorization via FIDXP |
| | #5 | Strategic Conflict Management / DCB | DCB detection and resolution, Testing and evaluation of CBRs, DSS acceptance and rejection test cases |
| | Scenario 1 Collaborative Simulation | | |
| **2** | #6 | Airspace Constraints | Airspace constraints ingestion |
| | #7 | Operation Modification | Operational plan modifications to avoid active airspace constraints for pre-departure and airborne operations |
| | Scenario 2 Collaborative Simulation | | |

The seven software sprints were designed to cover the MVP for PSU described in Section 2.4. Sprints 1–5 includes testing of PSU capabilities that would be needed for nominal operations to simulate Scenario 1. Sprints 6–7 includes testing of capabilities in modifying operations in the presence of an airspace constraint, to simulate Scenario 2. At the end of all sprint tests for a scenario, the collaborative simulation where three partners will exercise the capabilities of that scenario as a group together.

# 3 X4 Simulation Development

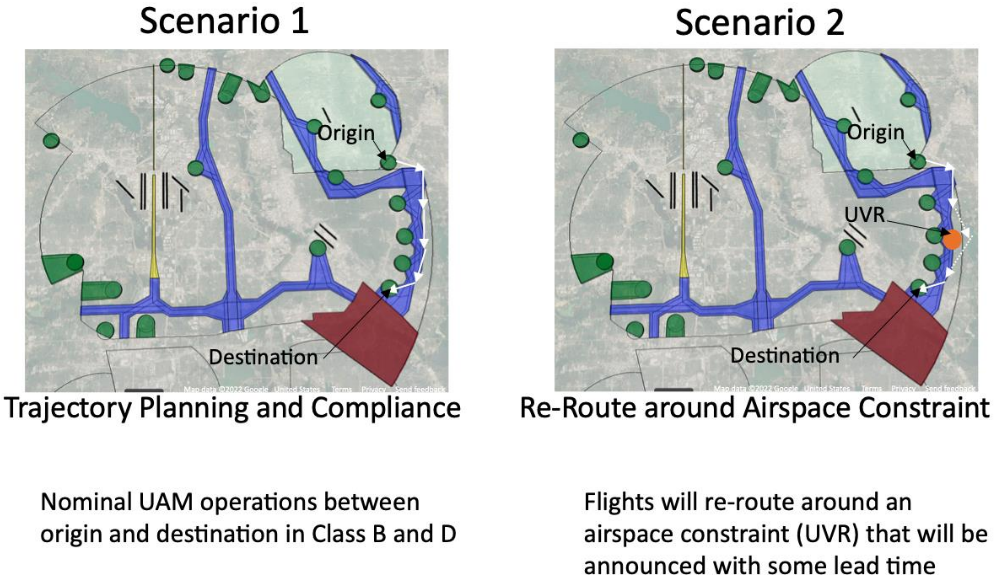
This section describes the two simulated operational scenarios and the refined capability definitions for PSU informed by industry discussions during X4.

## 3.1 Simulated Operational Scenarios

Two scenarios defined by NASA's AAM National Campaign Sub-Project in their Announcement for Collaborative Partnership Opportunities [9] were selected as use cases for evaluation in the simulation.

The focus of Scenario 1 was to traverse and conform to a defined operation plan under nominal conditions and to communicate with other UAM Operators in the airspace as needed. In Scenario 1, each PSU performed pre-departure flight planning for UAM Operators using the provided routes and airspace information from the ASDS, as seen in Figure 11 (left side) and submitted the operational plan to the PSU Network. This was followed by simulation of vehicle(s) that conformed to that operation plan. The white arrows show a notional depiction of a UAM flight traversing from origin in Class D airspace to a destination vertiport in Class B airspace.

Scenario 2 was an extension of Scenario 1's nominal flight operations with an objective to perform a re-route due to a temporary flight restriction (TFR) or a UAS Volume Reservation (UVR), required for public safety operations or some disasters such as fires in the area, on the route of the planned operation. The UVR would be announced by an entity that represented public safety or FAA. The PSU involved with the operation had to re-plan the operation so that it would not enter the volumetric restriction. Figure 11 (right side) shows a notional operation planned from Class D to Class B airspace. The notional restriction was announced in Class B airspace shown as an orange circle and required the UAM Operators to modify their plans either pre-departures or in-flight to reroute around the UVR by flying in Class G airspace and later rejoining the corridors in Class B airspace. During X4 testing, the UVR was announced in the middle of the simulation and ended before the end of the simulation to assess the impact to operations that had not departed and those that were already airborne.



Scenario 1

Trajectory Planning and Compliance

Nominal UAM operations between origin and destination in Class B and D

Scenario 2

Re-Route around Airspace Constraint

Flights will re-route around an airspace constraint (UVR) that will be announced with some lead time

*Figure 11. Scenarios simulated in X4*

## 3.2 Simulated Capabilities Development

While the X4 MVP for PSU served as a starting for planning X4 sprint and simulations activities, NASA organized and hosted a series of weekly meetings with partners to discuss and refine how these USS-based capabilities would be defined for the PSU. This section summarized the results of those discussion that drove the testing activities.

### 3.2.1 Access to Airspace Structure Definitions

To facilitate sharing of airspace structure information for UAM operations, the PSU would need access to a common set of airspace information for use in their operational planning. The initial set of airspace structure definition data that were required for PSU to create and share the operational intent to operate within the X4 airspace environment include:

- Corridors and tracks for UAM operations within Class B/C/D airspace, and associated performance requirements (e.g., airspeed)
- Arrival and departure procedures into and out of vertiports
- Vertiport locations and surrounding vertiport volumes

For X4, these data would be provided by a new service, the Airspace Structure Definition Service (ASDS), in the simulation environment, further described in Section 4.3.2. Future research would be needed to understand whether this data set would be provided by the FAA, Vertiport Operators, or UAM Operators. There are currently well-established methods in the NAS for ensuring that the airspace structure is known and accessible to all users and services provides, and that all users and service providers have the same information. UAM operations will likely build off those existing systems and data models.

### 3.2.2 Operational Intent Submission and Sharing

Operational intent includes "operation specific information including, but not limited to, UAM operation identification, the intended UAM corridor(s), aerodromes, and key operational event times (e.g., departure, arrival) of the UAM operation" [1]. For X4, UAM operational intent data served the following primary functions:

- To inform other UAM Operators of nearby operations within the UAM airspace environment
- To coordinate with other UAM operators on estimated time of arrival (ETAs) when utilizing shared resources such as vertiports
- To enable identification and distribution of known airspace constraints and restrictions for the intended area of operation

To support these functions, operational intent submitted by PSU and shared with other PSUs would include planned 4D trajectory (4DT) information. 4DT operational intent supported better utilization of resources where more accurate ETA predictions enable efficient airspace management. A 4D element specified a unique 3D (latitude, longitude, altitude) position at a given time, and 4DT was an ordered series of such 4D elements. For X4, within the 4DT, PSU would include, at a minimum, the waypoints where Demand-Capacity Balancing (DCB) among UAM operators were applied. Since UAM Operators' coordination of strategic plans relied on the 4DT information within the operational intent, PSUs were required to share 4DT operational intent with other PSUs, i.e., via PSU-PSU API. Operational volume(s), while not required for the shared intent, were used when PSU submitted operations to DSS (via PSU-DSS API) to allow PSU to discover relevant operations and airspace constraints using the existing implementation of DSS for UTM.

### 3.2.3 Conformance Monitoring

For UAM operations, it is expected that the vehicle or pilot, UAM operators, and PSU will play a role in maintaining conformance to the submitted operational intent. As conformance monitoring is a tactical function, and the focus of X4 was on the strategic functions, the decision for X4 was to develop simple requirements that were based on the 4DT operational intent submitted by the UAM Operator. This initial implementation will help gain valuable insight into the tactical layers and establish baseline for future work.

In X4, each PSU monitored conformance by checking vehicle telemetry information against submitted 4DT operational intent while the vehicle was active. PSU would alert other UAM operators, via the PSU Network, of non-conforming operations. To facilitate initial implementation of PSU in conformance monitoring, the following suggested (underlined) parametric values were developed as a starting point and would be informed by future research and demonstration activities:

- Telemetry data for an active operation was last sent by PSU for <u>10 seconds</u> or more
- Telemetry showed simulated aircraft were not within <u>1,500 feet</u> lateral and <u>250 feet</u> vertical within <u>60 seconds</u> of the Estimated Time of Arrival (ETA) at the discrete points within the operational intent submitted by the PSU

### 3.2.4 Airspace Authorization

It was assumed UAM Operators would be required to obtain an authorization when operating within the UAM Corridors inside Class B/C/D airspace. This authorization was referred to as an airspace authorization.

- An airspace authorization would grant an UAM Operator access to UAM corridor inside Class B/C/D per operation.
- UAM Operators could apply for airspace authorizations from a PSU qualified to provide airspace authorization services
- Qualified PSUs could access UAM airspace structure definitions and status information (e.g., open/close) to determine when a UAM operation is available (or not) for automated approval

In X4, the airspace authorization functionality was kept simple. To obtain airspace authorization, PSU would check the UAM Operator-submitted 4DT operational plan against performance requirements (e.g., speed) for operating within UAM Corridors. PSU would notify the FAA about the operation via the FIDXP, by submitting the 4DT operational plan and other additional information required (e.g., flight rule). Once the PSU received an acknowledgement from the FIDXP service, it would submit a copy of this operational plan to the DSS, to be shared with other PSUs.

### 3.2.5 Strategic Conflict Management

The Conflict Management concept for UTM and UAM were both built around the three conflict management layers defined in the ICAO Global Air Traffic Management Operational Concept (GATMOC): strategic conflict management, separation provision (also referred to as "tactical conflict management" in this paper), and collision avoidance [11]. The focus of X4 was on the first layer, Strategic Conflict Management (SCM).

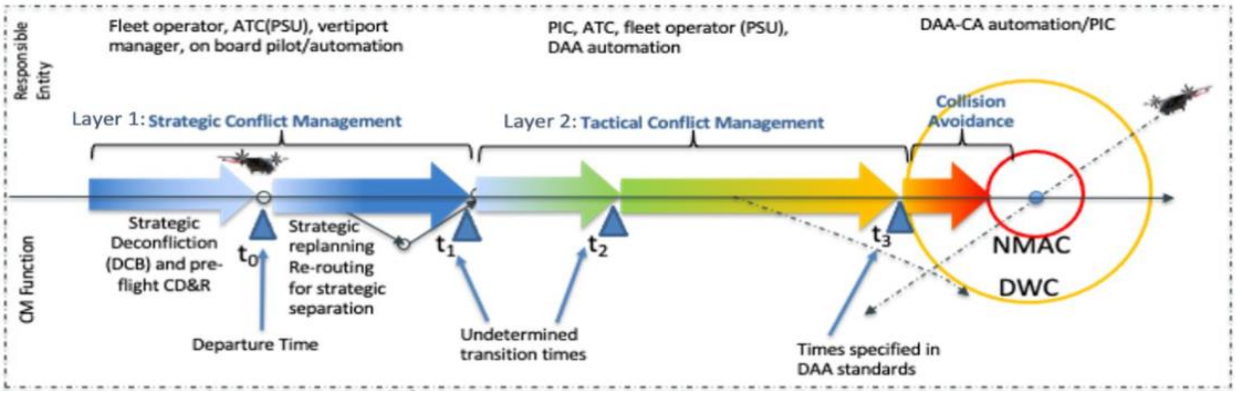


*Figure 12. Conflict Management Concept for UAM*

Figure 12 illustrates the relationship between the strategic conflict management and separation provision layers. In general, the SCM layer is applied so that the next layer – separation provision – can operate safely and efficiently.

During X4, NASA led discussions with seven industry partners to develop initial SCM concept and requirements for UAM. SCM capabilities and processes were applied to establish a shared strategic plan from which the actors – such as UAM Operators – in the system operate. The shared strategic plan was the result of a sequence of strategic processes and was pervasive continuously throughout UAM operations. These strategic processes could be broken down into several concepts, including airspace organization and management (AOM), demand-capacity balancing (DCB), and traffic synchronization (TS), as shown in the figure below.

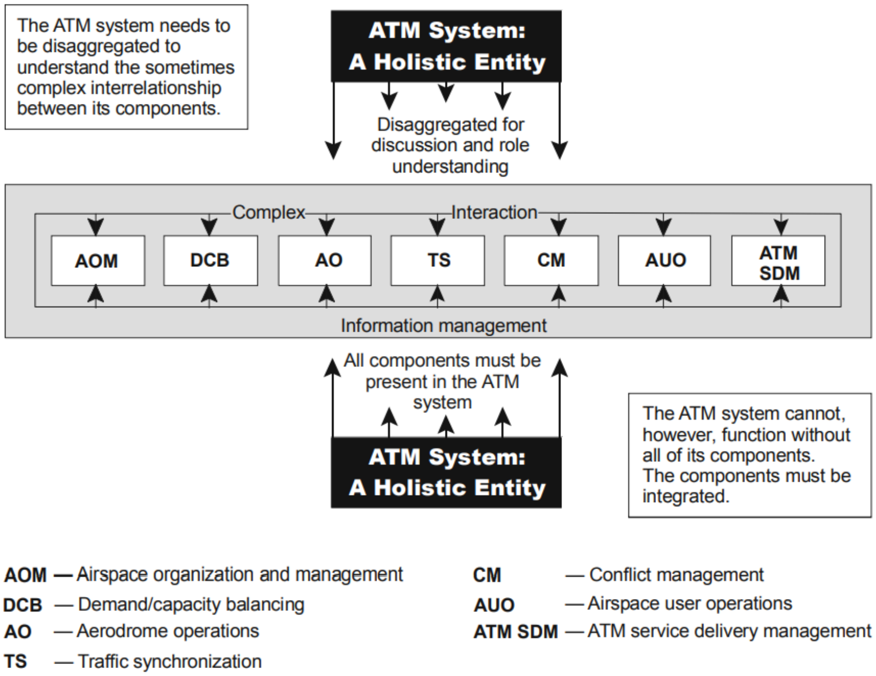


*Figure 13. The Seven Air Traffic Management (ATM) Concept Components from ICAO 9854*

For X4, as all vertiports and corridors were shared among UAM Operators, and these shared resources had capacity limits or constraints, UAM Operators would coordinate their strategic plans as part of the DCB concept. Under DCB, the UAM Operator responded to customer demand by creating or modifying operational intent subject to the constraints (e.g., capacity) that currently exist. In this model, the shared strategic plan included the 4DT operational intents for all UAM aircraft that have been submitted into the PSU network. The DCB processes were largely the responsibility of the UAM Operators, but Vertiport Operators and ATC may continue to play a role (e.g., by establishing the capacity of shared resources).

While DCB could be quite complex, the choice was made for X4 to keep it relatively simple as a first step toward understanding how DCB could be implemented in a federated paradigm: Each UAM Operator would coordinate their strategic operational intent, via PSU, to ensure their own operations will not exceed defined capacity constraints. CBRs were developed to define the way in which DCB should be performed among PSUs. The CBRs developed for X4 could be found in [12]. At a high level, PSUs were responsible for ensuring that operation plans submitted by UAM operators meet all applicable DCB constraints. To better define this DCB process, it was broken down into four steps:

1. Identification of capacity.

Capacity was determined by a variety of factors which may directly relate to capacity limitations, traffic density or complexity impacting human workload. Capacities can be specified in a variety of ways, such as flow rates of traffic through a resource, temporal separation of successive arrivals at a resource, or volume occupancy.

For X4, capacity constraints were set only at vertiports, and these vertiport capacities were made available through a common data source, namely the Capacity Information Service (CIS), to all UAM Operators. The constraint was specified as number of operations (including arrival and departure operations) per defined time bin. The CIS API described the constraints data, as well as how the bounds of time bins should be interpreted by PSUs to ensure consistency. For example, the values used in the collaborative simulations were 4 operations per vertiport per 12-minute bin. An operation falling exactly at the edge of a time bin was counted as part of the demand in the next time bin.

2. Identification of demand.

Demand was calculated based on strategic plans shared by operators, when available, or can be roughly estimated from historical data.

For X4, PSU must share information for DCB in their operational intents with the PSU Network, obtain information about other operational intents utilizing the shared resources (i.e., vertiports). The discovery of relevant operational intents was done via DSS.

3. Detection of demand-capacity imbalance.

DCB detection required assessing the demand at capacity constrained resources and comparing that demand to the capacity of the resource.

To do so, PSU must determine if operations being planned would cause a demand-capacity imbalance. If an imbalance was detected, PSUs were responsible for revising the operational plan such that it should do not cause any demand-capacity imbalances prior to submitting it to the PSU Network.

4. Resolution of demand-capacity imbalance.

If an imbalance was detected, it could be resolved through the modification of one or more operations involved. UAM Operators may choose to use ground delay, speed control, rerouting, or a combination of these to resolve the imbalance. Ground delay and speed control of operations could be used to adjust the demand to satisfy capacity constraints. Rerouting around resources that were heavily used can avoid oversubscribed resources.

The X4 CBRs did not prescribe how PSU would implement the demand-capacity imbalance detection and resolution capabilities, hence, X4 participants were free to choose how and where to implement this DCB functionality. Some participants chose to implement all DCB functionalities within their PSU, while others used an external DCB service that was built and made available by one of the X4 partners for detection of demand-capacity imbalance (Step 3). Regardless of either approach, DCB resolution (Step 4) were all done within each participants' PSU. For NASA implementation of DCB, see Appendix: NASA Implementation of DCB.

### 3.2.6 Airspace Constraints and Dynamic Replanning.

In the presence of temporary airspace constraints that prevent UAM operations from operating its planned active duration, the UAM Operators would need to be aware and notified of such constraints. These temporary airspace constraints could be due to a variety of reasons, due to operations by public safety, Temporary Flight Restrictions (TFRs), weather events, or hazards in the area.

In X4, these temporary airspace constraints were defined in similar ways to "UAS volumes reservations" (UVR) which had defined spatial and temporal boundaries. Upon notification, the UAM Operator will re-route all impacted pre-departure and airborne operations around the airspace constraint by submitting modified operational plans via the PSU.

In UTM, such UVRs were created and managed by public safety. While the UVR construct may be leveraged initially for UAM to understand how UAM Operators may be informed of temporary airspace constraints such as TFRs, more research would be needed to understand how and whom this information would be managed for UAM within the NAS environment. In X4, NASA played the role of this entity and provided the service called Airspace Constraint Management (ACM) PSU to publish and update UVRs. However, there are currently well-established methods in the NAS for ensuring that the airspace constraints are known and accessible to all users and services providers in a timely manner. UAM operations will likely build off those existing systems and data models.

### 3.3 Community-Based Rules Development

This section provides a brief overview of the purpose and categorization of CBRs. The reader is encouraged to review References [10], and [12] for a more in-depth description of CBRs, considerations for their development, and how government and industry might interact to develop, review, and administer UAM CBRs.

Before development of CBRs that capture agreement on how UAM operations are to occur, there must be agreement on how such CBRs will be developed, reviewed, approved, updated, and retired. Thus, we proposed two broad categories of CBRs: Administrative and Operational, as well as a further decomposition of related CBRs into groups hereafter referred to as *CBR Topic Areas*.

1. **Administrative CBRs.** Administrative CBRs address how CBRs will be developed, reviewed, approved, modified, and retired when they are replaced or no longer needed. Additionally, administrative CBRs may define minimum expected content for operational CBRs. Because administrative CBRs will detail review, approval, and administration, they will need to be developed prior to operational CBRs.
2. **Operational CBRs.** As stated in Reference [10] "Operational CBRs are those that reflect agreements on the direct conduct of operations, rather than focusing on the management of the CBRs themselves. At their heart, they concentrate on actions, exchanges, and rules to ensure overall service expectations and needs are met."

CBRs will cover a broad range of elements and interactions across UAM domains. Grouping CBRs into related topic areas may be useful to help UAM industry allocate development of CBRs more effectively. Additionally, it may not be efficient to review CBRs individually, but rather to do so as a set of closely related CBRs that address a specific capability (e.g., Demand Capacity Balancing).

Development of X4 CBRs focused primarily on Operational CBRs, and the scope was limited to the X4 Strategic Conflict Management. It was an initial effort to explore CBRs with industry partners, focusing on what was required for strategic stages of cooperative traffic management. As a result of this collaboration, 24 CBRs were developed across 5 *Topic Areas*:

1. Onboarding Requirements
2. Operational Intent
3. Conformance Monitoring
4. Demand Capacity Balancing
5. Airspace Constraint Management

For a description of the X4 CBR development process and the 24 CBRs developed for X4, the reader is referred to Reference [12].

# 4 X4 Simulation Execution

This section describes the process of conducting the planned software sprints and collaborative simulations with seven airspace partners, as well as a detailed description of the X4 simulation architecture that was designed to demonstrate the defined PSU capabilities and CBRs for SCM.

### 4.1 Test Execution

Prior to each software sprint, NASA developed and provided test procedures and relevant Application Protocol Interfaces (APIs) to all partners. The final X4 APIs can be found in [13].

To proceed to the next software sprint, each partner needed to successfully complete the previous sprint. At the end of each software sprint test, data from partner PSUs were collected where it would be analyzed and verified that requirements allocated for the PSUs were met.

A Data Collection Environment was set up by NASA to collect operational intents, operations state changes, simulated telemetry data, and other additional data for each operation submitted by each PSU – both during and after each test.

During the test, operational intents were collected by inter-PSU communications to the NASA Universal Data Collector (UDC) that was part of the Data Collection Environment. All operational intents and its status changes during the test were posted to UDC. Each participating PSU must inform UDC about its operations because a subscription, with a wide airspace volume surrounding DFW area defined in test scenarios, was submitted to DSS by UDC before each test. Telemetry data for each operation was also collected by inter-PSU communications to UDC. When UDC is informed that an operation's state has changed to "Activated", meaning the aircraft departed, it started polling for position data from PSU that originated the operation at regular intervals of once every 10 seconds. When the PSU was polled, it would send position data and time when data was captured back to UDC PSU. Polling for telemetry data continued until UDC got informed that the operation had terminated which means the aircraft had landed.

After each test was done, each participant would submit additional data required for the analysis but not captured during the live test session. These PSU "log" data was defined via an established API, which included:

- Messages exchanged between its PSU and other PSU(s)
- Messages exchanged between its PSU and DSS
- Messages exchanged between its PSU and FIDXP
- Messages exchanged about UVR
- Operational intents prior to any DCB adjustments or rerouting due to UVR
- Operational intents for planning attempts that were denied by the DSS

The data collected by UDC, as well as the post-test "log" data submitted by participant PSU, were stored in a Postgres database. These data were processed, and test results are summarized in Section 5.

The results of interim testing were updated and shared with all partners. The final testing results determined whether the PSU requirements are satisfied sufficiently to move the partner forward to the next sprint.

## 4.2 Traffic Demand

To test DCB capabilities developed by NASA and by seven airspace partners, NASA constructed simulated UAM traffic demand managed by multiple UAM Operators and shared them with the airspace partners prior to each simulation. The purpose of these simulated traffic demand was to create sufficient demand-capacity imbalances at vertiports to assess how the PSUs would update their operational plans to resolve the imbalances and to understand how multiple PSUs would interact during the two collaborative simulations.

Based upon the airspace constructs and adaptation described in Section 2.3, a subset of the vertiports were selected as Origin-Destination (OD) pairs to support various objectives for X4 simulations, including exercising DCB (i.e., using vertiports to support more than one OD pair), exploring partners' routing choices through Class B/D and in Class E/G, and those that went through the UVR for Scenario 2. Figure 14 shows the twelve routes connecting the selected origin-destination vertiport pairs used for Scenario 1 Collaborative Simulation. The traffic demand of each UAM Operator was evenly distributed over these routes but had a peak in the 1.5-hour long simulation run, ensuring sufficient demand-capacity imbalances for each participant to evaluate its DCB capability.

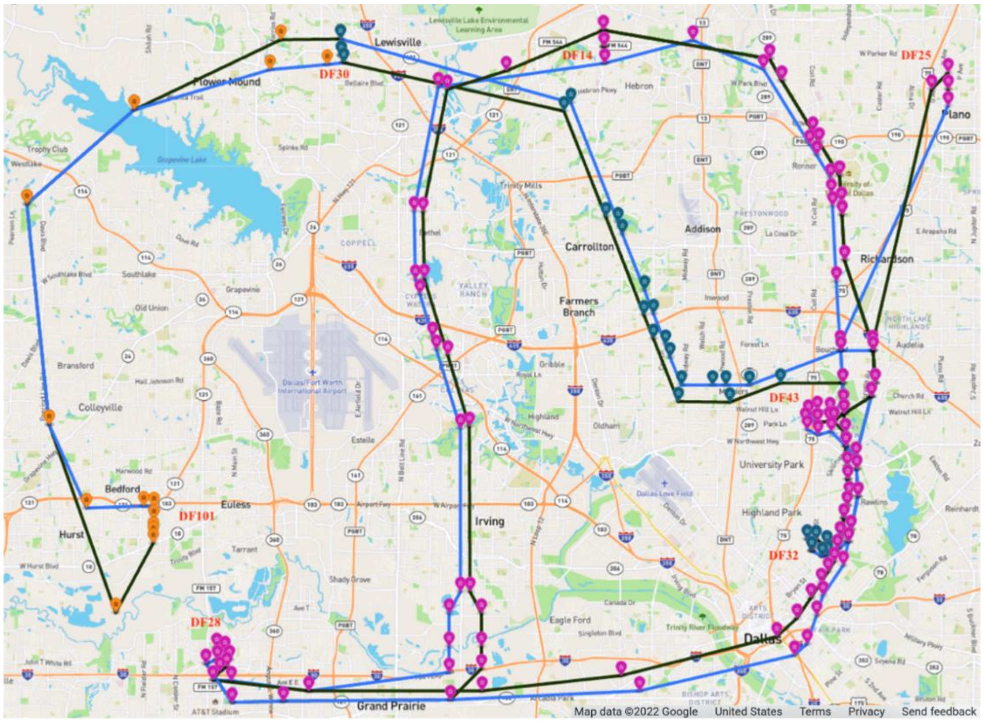
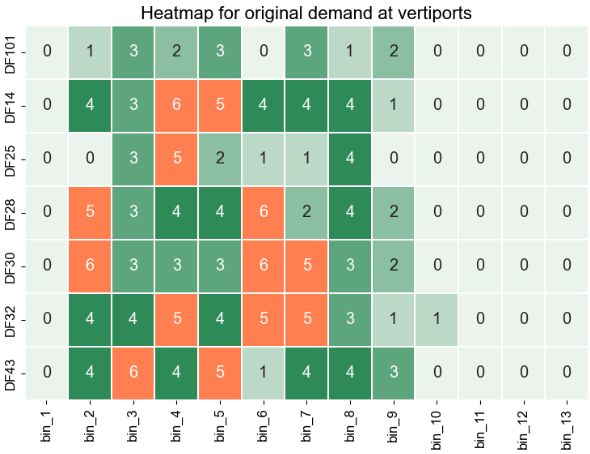


*Figure 14. Routes used in Scenario 1 Collaborative Simulation*

As shown in Figure 15, it shows the desired operations at each of the seven vertiports and how they distribute over the duration of the simulation. Since the capacity for this simulation was 4 operations per vertiport per 12-minute time bin, the operations are shown in 12-minute time bins. The numbers in the cells indicate the number of operations in that time bin for a particular vertiport. Cells that are over-capacity (i.e., > 4) are highlighted in orange color.



Heatmap for original demand at vertiports

| | bin_1 | bin_2 | bin_3 | bin_4 | bin_5 | bin_6 | bin_7 | bin_8 | bin_9 | bin_10 | bin_11 | bin_12 | bin_13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DF101 | 0 | 1 | 3 | 2 | 3 | 0 | 3 | 1 | 2 | 0 | 0 | 0 | 0 |
| DF14 | 0 | 4 | 3 | 6 | 5 | 4 | 4 | 4 | 1 | 0 | 0 | 0 | 0 |
| DF25 | 0 | 0 | 3 | 5 | 2 | 1 | 1 | 4 | 0 | 0 | 0 | 0 | 0 |
| DF28 | 0 | 5 | 3 | 4 | 4 | 6 | 2 | 4 | 2 | 0 | 0 | 0 | 0 |
| DF30 | 0 | 6 | 3 | 3 | 3 | 6 | 5 | 3 | 2 | 0 | 0 | 0 | 0 |
| DF32 | 0 | 4 | 4 | 5 | 4 | 5 | 5 | 3 | 1 | 1 | 0 | 0 | 0 |
| DF43 | 0 | 4 | 6 | 4 | 5 | 1 | 4 | 4 | 3 | 0 | 0 | 0 | 0 |

*Figure 15. Desired Operations at Vertiports*

During the simulation, these desired operations would go through each partner's DCB process and be updated using their DCB resolution algorithm. As part of the evaluation at the end of the simulation, it was expected there should not be any over-capacity bins, as each participant was expected to resolve predicted demand-capacity imbalances prior to submitting an operation. The results will be described in Section 5.

## 4.3 Simulation Architecture

As shown in Figure 16 below, the X4 simulated architecture evolved from the UAM Notional Architecture to include additional services needed to support capabilities described in Section 3.2 for UAM strategic conflict management.

The X4 simulated architecture included an initial prototype of the FAA-Industry Exchange Protocol (FIDXP), prototype of a service that provided UAM airspace structure information to UAM Operators (ASDS), third-party services (DSS, PSU), other services to facilitate UAM strategic conflict management (Demand-Capacity Balance Service, Capacity Information Service), and services for data collection and dynamic density UAM metric.

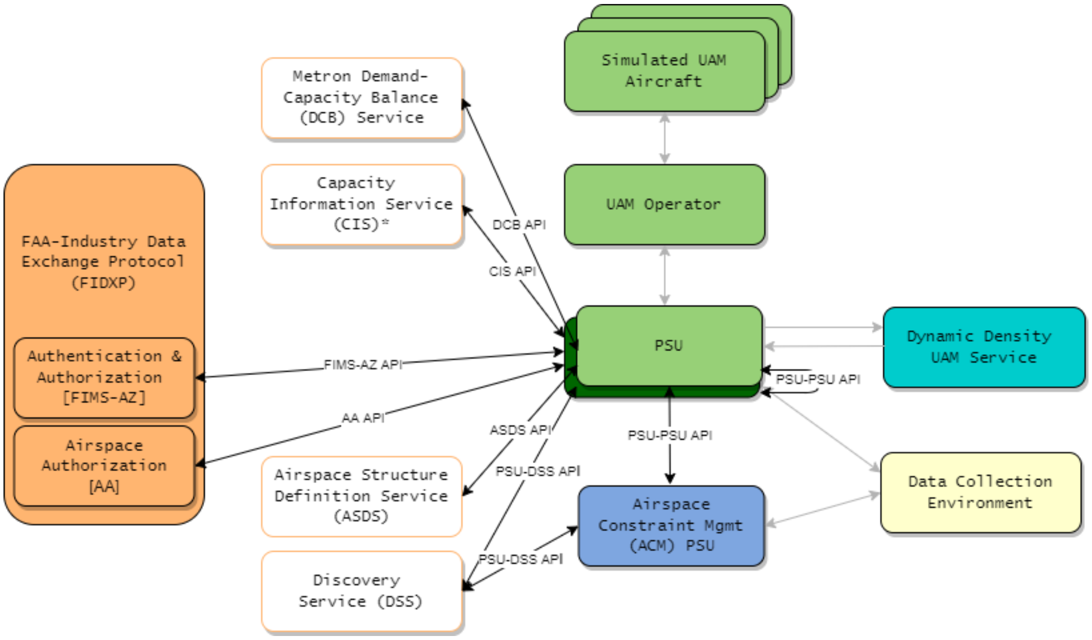


*Figure 16. X4 Simulation Architecture*

To facilitate how the information would be exchanged among PSUs and with other services, NASA developed and provided data model definitions and Application Protocol Interfaces (APIs) that were made publicly available [13]. High-level descriptions of these services are provided below.

### 4.3.1 FAA-Industry Data Exchange Protocol (FIDXP)

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.

In X4, a prototype FIDXP was developed for simulation. The FIDXP for X4 provided:

- Authentication and authorization of all services, to ensure access was provisioned to those permitted to obtain it. Leveraging the FIMS existing functionality (known as FIMS AZ) developed by NASA for UTM, it provided the method of authentication for all PSUs and services that were used by PSU (i.e., DSS, ASDS, DCB Service).
- Airspace authorization functionality to allow UAM Operators to obtain an authorization prior to operating within the UAM Corridors inside Class B/C/D airspace, via the PSU.

### 4.3.2 Airspace Structure Definition Service (ASDS)

The Airspace Structure Definition Service (ASDS) was a simulation component of the X4 architecture that provided vertiports and airspace structures information, as discussed in Section 2.3. For X4, 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.

### 4.3.3 Discovery and Synchronization Service (DSS)

Discovery and Synchronization Service (DSS) was an open-source implementation to meet certain ASTM standards for UTM [14] that had been built and maintained by industry. For UTM, the DSS allowed 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 detection by identifying operational volumes that intersect each other.

In X4, NASA deployed v0.3.17 of the InterUSS specification for DSS and provided it as a service within the X4 system architecture. DSS was utilized by all participating PSUs and DCB service to facilitate automated data exchanges between one another within the PSU Network, specifically:

- Discovery – It enabled UAM Operators to register into an airspace, be aware of other UAM Operators in the airspace, and to submit operations, via the PSU.
- Synchronization – It validated that the PSU had obtained all relevant data from other PSUs. This was designed to ensure that the PSU assisting the UAM Operator had complete and up-to-date information about other operations and airspace constraints in the area of that operation.

DSS was an integral part of the federated architecture that enabled discovery of relevant demand for DCB planning. It provided PSUs and DCB service a mechanism to obtain relevant operational plans from other PSUs for calculating demand at shared resources (i.e., vertiports), and to ensure operational plans among PSUs and DCB service used for such DCB planning were synchronized.

### 4.3.4 Provider of Services for UAM (PSU)

A PSU is an entity that provides services to the UAM Operator to help them meet UAM operational requirements that enable safe, efficient, and secure use of the airspace [1]. 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. In X4, an initial implementation of the PSU was tested for these functions:

- Submitting trajectory-based operational intent and share with the PSU Network
- Modifying operational intent and states and submit to the PSU Network
- Sharing vehicle telemetry with PSU Network
- Monitoring conformance of the operational intent
- Submitting operational plan notification to FIDXP with an initial implementation of Airspace Authorization
- Ensuring submitted operational plan meet all applicable Demand-Capacity Balancing (DCB) constraints
- Receiving airspace constraint information and identify impacted operations to the UAM Operator for replanning

### 4.3.5 Airspace Constraint Management (ACM) PSU

In X4, during Scenario 2 testing, a special, separate PSU whose only role was to create and manage a UAS Volume Reservation (UVR) Constraint was developed and tested. It was assumed, and captured as a CBR, that appropriate authorization was required for this special PSUs to create and share airspace constraints. This separate PSU, called the ACM PSU, was used to submit the UVR constraint and broadcast its information (e.g., location, geometry, time parameters) to other PSUs that were subscribed to the area. The ACM PSU had a granted role for ‘constraint_management’ only and was provided by NASA during X4 simulations.

### 4.3.6 Dynamic Density UAM Service

The System Wide Safety (SWS) Project under the Airspace Operations and Safety Program (AOSP) within NASA’s Aeronautics Research Mission Directorate (ARMD) is developing services that will provide safety predictions for emerging operations. A dynamic density metric was developed by the SWS Project for the emerging UAM concept, to predict airspace congestion that may lead to loss of separation between aircraft or less efficient operations [15]. During the X4 collaborative simulations, a prototype for the Dynamic Density Service developed by the SWS project, that could support In-Time Aviation Safety Management, was integrated and tested. This service obtained UAM operational plans and telemetry information through the PSU Network and calculated the dynamic density metric for the X4 corridors. The metric was visualized on multiple displays, which included the one shown in the figure below.

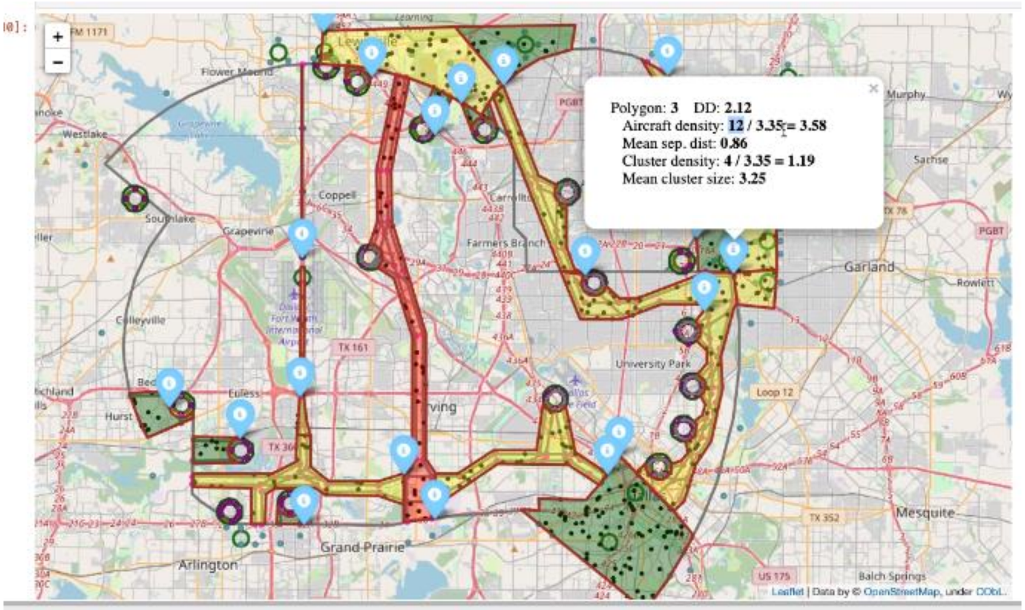


*Figure 17. Prototype Display of DD Showing Real-Time Information*

Bright green dots show most recent known positions of all aircraft. Corridors are color-coded for negligible (gray), low (green), moderate (yellow), and red(high) DD. Details are available on demand, as shown for corridor E.

### 4.3.7 Data Collection Environment

X4 was a collaboration activity between the UAM and National Campaign (NC) Sub-Projects. As part of this collaboration, the NC Airspace Testing and Integration (ATI) Team provided data collection capabilities to enable collection of real-time and post-simulation data during each test activity with airspace partners.

The Data Collection Environment was utilized by not just the X4 Simulation, but also for data collection purposes during NC flight trials. This Data Collection Environment included the Universal Data Collector (UDC), Data Pipeline, real-time database, and real-time visualization:

- The UDC was developed by NASA that leveraged existing PSU–PSU communication to collect data that were shared in the PSU Network. It enabled data acquisition, collection, and dissemination of all registered UAM service providers.

- The Data Pipeline transported high-frequency, high-throughput data from UDC to visualization and database. It also accepted the end-of-test logging records from all PSU.
- The real-time database was a set of repositories-of-record utilized to store and recall both real-time and post-simulation data for X4 and NC flight tests.
- The real-time visualization was a web-based, open-source platform used to show operations status and to visualize vehicle positions and telemetry in real-time using 2D graphics.

# 5 X4 Results and Findings

## 5.1 Partner Results

All seven partners and NASA successfully completed all seven software sprints by demonstrating required capabilities for each sprint. The two collaborative simulations were opportunities to demonstrate how multiple PSUs could work together in a collaborative environment with higher total simulated traffic demand.

*Table 2. Partner Software Sprints and Collaborative Simulation Results*

| Software Sprint / Collaborative Simulation | Results |
|---|---|
| Sprint #1 Connectivity | All seven partners completed |
| Sprint #2 Operational Intent | |
| Sprint #3 Nominal Flight | |
| Sprint #4 Airspace Authorization | |
| Sprint #5 Strategic Conflict Management / DCB | |
| Scenario 1 Collaborative Simulation | 2 groups partial, 1 group incomplete |
| Sprint #6 Airspace Constraints | All seven partners completed |
| Sprint #7 Operation Modification | |
| Scenario 2 Collaborative Simulation | 2 groups partial, 1 group incomplete |

The results presented in the following sections are for the collaborative simulations. Each collaborative simulation had three groups (referred to as Group 1, 2, 3) of three participants (assigned as Participant 1, 2, 3) each. For Scenario 1, each participant was assigned 32 operations for a total of 96 operations, which are evenly distributed to 12 routes connecting 7 vertiports. For Scenario 2, certain routes were removed from the previous Scenario 1 to simplify the traffic interaction with the UVR. As the result, participants 1, 2, and 3 were assigned 28, 29, and 30 operations, respectively, with a total of 87 operations.

## 5.2 System Performance Metrics

Before the start of X4 simulations, we identified a set of metrics to help understand the system performance and effectiveness. These were conducted with the aggregated data from each participant during the two collaborative simulations. These metrics include:

- total operations simulated
- trajectory conformance
- demand capacity imbalance resolution
- ground delays
- dynamic replan rate in response to UVRs

### 5.2.1 Total Operations Simulated

The demand scenario developed by NASA and shared with airspace partners for executing Scenario 1 and Scenario 2 collaborative simulations included 12 routes with 96 total operations, and 11 routes with 87 total operations, respectively. Figure 18 shows the number of operations that were successfully submitted and flown by simulated UAM operators within each group. In each case, some participant's PSU within the group had technical issues where several operations did not get submitted, some operations did not get activated, and occasionally, the operations data could not be collected during the simulation due to a variety of reasons.

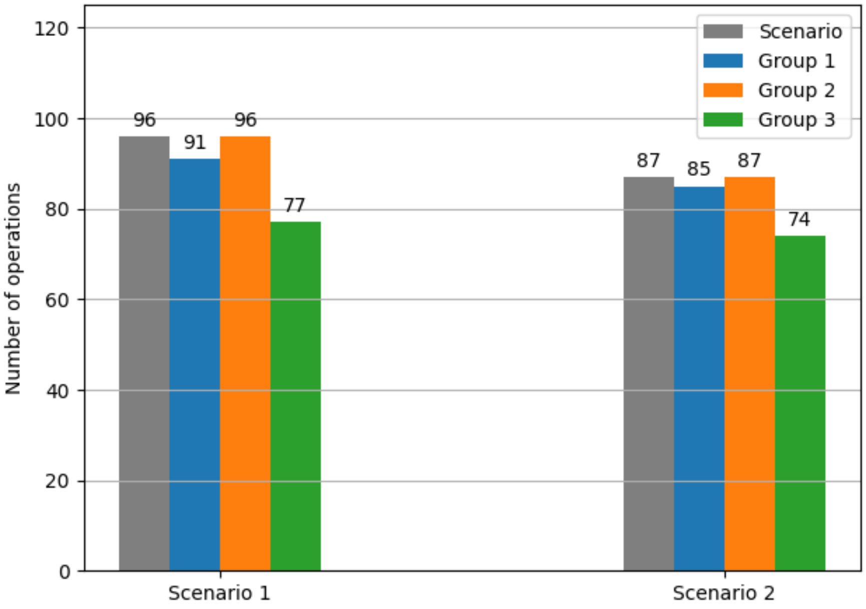


Figure 18. Total Operations Simulated During Collaborative Simulations

### 5.2.2 Trajectory Conformance

For X4, trajectory conformance meant that simulated aircraft telemetry should be within lateral, vertical, and temporal bounds at each discrete point defined within the operational intent submitted by the PSU. These discrete points include required trajectory points (i.e., vertiport) as well as other optional points as defined by the UAM operator. The parameters used in X4 are placeholder values to test initial conformance monitoring for trajectory-based operational plans. As shown in Figure 19, in each simulation, some operations were not conforming based on these criteria described in Section 3.2.3:

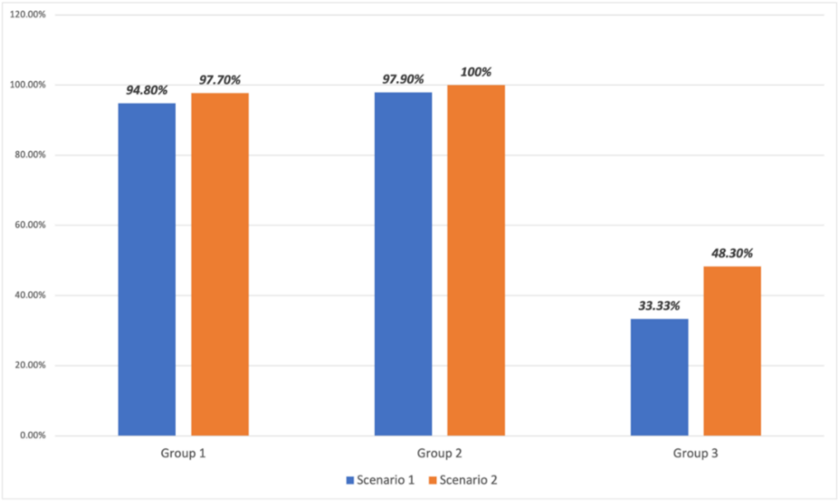
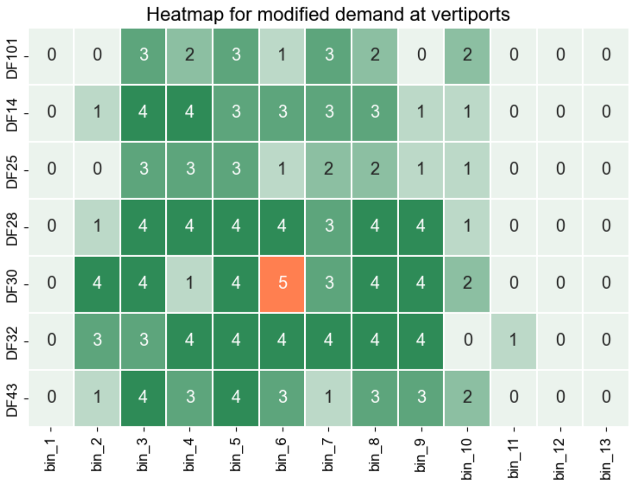


Figure 19. Trajectory Conformance Results

### 5.2.3 Demand Capacity Imbalance Resolution

As described in Section 5, NASA provided the demand scenarios designed to evaluate demand-capacity balancing capabilities to each airspace partners. It is expected that partners' PSU would resolve the demand capacity imbalances by updating the operational intent so that vertiport capacity constraints would be adhered to. Figure 20 shows an example of demand-capacity imbalance from Scenario 2 collaborative simulation. The numbers in cells indicate the number of operations in that time bin. Time bins that are over-capacity (i.e., > 4 operations) are highlighted in orange color.



| | bin_1 | bin_2 | bin_3 | bin_4 | bin_5 | bin_6 | bin_7 | bin_8 | bin_9 | bin_10 | bin_11 | bin_12 | bin_13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DF101 | 0 | 0 | 3 | 2 | 3 | 1 | 3 | 2 | 0 | 2 | 0 | 0 | 0 |
| DF14 | 0 | 1 | 4 | 4 | 3 | 3 | 3 | 3 | 1 | 1 | 0 | 0 | 0 |
| DF25 | 0 | 0 | 3 | 3 | 3 | 1 | 2 | 2 | 1 | 1 | 0 | 0 | 0 |
| DF28 | 0 | 1 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 1 | 0 | 0 | 0 |
| DF30 | 0 | 4 | 4 | 1 | 4 | 5 | 3 | 4 | 4 | 2 | 0 | 0 | 0 |
| DF32 | 0 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 0 | 1 | 0 | 0 |
| DF43 | 0 | 1 | 4 | 3 | 4 | 3 | 1 | 3 | 3 | 2 | 0 | 0 | 0 |

*Figure 20. Example of Demand-Capacity Imbalance from Scenario 2 Collaborative Simulation.*

Table 3 shows the summarized results of resolved and unresolved demand-capacity imbalances for all the collaborative simulations.

*Table 3. Number of Resolved and Unresolved Demand-Capacity Imbalances*

| | **Scenario 1** | | **Scenario 2** | |
|---|---|---|---|---|
| **Group #** | Resolved | Unresolved | Resolved | Unresolved |
| Group 1 | 18 | 0 | 11 | 1 |
| Group 2 | 22 | 4 | 14 | 0 |
| Group 3 | 10 | 1 | 8 | 2 |

In some cases, some groups were able to resolve all imbalances. In other cases, there were more operations submitted than the capacity, hence resulted in unresolved imbalance. The unresolved demand capacity imbalances were attributed to:

- Issues within PSU's demand-capacity balancing algorithm. Since each PSU was treated as a black box, there was no available data to understand what exactly caused the imbalance.
- Timing and synchronization handling by DSS, multiple PSUs and DCB service. There was an instance during testing when two PSUs (referred to as "PSU A" and "PSU B") submitted operations around the same time when there was only one available capacity for that time bin at the vertiport. "PSU A" was planning its operation and requested information from DCB service, while the "PSU B" submitted its operation to DSS and was accepted. The "PSU A" then submitted its operation to DSS, and was also accepted, which caused an imbalance since "PSU A" used DCB service which did not have the updated operation for "PSU B" yet. This issue highlighted the fact that as new services are added to the federated architecture, it added a level of

complexity to ensure the system could provide accurate DCB results while closing on a solution timely.

### 5.2.4 Ground Delays

In X4, it was left up to the partners on how they implemented the demand-capacity imbalance resolution. However, all operators, including NASA, employed the simplest resolution strategy by assigning pre-departure delays to operations with predicted demand-capacity imbalance. Figure 21. Mean Pre-Departure Delay in Scenario 1 Collaborative Simulation shows the average ground delay assigned by all three groups and the standard deviation of those delays during Scenario 1 collaborative simulation. Both the average ground delay and its standard deviation were calculated for only those aircraft that were assigned delays.

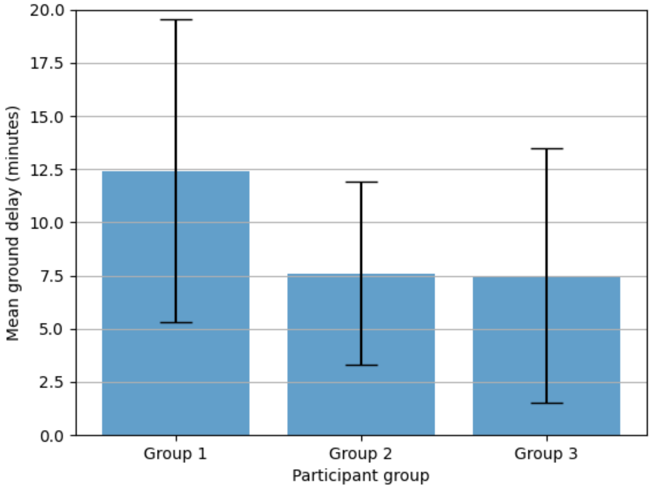


*Figure 21. Mean Pre-Departure Delay in Scenario 1 Collaborative Simulation*

For the results shown in Figure 21, Group 1 had 33 delayed operations, Group 2 had 27, and Group 3 had 16. The differences in number of delayed operations and assigned ground delays arise from the differences in participants' implementation of their own DCB resolution algorithms. For example, the average ground delay was higher in some groups as the departure time were rescheduled to the middle of the next available time bin, rather than the beginning of the time bin.

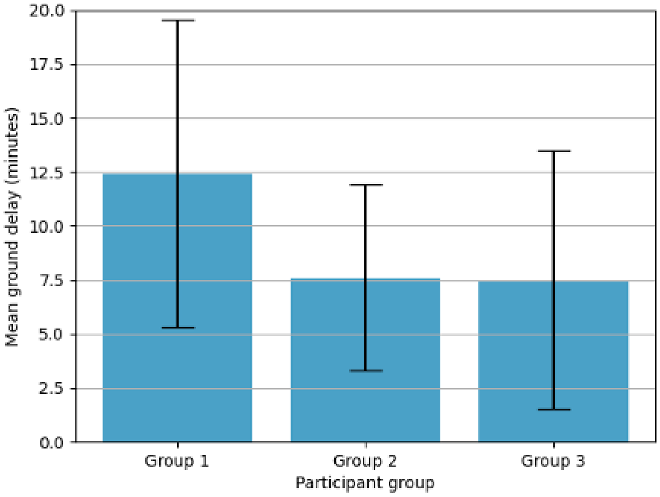


*Figure 22. Mean Pre-Departure Delay in Scenario 2 Collaborative Simulation*

Figure 22 shows the average pre-departure delays and their standard deviation for Scenario 2 collaborative simulation. Group 1 had 22 delayed operations, Group 2 had 20, and Group 3 had 9.

### 5.2.5 Dynamic Replan Rate In Response to UVRs

This metric measures how many operations that were designed to fly through the pre-defined UVR area were successfully re-routed to avoid the UVR during Scenario 2. The demand scenario included 9 operations that were assigned to the flight route that went going through the pre-defined UVR area, but only 6 operations of those operations were during when UVR was active. Each participant was expected to identify those 6 operations correctly and reroutes those operations which includes 3 airborne and 3 pre-departure operations. Table 4 summarizes the results.

In some cases, the operations did not get successfully re-routed due to dual purpose of operational volumes(s) in DSS: (1) for DCB demand identification and (2) for detecting overlaps with UVR. Some PSUs only provided operational volume(s) surrounding the departure and arrival vertiports required for DCB, but if the UVR was along the route but outside of the vertiport operational volume(s), DSS determined that the operation did not overlap with the UVR. Hence, the PSU was not informed about UVR even though it would impact its operation.

*Table 4. Dynamic Replan Rate Results in Scenario 2 Collaborative Simulation*

| Group | Airborne Reroutes (completed / expected) | Pre-departure Reroutes (completed / expected) | Total % Operations Replanned |
|---|---|---|---|
| **Group 1** | 3 / 3 | 3 / 3 | 100% |
| **Group 2** | 3 / 3 | 3 / 3 | 100% |
| **Group 3** | 2 / 3 | 2 / 3 | 66.7% |

## 5.3 Lessons Learned

X4 accomplished NASA's objectives and all participants, including NASA and seven airspace partners, successfully implemented initial PSU capabilities for strategic conflict management, which included operational intent submission and sharing, conformance monitoring, airspace authorization, demand-capability balancing, airspace constraints and dynamic replanning. X4 was an opportunity to work with industry and advance the development of these capabilities in a collaborative environment. This section captured lessons learned identified through discussions, industry partner feedback, and software sprint testing during X4:

**#1. Having a Concept of Use (ConUse) defined prior to the activity would accelerate the time and effort from concept development to testing.**

X4 was inspired by NC-1 scenarios and drew from FAA ConOps v1.0. The lack of a defined ConUse – detailing specific use cases, defining current and new system actors and the roles of these actors, identifying how and what information would be exchanged – hampered further development of some PSU capabilities (e.g., airspace authorization, conformance monitoring) during X4.

For future simulation and R&D efforts, collaboration between the FAA, industry, and other stakeholders to develop and establish ConUse prior to the effort would be essential. The ConUse would mature conceptual definitions, advance select capabilities that could be part of a cooperative airspace management system for UAM, and help derive scenarios, requirements, and system designs.

**#2. While the UAM Notional Architecture provided a starting point for a federated architecture that support services provided by third-party providers, the USS for UTM and Provider of Services for UAM (PSU) differ in its definition of capabilities.**

While the UTM federated paradigm was embraced as a starting point for how UAM Operators would like to operate, UTM and UAM have very different operating assumptions and environment. These capabilities for PSU were refined during X4:

- ***Access to Airspace Structure Definitions.*** UTM is focused on operations below 400 feet, while UAM operations are integrated in the ATM environment, subject to current NAS policies and regulations such as VFR and IFR, and airspace classes. A common source of airspace definition information (e.g., vertiport locations, airspace structures for UAM operations within Class B/C/D airspace, and arrival and departure procedures into and out of vertiports) should be made available to UAM Operators for their operations planning. For X4, these data were provided by the ASDS hosted by NASA, however, there are currently well-established methods in the NAS for ensuring that the airspace structure is known and accessible to all users and services provides, and that all users and service providers have the same information. UAM operations will likely build off those existing systems and data models.

- ***Operational Intent Submission and Sharing.*** UAM Operators shared operational intent information with other UAM Operators via the PSU and through the defined APIs. In X4, trajectory-based operational intent was introduced to enable strategic conflict management. The X4 operational plan was a 4DT specifying the sequence of waypoints to follow, and each waypoint was 3D position (latitude, longitude, altitude) at a given time. This differed from the UTM concept of operational volumes, as 4DT provided more precise predictions that enable efficient airspace management, increase solution space for DCB, and improve predictability in the ATM environment.

- ***Conformance Monitoring.*** For UAM operations, it is expected that the vehicle or pilot, UAM Operators, and PSU will play a role in maintaining conformance. In X4, PSU's conformance monitoring function was kept simple and was limited to strategic 4DT operational intent submitted by the UAM Operator. PSU monitored conformance of its managed operations by checking telemetry information against discrete waypoints within the 4DT operational plan, where conformance criteria was met by staying within the defined vertical, horizontal, and time bounds around the waypoints. This differed from the UTM concept of conformance monitoring by bounding operational uncertainty using operational volumes. More work will be needed to develop conformance monitoring for the tactical layers, understand what drives the conformance criteria, and how other operations would be impacted by non-conforming operations.

- ***Airspace Authorization.*** X4 focused on VFR operations with defined airspace constructs and relied on simplified assumptions for UAM operating with the ATM environment. Leveraging UTM as a starting point, it was assumed that the UAM Operators would obtain an airspace authorization from a qualified PSU to access UAM corridors within Class B/C/D airspace, prior to each operation. Initial data exchange between PSU and FIDXP was tested in X4. However, as UAM operations are subject to current flight rules and airspace classes in the NAS, it was unclear if airspace authorization via PSU would apply until we understand how UAM automation would interact with ATC and ATM for different flight rules and airspace classes.

- ***Strategic Conflict Management.*** UAM Operators would need to coordinate on the use of shared resources (e.g., vertiports, airspace structures) as these resources have capacity limits. In X4, DCB with simplified assumptions were introduced to explore required data exchanges with DSS and among PSUs and other services. DCB requirements and CBRs were developed to facilitate how PSUs would coordinate and cooperatively manage shared resources, however, the implementation was left to each partner. NASA and one partner chose to implement it as part of their PSU. The remaining six partners chose to utilize a separate DCB service provided by one of the seven partners. This separate DCB service was used to only detect any predicted demand-capacity imbalance, while each partner's individual PSU would still be responsible for resolving the imbalance. Both approaches provided reasonable results, however, some complexities on implementing DCB with current DSS was identified and will be described in the next lesson learned.

- ***Airspace Constraints and Dynamic Re-planning.*** The characteristics of UTM-inspired UVR were applied to UAM operations when simulating Scenario 2 in X4. The UVR represented a temporary airspace constraint with defined spatial and temporal boundaries that prevented UAM operations from operating inside it. In X4, leveraging this UVR construct, it was demonstrated that PSUs with operations that would be impacted by the UVR could be informed via the existing information exchange protocol between PSU and DSS. However, airspace constraints impacting UAM operations could be in place due to a variety of reasons (e.g., TFR, weather, hazards) and not all constraints could be represented as an UVR (e.g., deteriorated weather conditions may indicate reduced – but not necessarily zero – capacity at shared resources). Hence, future research should consider how other types of airspace constraints information would be disseminated to the PSU Network so that UAM Operators would be able to modify their operations dynamically.

Some of these findings were also noted by our X4 airspace partners in their feedback:

*– "Implementation of the conformance monitoring functionality highlighted the fact that in the UAM domain this is a multi-faceted function that requires much more conceptual development"*

*– "The Authorization function did not seem to be needed for the use case simulated, but did require some development, so could probably have been left out."*

**#3. While existing DSS developed for UTM provided a way for PSU and other UAM services (such as DCB Service) to discover relevant operations from each other, additional complexity and challenges were found during X4 testing and illuminated the need for a more suitable solution for UAM.**

- DSS did not retain past operations, and since DCB required knowledge of operations, including those that successfully landed, workarounds were implemented in X4 for DCB to work. Also, when an operation was deleted from DSS, PSU was not required to indicate whether the operation was completed or canceled – such distinction would be necessary since completed operations would be counted towards DCB demand, but canceled operations would not.

- PSUs and DCB Service relied on DSS to discover relevant demand, by creating operational volumes around the shared resources. To ensure all relevant demand was accounted for, the size of operational volumes had to be very specific and dependent on the defined capacity at each resource. For example, assumed the capacity was 4 operations per 12-minute time bin at a vertiport, the operational volume should be sized such that it would be at least +/- 6 minutes (i.e., half the time bin) around its ETA at that vertiport. Such intricate requirements may be difficult to enforce and could be very error prone, resulting in unresolved demand-capacity imbalances in the system.

- Initial capabilities for strategic conflict management relied on multiple services – DSS, PSUs, and DCB Service – to work together. As new services like DCB Service were added to the federated architecture, it added a level of complexity to ensure the system can close on a solution on a timely manner, especially when it got perturbed by other events. During X4 testing, some issues due to timing and synchronization were discovered and resulted in demand capacity imbalance in the system. While data synchronization is necessary in a federated architecture, there might be other ways to design DSS so that it enables PSUs and other services to close on a solution timely and to provide accurate DCB results.

- Current DSS relied on operational volume(s) submitted by PSU to determine whether a PSU would be notified of an UVR. The dual purpose of operational volume(s) for DCB and UVR caused some inconsistency on how PSU might be notified of UVR within X4. This finding illuminated the need to establish requirements for DSS for UAM operations to ensure airspace constraints information can be distributed to UAM Operators accurately and timely.

Some of these findings were also noted by our X4 airspace partners in their feedback:

*"Implementation of DCB services for UAM even in the simple form may be challenging due to intricacies of existing UAM infrastructure and protocols (e.g., DSS)"*

*"Robust and timely communication among stakeholders in the federated architecture needs to be ensured to provide accurate DCB results"*

# 6 Conclusion

X4 was a year-long effort where seven NC-1 airspace partners and multiple NASA projects and stakeholders came together to test initial concepts for conducting Strategic Conflict Management for UAM. Given there was universal consensus between NASA, FAA, and industry in continuing to pursue a federated system approach to enabling UAM operations, the FAA ConOps v1 UAM Notional Architecture [1] was leveraged as the starting point for X4.

During X4, PSU capabilities were refined and tested. It was the first-time trajectory-based operational intents were exchanged among PSUs, demand-capacity balancing for strategic conflict management among UAM operations were developed and tested, and initial CBRs for enabling cooperative traffic management were developed with industry.

Prototyped PSU capabilities and new services were tested in a simulated environment hosted by NASA, and all seven partners and NASA successfully demonstrated the required capabilities at the completion of X4.

X4 was a complex effort and is only the beginning. There are still many open questions on airspace management left to be resolved. While X4 provided some insights into the involvement of multiple entities and their roles and responsibilities in the UAM environment and how those entities would need to evolve over time as UAM operations go fully functional, there was a lot of effort involved in the strategic and tactical realms of the operations which were not tested in X4 and needed to be addressed.

# 7 Next Steps

NASA plans to bring X4 findings to industry working groups and continue working with National Campaign industry partners to target UAM airspace concepts and technologies for UML-3 timeframe.

To continue evolving the airspace capabilities, NASA developed and published an initial draft of the UAM Airspace Research Roadmap [16] that detailed key research efforts for the UAM Sub-Project, informed by NASA, FAA, and industry. The UAM Airspace Research Roadmap will be the living document describing the evolution of UAM airspace capabilities and will continued to be updated as it provides a single, consolidated view for the various airspace research areas managed by the UAM Sub-Project.

There are two successive NASA research efforts that have been planned over a three-year period:

1. The X5 simulation will continue as part of a series of simulation activities conducted after X4, to develop and test a set of initial UAM airspace capabilities in collaboration with industry. X5 will expand on the strategic conflict management capabilities developed in X4 and will integrate tactical conflict management capabilities to conduct a strategic and tactical interoperability evaluation.
2. The Operational Integration Assessment (OIA) is an integrated, real-time demonstration conducted with the FAA, NASA, and other stakeholders to evaluate concepts and prototypes in an operational environment, focusing on how they enable UAM operations to scale beyond what the as-is NAS can accommodate. Evaluating these prototypes in their intended operational settings leads to more robust systems for future research, safely accelerating the timeframe in which UAM operations can scale up.

A draft of a Concept of Use (ConUse) document that defines a specific set of use cases and the underlying operational environment for UAM operations at initial scale, leveraging innovative approaches and technologies that begin the transition towards full-scale UML-4 operations, is currently in development. The use cases have been initially developed and vetted through partnership with the FAA William J Hughes Technical Center (WJHTC), leveraging joint capabilities designed to increase operational realism of the associated scenarios. The use cases will undergo further revisions, additions, and iterations as the research continues to mature and will be the guiding document for the X5 and OIA activities.

# A. Appendix: NASA Implementation of DCB

During X4 testing, NASA implemented its own DCB detection and resolution algorithm within the PSU and did not utilize the separate DCB service provided by one of the seven partners. This section describes the details of the DCB detection and resolution as a reference. This implementation followed the sequence of events in operation planning pertaining shown in Figure 23 below.

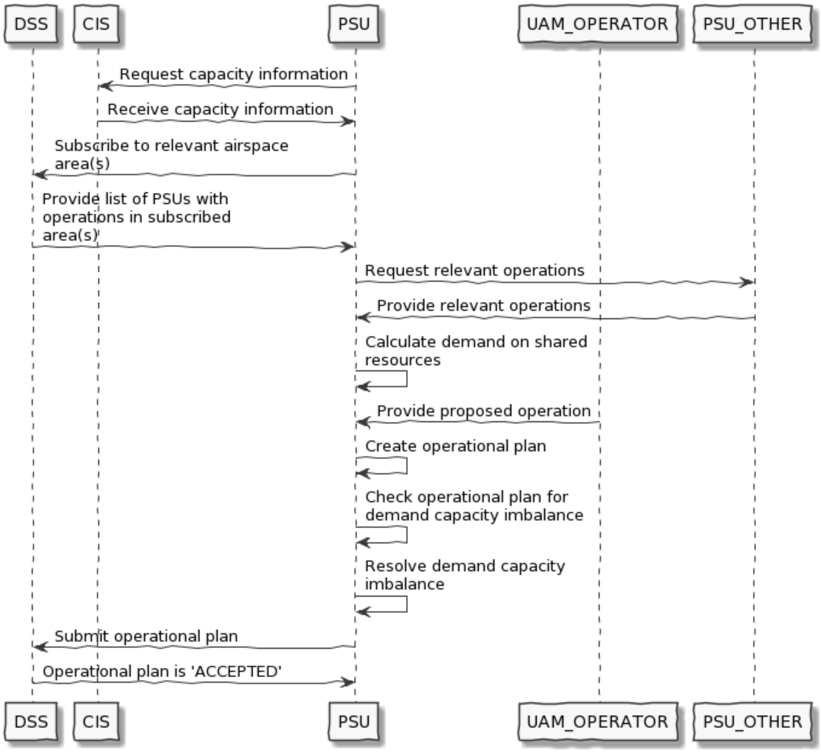


*Figure 23. Operation Planning Flow with Demand-Capacity Imbalance Detection and Resolution*

NASA's PSU relied on information about other operations to conduct DCB. To obtain that information, NASA PSU subscribed to the entire DFW metropolitan area with the DSS to get notified whenever a new operation from any participants was accepted by the DSS within the area. Through this notification, NASA PSU became aware of other PSUs that had relevant operations, communicated with them to obtain relevant operational intent information, so that it could calculate planned demand at shared vertiports.

Whenever the UAM Operator proposed an operation to the PSU, PSU would detect whether there would be a DCB imbalance by comparing the planned demand against the defined capacity. In the case when a DCB imbalance was detected, the PSU would resolve the imbalance by applying simple ground delay to the proposed operation, accounting for both the arrival and departure vertiports. In Figure 24, the top illustrates a timeline of the departure vertiport (Vertiport A) and the bottom illustrates a similar timeline but for the arrival vertiport (Vertiport Z). The timelines are shown in 12-minute increments to demonstrate the defined capacity time windows. Black circles indicate operations that have already been accepted that are utilizing the vertiport. The red circle indicates the desired times of the proposed operation at departure (at Vertiport A) and arrival (at Vertiport Z).

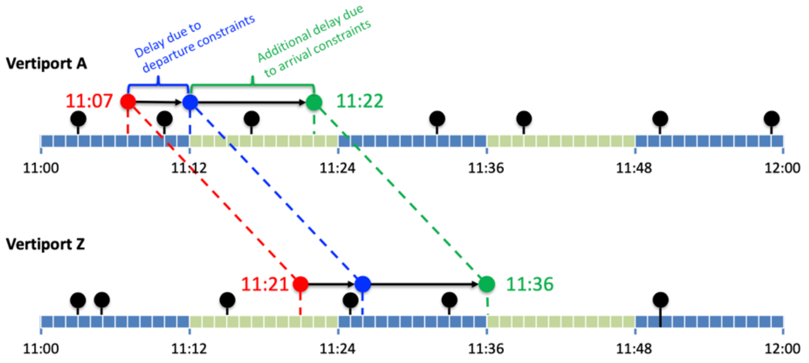


*Figure 24. Applying Ground Delay to Resolve DCB Imbalances*

In this example, capacity constraints at both vertiports are 2 operations per 12-minute time window. The proposed operation was originally planned for 11:07 departure and 11:21 arrival. Using ground delay resolution strategy, the departure would be delayed by 5 minutes to depart at 11:12 and arrive at 11:26, as shown by the blue circles. However, it would not satisfy the arrival vertiport constraint given there are 2 operations already scheduled for that time bin. The next available arrival vertiport time bin starts at 11:36, so the arrival would need to be shifted further right to be within this time bin – as shown by the green circles. As the total flight time remains unchanged, the entire operation would be shifted right by an additional 10 minutes – as shown by the green circles. PSU would update arrival and departure times based on this and submit the operation to the PSU Network. As a result of this demand-capacity imbalance resolution, the operation incurred a total ground delay of 15 minutes.

Additional details of the DCB detection and resolution algorithm that NASA developed and used for X4 simulations can be found in [17]. In X4, it was assumed that once the operational intent is accepted, the plan will not need to be updated. Future work could account for when accepted operational intents may need to be modified due to higher priority operations (e.g., emergency aircraft) and changes in capacity due to changing weather conditions.

## B. References

[1] Federal Aviation Administration Report (2020). *Urban Air Mobility (UAM) Concept of Operations Version1.0*. Available: https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf

[2] NASA Report (2021) *Advanced Air Mobility Mission Overview*. Available: https://www.nasa.gov/aam/overview/#:~:text=NASA's%20vision%20for%20Advanced%20Air,new%20aircraft%20that%20are%20only

[3] NASA Technical Memorandum (2021). *X3 Simulation with National Campaign Developmental Test (NC-DT) Airspace Partners*. Available: https://humansystems.arc.nasa.gov/publications/NASA-TM-20210011098.pdf

[4] Tarafdar, S., Rimjha, M., Hinze, N., Hotle, S., Trani, A.. Smith, J., Dollyhigh, S., Marien, T. (2021). *Comparative Study of Urban Air Mobility (UAM) Landing Sites for Three Study Area*s. AIAA. Aerospace Research Central. Available: https://arc.aiaa.org/doi/10.2514/6.2021-3210

[5] Goodrich, K. H., Theodore, C. R. (January 2020). *Description of the NASA Urban Air Mobility Maturity Level (UML) Scale*". AIAA SciTech 2021 Forum. Available: https://ntrs.nasa.gov/api/citations/20205010189/downloads/UML%20Paper%20SciTech%202021.pdf

[6] NASA Press Release (2021) *Advanced Air Mobility National Campaign* Partners. X4 official announcement with partner names. Available: https://www.nasa.gov/aeroresearch/advanced-air-mobility-national-campaign-partners

[7] Federal Aviation Administration (2014). Order JO 7110.65V. *Air Traffic Control.* Available: https://www.faa.gov/documentlibrary/media/order/jo_7110.65v.pdf

[8] Johnson, W., Silva, C., Solis, E. *Concept Vehicles for VTOL Air Taxi Operations.* (January 2018). American Helicopter Society. International Technical Meeting Aeromechanics Design for Transformative Vehicle Flight. San Francisco, CA. Available: https://ntrs.nasa.gov/api/citations/20180003381/downloads/20180003381.pdf

[9] ARMD Advanced Air Mobility National Campaign-1 Announcement of Collaborative Partnership Opportunities (2021). *Official US Government System*. Available: https://sam.gov/opp/62ed89f4e4374d22aafc85e1a9661322/view

[10] NASA Contractor Report (2022). *UAM Research – X4: Introduction to Community Based Rules (CBRs)*. Available: https://ntrs.nasa.gov/citations/20220015818

[11] International Civil Aviation Organization (ICAO). (2005) *Global air traffic management operational concept*. ICAO, Doc. 9854, First Edition. Available: https://www.icao.int/Meetings/anconf12/Document%20Archive/9854_cons_en[1].pdf

[12] NASA Technical Memorandum. (2022). *National Campaign (NC)-1 Strategic Conflict Management Simulation (X4) Community Based Rules*. Available: https://ntrs.nasa.gov/citations/20220015823

[13] Github Repository. (2022). UAM-APIS. Available: https://github.com/nasa/uam-apis/tree/x4/openapi

[14] Github Repository (2022). *USS to USS Communication and Synchronization.* Implementation of the discovery and synchronization service and a monitoring framework to test UAS Service Suppliers (USS). Link: https://github.com/interuss/dss

[15] Sprikovska, L., Kulkarni, C., Watkins, J., Martin, L. (2022). *Urban Air Mobility Airspace Dynamic Density*", AIAA Aviation Conference: 2022-3403. Available: https://ntrs.nasa.gov/citations/20220006541

[16] NASA Technical Memorandum (2022) *UAM Airspace Research Roadmap Revision 1.2*. Available: https://aam-cms.marqui.tech/uploads/aam-portal-cms/originals/4e0bf902-7730-424e-8173-3e1fc692958b.pdf

[17] Lee, H., Moolchandani, K. A., Arneson, H. (September 2022). *Demand Capacity Balancing at Vertiports for Initial Strategic Conflict Management of Urban Air Mobility Operations*. 41st Digital Avionics Systems Conference (DASC), Portsmouth, VA. Available: https://ieeexplore.ieee.org/document/9925753

# C. Acronyms/Abbreviations

| Acronym | Description |
|---|---|
| 2D | Two-Dimensional |
| 4D | Four-Dimensional |
| AA | Airspace Authorization |
| AAM | Advanced Air Mobility |
| ADS | Automatic Dependent Surveillance |
| ANSP | Air Navigation Service Provider |
| AO | Aerodrome Operations |
| AOM | Airspace Organization and Management |
| AOSP | Airspace Operations and Safety Program |
| API | Application Protocol Interface |
| ASDS | Airspace Structure Definition Service |
| ATI | Airspace Testing and Integration (Team) |
| ATM-X | Air Traffic Management-eXploration |
| CBR | Community-Based Rules |
| CIS | Capacity Information Service |
| ConOps | Concept of Operations |
| ConUse | Concept of Use |
| DAL | Dallas Love Field Airport |
| DCB | Demand-Capacity Balancing |
| DD | Dynamic Density |
| DFW | Dallas-Fort Worth International Airport |
| DSS | Discovery and Synchronization Service |
| eVTOL | Electric Vertical Take-Off and Landing |
| FAA | Federal Aviation Administration |
| Acronym | Description |
| FAA | Federal Aviation Administration |
| FIDXP | FAA-Industry Exchange Protocol |
| GATMOC | Global Air Traffic Management Operational Concept |
| http | Hypertext Transfer Protocol |
| IAP | Instrument Approach Procedures |
| ICAO | International Civil Aviation Organization |
| JWS | Java Web Service |
| MSL | Mean Sea Level |
| MVP | Minimum Viable Product |
| NASA | National Aeronautics and Space Administration |
| NAS | National Airspace System |
| NC | National Campaign |
| PIC | Pilot in Command |
| PSU | Providers of Service for UAM |
| SCM | Strategic Conflict Management |
| SIDS | Standard Instrument Departures |
| TFR | Temporary Flight Restriction |
| TS | Traffic Synchronization |
| UAM | Urban Air Mobility |
| UAS | Unmanned Aircraft Systems |
| UDC | Universal Data Collector |
| UML | UAM Maturity Level |
| UTM | Unmanned Aircraft Systems (UAS) Traffic Management |
| USS | UAS Service Provider |
| UVR | UAM Volume Reservation |
| V2V | Vehicle to Vehicle |