Chapter 9
Strategic Deployment of Drone Centers and Fleet Size Planning for Drone Delivery

9.1 Introduction

The parameters of a specific UTM application are important not only for considering the feasibility of Unmanned Aircraft Systems (UAS) package delivery within the state but also for determining the impact and ultimately the efficient operation of drone delivery. UAAMS allows the Utah Department of Transportation (UDOT) to assess different assumptions of the model and run "what-if" scenarios by generating animation of the optimized airspace network. The platform provides the state with more clarity about the energy impacts of large-scale drone delivery, as well as a viable airspace network. The tool can further inform the UDOT Division of Aeronautics to develop policies and negotiate with industry stakeholders.

Through this UTRAC research project, the implementation and deployment of the UAAMS was successful and will be available for continuing research in the development of advanced air mobility in the state of Utah. This type of tool is critical for research in this area, as it incorporates the latest software and infrastructure development techniques available. Also shown was the viability of considering the large-scale impacts (e.g., environmental) of advanced air mobility on specific communities by using micro-simulation technology. In contrast to micro-simulations performed for human-controlled ground and air traffic, in this case a model for the autonomous agents has the potential to be exact, since their algorithms must be documented. Future improvements will consider optimizations to the object function in the optimization procedure—this would allow a more thorough exploration of the possible configurations of vehicle and vertiport parameters.

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9.1.1 Problem Statement

In a 2017 report by the RAND corporation [62], analytical methods for calculating the total energy consumed by a mix of delivery trucks and drones were developed and shown to be highly dependent on the layout of distribution centers as well as distance traveled by delivery vehicles. This suggests that the city layout, i.e., street connectivity and other network parameters, are important considerations for energy-conscious policies. While industry stakeholders must determine the market viability of drone delivery, they are not required to calculate the external and indirect costs that may be associated with this burgeoning industry. The web-based platform developed for this report, called the Utah Advanced Air Mobility Simulator (UAAMS), enables researchers, planners, and practitioners to record and update assumptions about the distribution of vertiports, traffic, population, and other requirements that may affect the operation of the transportation network. These parameters are important not only for considering the feasibility of Unmanned Aircraft Systems (UAS) package delivery within the state but also for determining the impact and ultimately the efficient operation of these new transportation technologies. Furthermore, additional analysis and what-if scenarios may be developed using this simulator. Example Jupyter notebooks (python) are provided to help guide development; however, users are not limited to any particular programming language. To facilitate the iterative process needed for the development of Advanced Air Mobility in the State of Utah, UAAMS is a web-based software and can be accessed from any web browser. Additionally, the simulator is delivered with the open-source web-map server, GeoServer (https://geoserver.org), which contains the geospatial data used or generated by the simulations. This enables multiple agencies within the state, who often use Geographic Information Systems (e.g., ArcGIS), to communicate planning efforts and incorporate data from, or provide data to, these simulations. Figure 9.1 shows the main features of the software developed for this project:

1. Simulator Form: The simulator form enables the client to enter assumptions about the vehicles and the environment, and then execute the simulation.
2. 3D Map Interface: A viewer for map and simulation data.
3. File System Explorer: Input and output files for simulations (e.g., vertiport locations and result figures) may be stored in the filesystem. Additionally, all the source codes for simulations are accessible through this file system explorer.
4. Simulation Output Viewer: Simulations produce a number of figures that can be viewed here.

An initial simulation implementation was developed for this report to demonstrate the workflow for running simulations, as well as developing new ones, and is described in the sections that follow. The UAAMS is deployed to US data centers on Google Cloud and is accessible by anyone with authorized credentials by visiting the URL https://utrac.georq.io.

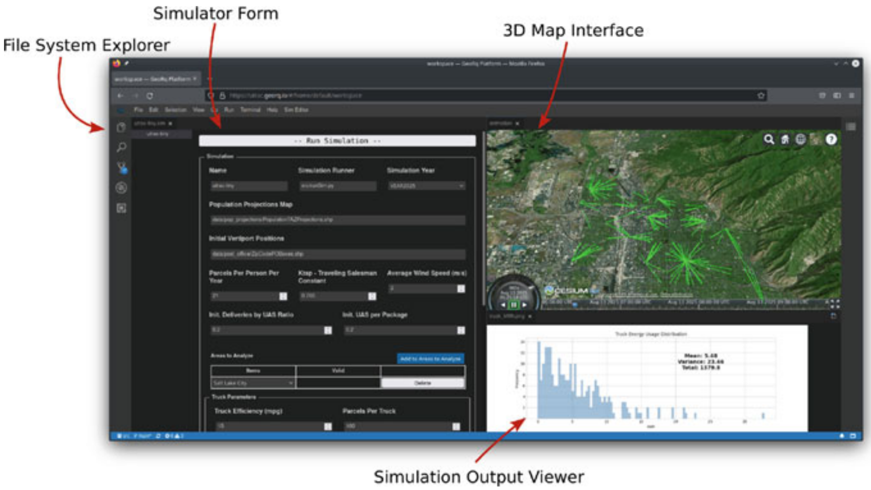


Fig. 9.1 The Utah advanced air mobility simulator (UAAMS)

9.1.2 Objectives

The motivation for this work is to provide regulators, policymakers, and industry stakeholders with a data-driven framework for assessing the energy costs and trade-offs of large-scale drone delivery in the state of Utah. The primary objective is to produce a web-based platform that takes inputs of state-wide road network, the total number of (drone-deliverable) packages to deliver on a given day and their destinations, and energy and cost assumptions per vehicle, and produces a state-wide airspace network, delivery schedule, and truck/drone fleet mix. A secondary goal is to optimize the network to ensure that drones are strategically deconflicted as required by FAA/NASA and the total energy over that day is minimized. Overall, this program will provide the state with more clarity about the energy impacts of large-scale drone delivery, as well as a viable airspace network.

9.1.3 Scope

This research involves three major components: data collection, optimization model development, and web-based platform development. We first gathered data on the state-wide roadway network, population data (year 2025), Traffic Analysis Zone (TAZ) boundary, and post office locations. The dataset enabled the creation of delivery zones to simulate package delivery coverage area for each drone center. In addition, the air delivery network was created by lifting the virtual highway network into the sky. This includes generating airways, deconflicting zones for Utah considering the delivery scheduling, launching/landing lanes, etc. An optimization model was developed to determine the schedule and deployment of drones within the study area. The developed system model with the optimization component was then implemented onto a web-based platform where people can assess different assumptions of the model and run what-if scenarios by generating animation of the optimized airspace network.

The rest of the discussion is structured as follows. Section 9.2 summarizes the research methods. Section 9.3 illustrates the web-based platform along with a case study for a medium-sized simulation with 33 TAZs. Section 9.4 presents the results and findings, and outlines the lessons learned for follow-up research. Appendix D of the UDOT Technical Report [93] includes the user guide of the developed web-based platform.

9.2 Research Methods

9.2.1 Overview

Large-scale drone delivery is on the horizon nationwide, as it has the potential to decrease pollution and help alleviate road congestion. Up until now, industry is mainly concerned with the market viability of drone deployment, and very little attention has been paid to external costs such as energy trade-off. The benefits of drone deployment, however, are largely dependent upon layout of distribution centers and distance traveled. To this end, we employ a data-driven approach to strategically replace ground-based delivery networks with air-based drone deployment. In this project, we structured the airspace by regulating and treating it as lanes, and optimized drone dispatch. Figure 9.2 shows the methodological framework of our research.

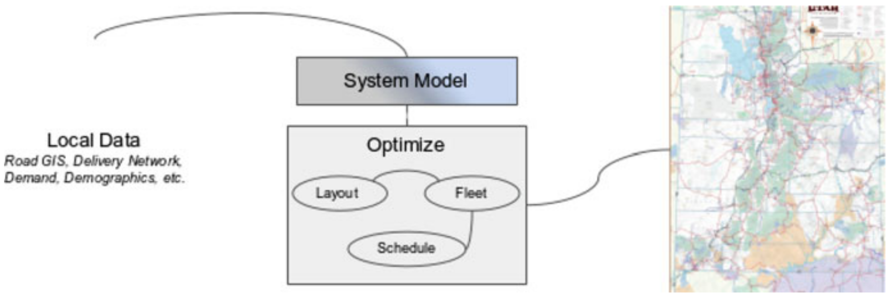


Fig. 9.2 Methodology framework of proposed drone network optimization

9.2.2 Data Source

The main data sources utilized to be fed into the airspace network construction consist of four parts:

1. Population projection: This is retrieved from the Utah Geospatial Resource Center (UGRC) [116] and is collected at the TAZ level. Year 2025 data was retrieved as the demand input. The population projection was further converted into parcel demand estimation, where on average 21 parcels/capita/year was assumed initially [42].
2. Post office locations: This is retrieved from UGRC [118] to serve as potential truck delivery centers. Figure 9.3 shows the overlay of post office locations with the TAZ boundary.
3. Utah road network: This is retrieved from UGRC [117] and the layout is used to create the elevated virtual airways in the sky for the drone fleet.
4. Utah building footprints and addresses: This is retrieved from UGRC [115] and provides the locations of possible drone deliveries for demand modeling.

9.2.3 Optimization Setup

The optimization procedure considers possible locations for vertiports to answer the question: Does there exist a set of vertiport locations that minimizes the total energy requirements? Since the spatial distribution of vertiports affects which addresses are served by them, the distances traveled and energy consumed by UAS are affected by their placement. Other parameters, such as vehicle characteristics, the proportion of packages that are delivered by UAS, and the routes of UAS and trucks have important effects, but were not considered in this procedure. To gain some intuition about how the locations of drone ports can affect the deliveries of packages, consider the relative locations of a drone center, truck center, and two TAZs in Fig. 9.4. At the start of the optimization, the drone center and the truck center are co-located. Package deliveries are scheduled according to the procedure that assigns aircraft to addresses that are within range and capabilities (according to the simulation parameters), and then fills the resulting demand with truck deliveries. For more efficient simulation, the truck distances and energy are calculated by solving a probabilistic traveling salesman problem [62]. In contrast to the regular shaped cells used for this calculation in [62], this simulation calculates the resulting convex hull that encompasses the truck-assigned demand.

At each iteration of the optimization, the drone centers are moved to a new location, the simulation is re-run, and the resulting total energy is calculated. The optimization is complete when further updates to the locations of the drone centers result in an increase in the total energy consumption. Several methods for optimizing vertiport locations were considered for this project, with the settled approach being

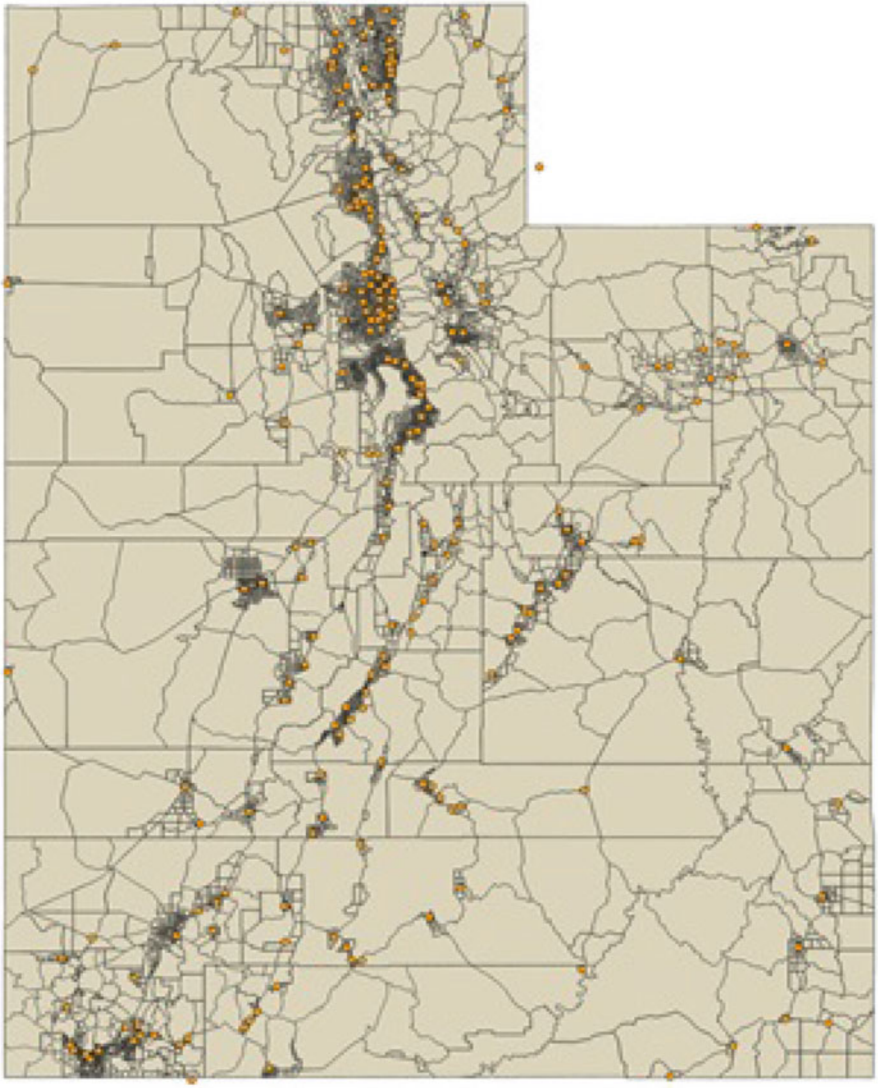


Fig. 9.3 TAZs with post office locations

the Covariance-Matrix Adaptation Evolution Strategy (CMAES) [28]. The objective was to minimize the total energy required by both UAS and trucks to deliver a set of packages in an area. Only the locations of the vertiports were considered variables in the optimization, while the job mix, number of vertiports, and vehicle parameters were held constant. Therefore, the number of variables in the optimization equals the number of vertiports under consideration. Figure 9.5 shows a plot of a sample optimization run for a single TAZ.

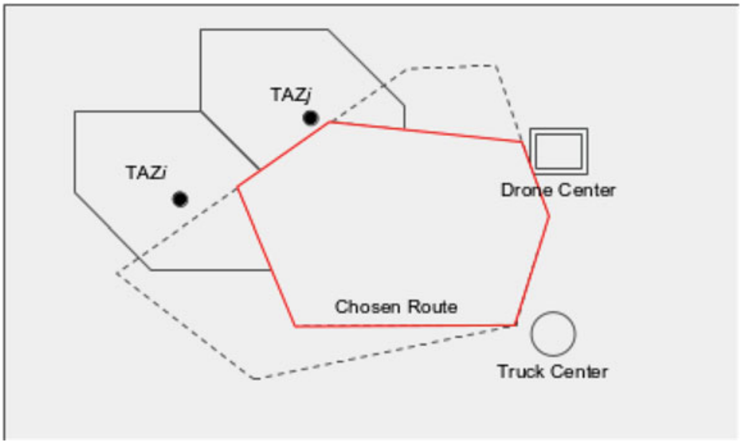


Fig. 9.4 A diagram showing how delivery routes (in red) are influenced by the placement of drone centers (i.e. vertiports) and truck centers relative to the travel analysis zones (TAZ)

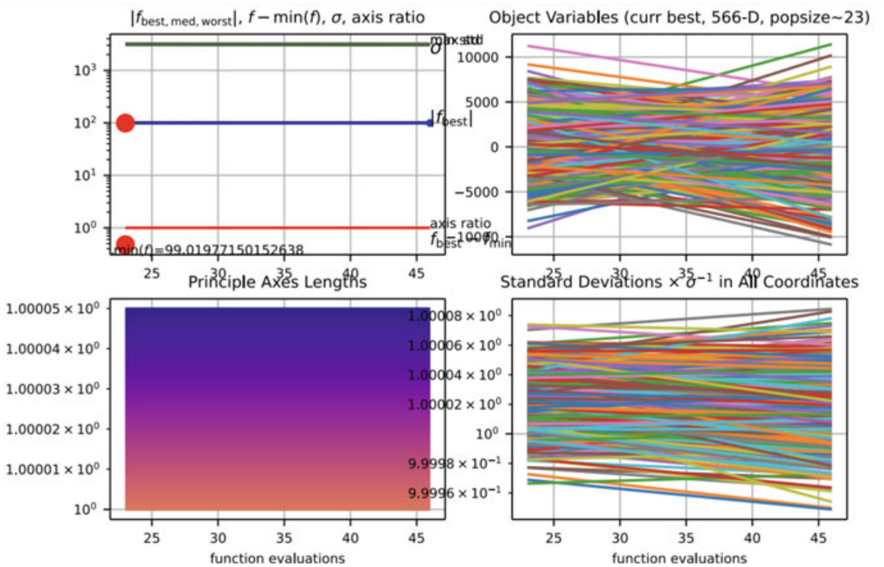


Fig. 9.5 Optimization iterations showing divergent behavior

9.3 Web-Based Platform

9.3.1 Overview

A simulation that extends what was described in the RAND report is provided along with UAAMS. This simulation incorporates all the parameters listed in Table 9.1.

Table 9.1 The simulation parameters

Form field	Description
Simulation parameters	
Name	Simulation name
Simulation runner	Python script name
Simulation year	Pop. projection year
Population projections map	shapefile/geojson file
Initial Vertiport positions	post office locs.K
Parcels/Person/Year	avg # packages
Ktsp	TSP constant
Average wind speed	avg wind speed felt
Init. deliv. by UAS ratio	From trucks to UAS
Init. UAS per package	UAS/package at vertiport.
Areas to Analyze	areas from TAZ dataset
Truck parameters	
Truck efficiency	Truck efficiency mpg
Parcels per truck	Truck package load
UAS parameters	
UAS payload mass	Payload mass (kg)
Lift-to-drag ratio	Of UAS
UAS vehicle mass	UAS mass (kg)
Power transfer efficiency	Motor to propeller
Cruise speed	UAS cruise speed
Power consumption	Of electronics
Climb rate	UAS climb rate
Maximum range	Of UAS
Package load time	Onto a UAS
Cruise Altitude	UAS cruise altitude (m)

In contrast to the RAND report, this simulator considers the real locations of addresses in Utah [118], as well as the projected population densities in order to simulate projected demand that is more accurately distributed throughout the state. Figure 9.6 shows a cross-section of these datasets.

The simulation implementation progresses along the following steps:

- Load Vertiport Locations
- Load Truck Depot Locations
- Load Population Projections (TAZ Zones)
- Load Building Locations
- Initialize UAS Model
- Filter TAZ Based on Requested City Areas
- Create Demand (Parcel Requests for a Day)
- Source Parcel Requests to Nearest Vertiport
- Calculated Parcel Requests within UAS range and Capability
- Calculate Truck/UAS Job Mix

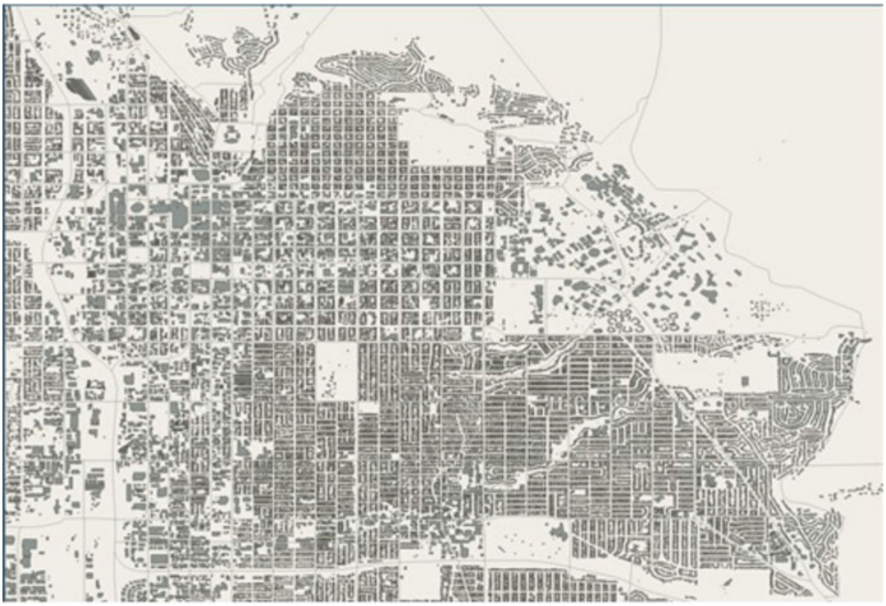


Fig. 9.6 Utah Buildings dataset overlaid on population projections dataset

- Generate UAS Trajectories
- Estimate UAS Round-Trip Times
- Estimate UAS Energy Requirements
- Estimate Truck Energy Requirements
- Generate Animation
- Generate Results

9.3.2 Case Study

A medium-sized simulation was executed that included 33 TAZs as a case study to demonstrate the web-based platform.

9.3.2.1 Simulation Form

A simulation form is displayed whenever a file with the suffix .sim is clicked in the workspace explorer. As this form is edited by the user, the parameters are written to the .sim file (the raw json format can be viewed by opening the file in the code editor as shown in Fig. 9.7). When the Run Simulation button is clicked at the top of the form, the python program defined in the Simulation Runner field is executed and the .sim file is provided as an argument to the program.

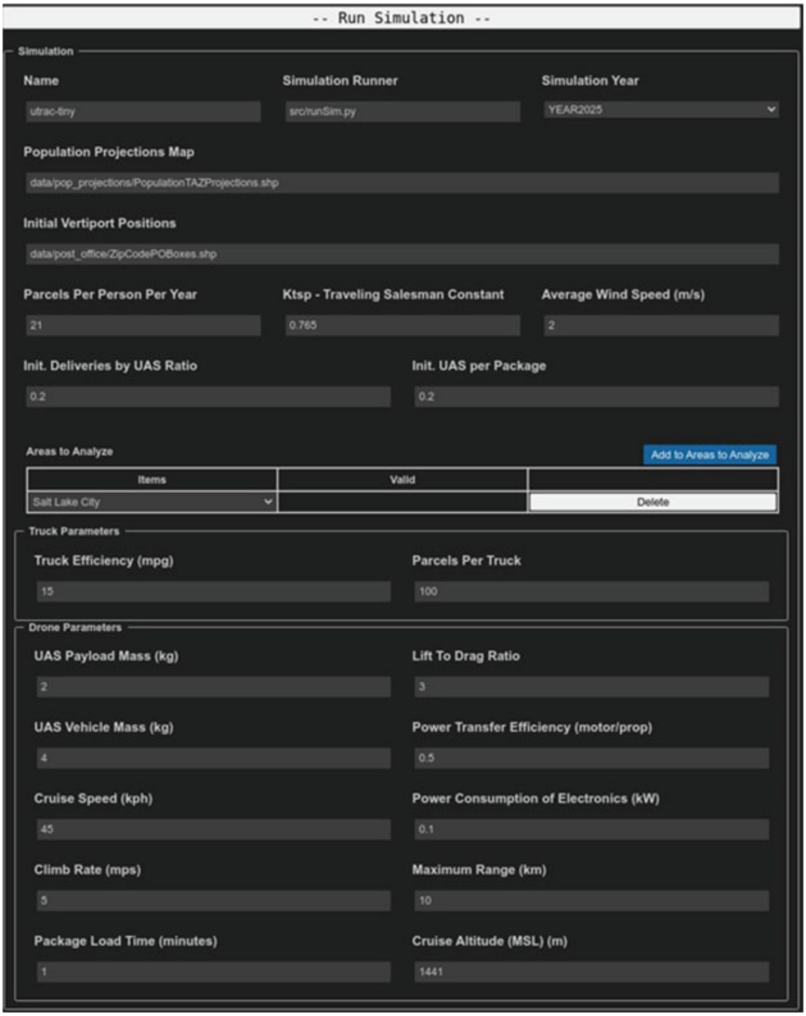


Fig. 9.7 The simulation form

9.3.3 Simulation Procedure

The following section describes each step of the simulation in detail. The complete source code of the simulation is delivered with UAAMS and accessible from the file explorer.

Load Input Location Data This step includes loading the following location data:

1. Vertiport Locations
2. Truck Depot Locations

3. Population Projections (at the TAZ level)
4. Building Locations

Depending on the size of the dataset, the location data can be loaded either from the filesystem or from a web-map server (one is provided with UAAMS). For example, the population projections dataset was small enough to have loaded from a shapefile located on the filesystem into memory, while the building locations dataset is too large to handle in this way. The buildings dataset is loaded into the web-map server offline, then during the simulation the server is queried within constrained areas.

Initialize UAS Model The UAS model considered for this simulation is derived from a study conducted by D'Andrea [29]. The parameters considered are listed in Table 9.1.

Filter TAZ Zones Based on Requested City Areas The simulation can consider a subset of areas in Utah, defined by the "City Areas" column in the Population Projections dataset [116].

Create Demand (Parcel Requests for a Day) For each TAZ under consideration, uniformly sample the building centroids within that TAZ from a binomial distribution with intensity given by the estimated number of parcels per person per day.

Source Parcel Requests to Nearest Vertiport For each parcel request in the demand dataset (from the last step), calculate the nearest vertiport that can serve that request.

Calculate Truck/UAS Job Mix Fixed by user input into the simulation form.

Generate UAS Trajectories For each parcel request that is served by a UAS, generate a trajectory based on the vehicle parameters provided in the simulation form.

Generate Animation To help visualize the distribution and density of drone flights that meet the demand specified in the simulation, a 3D animation (see figure below) is generated that can be viewed within the workspace. The animation is specified by an open-source human/machine readable file called CZML [6]. Figure 9.8 shows an example frame from this animation.

Generate Results Results are generated and stored in figures as described in Fig. 9.9.

9.4 Conclusions and Future Work

The implementation of a cloud-based collaborative simulator represents the bulk of this UTRAC project. A major unexpected hurdle was the need for significant memory and compute resources to execute the simulations. In particular, the

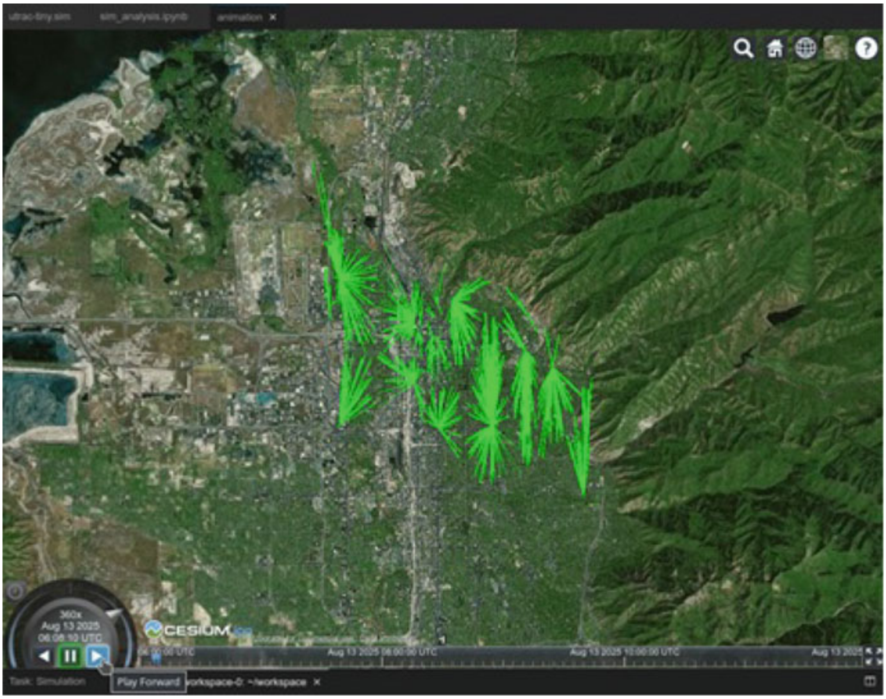


Fig. 9.8 One Frame of the simulation animation results

building dataset represented a challenge and required the use of a web-map server rather than simply loading the entire shapefile into memory. During the demand creation step in the simulation implementation, small areas were queried to avoid overwhelming memory resources.

With regard to the test simulation, the total energy required by both UAS and trucks combined was slightly more than the required energy if trucks were to meet the same demand alone. This could be a result of the chosen vehicle parameters, as well as the location distribution of vertiports. Despite this result, it may still be desirable to take advantage of the short distance and round-trip times that UAS has to offer.

Another challenge was encountered with the optimization objective. It was found to be computationally difficult to consider all the vertiport locations, as well as the various input parameters that could have been considered. The algorithm that was chosen to perform the optimization is called the Covariance-Matrix Adaptation Evolution Strategy [28] because it has a good reputation for handling highly non-linear problems with many variables. However, the algorithm proved to be rather slow, likely due to the random sampling and database querying that occur during the demand creation step. Consequently, in the time allotted for optimization, the algorithm did not successfully converge to a solution.

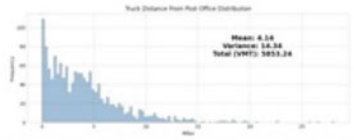
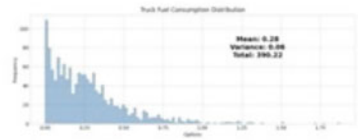
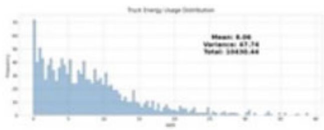
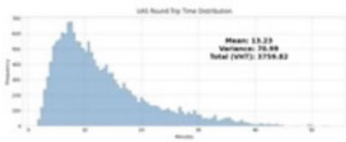
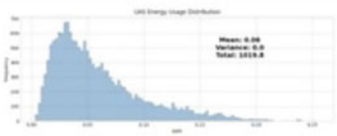
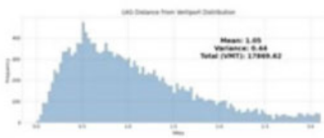
Figure	Description	Example
truck_distances.png	The distribution of distances that trucks traveled during the simulation.	
truck_gallons.png	The distribution of gallons consumed by trucks during the simulation.	
truck_kWh.png	The distribution of energy consumed by trucks during the simulation.	
uas_rt_time.png	The distribution of round-trip times for UAS during the simulation	
uas_kWh.png	The distribution of energy consumed by UAS during the simulation.	
uas_distances.png	The distribution of distances traveled by UAS during the simulation.	

Fig. 9.9 Simulation-produced plots

Overall, the implementation and deployment of the UAAMS was successful and will be available for continuing research in the development of advanced air mobility in the state of Utah. This type of tool is critical for research in this area, as it incorporates the latest software and infrastructure development techniques available. Also shown was the viability of considering the large-scale impacts (e.g., environmental) of advanced air mobility on specific communities by using micro-simulation technology. In contrast to micro-simulations performed for human-controlled ground and air traffic, in this case a model for the autonomous agents has the potential to be exact, since their algorithms must be documented.

Less certain are the emergent effects that may result from the parallel execution of these algorithms, and the environmental impacts of their collective behavior.

This UTRAC project has resulted in feedback from stakeholders that can be used to improve the simulation tool, as well as the resulting analysis. For example, simplifications to the workspace are necessary for non-developer, or non-engineer, stakeholders (e.g., planners). It is crucial to enable a frictionless communication between them and a tool like UAAMS has the potential to fill this role. Future improvements will also consider optimizations to the object function in the optimization procedure—this would allow a more thorough exploration of the possible configurations of vehicle and vertiport parameters.