VAMOS! A Regional Modeling and Simulation System for Vertiport Location Assessment

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This paper presents an approach to assess the suitability of vertiport locations and evaluate the feasibility of flights between them for the Advanced Air Mobility (AAM) concept. The motivation for the work comes from the infrastructure challenges to implement the AAM concept. The question of where should the vertiports be placed led to the development of the technology described in this paper. A modeling tool gathers various attributes desired by the local community (city or county planning departments) and aggregates them to create suitable vertiport locations. Site suitability is modeled with a composite suitability metric that is a weighted function of several characteristics of a location, some favorable and some not, all of which are a function of desired proximity to the site being considered. Then, a simulation system conducts a fast-time simulation of origin-to-destination operations in the urban region. The flight of various vehicles, with winds and obstacles, is simulated between the selected vertiport locations to assess feasibility of flight. The noise footprints and the battery depletion are also computed. A prototype system encompassing both, the vertiport location suitability assessment tool and the flight feasibility simulation system, was developed and evaluated with subject-matter experts in regional planning from four metropolitan areas. The outcome of those evaluations suggests the use case is sound and the prototype brings needed consistency to the decision-making process.

I. Introduction

There is increasing interest in the Urban Air Mobility concept and the realization of electric Vertical Take-Off and Landing (e-VTOL) vehicles flying in the National Airspace System [1]. The term Urban Air Mobility (UAM) refers to the mode of transportation utilizing piloted and highly automated airborne vehicles for transporting goods and/or people [2]. The concept of Advanced Air Mobility represents the larger scope encompassing UAM, with inclusion of commercial inter-city (longer range/thin haul), cargo delivery, public services, and private/recreational vehicles [3]. NASA, FAA, and industry are investigating various aspects of this new mode for cargo and human transportation [4].

For Advanced Air Mobility (AAM) to meet societal needs, it must be scalable. The primary obstacle to the scalability of this new aviation system may be the extent to which AAM operations are respectful of the needs and sensitivities of the communities they serve. A driving consideration in this regard is the placement of the vertiports, which constitute the primary interface between the AAM system and the public. Concerns around safety, noise, emissions, access, convenience, equity, congestion, and a host of other considerations all converge at the vertiport. So, the selection of each vertiport location must incorporate all these factors, and the suitability and acceptability of that location will, in large part, dictate the viability of AAM for that local area.

More broadly, the ability to consistently identify suitable, acceptable locations for vertiports across metropolitan areas nationwide is expected to dramatically increase the capacity of the AAM system. This would accelerate the growth of AAM networks because, in the absence of such guidance, poor siting choices are likely to activate adverse economic, political and/or public responses.

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This paper introduces the Vertiport Assessment and Mobility Operations System (VAMOS!) technology developed at NASA. It presents a novel approach to inform decisions about site selection for vertiports, incorporating the desire to have attributes desired for a vertiport from a local/regional community perspective. The solutions are computed quickly, and users find the method fast and simple to work with, and they are tested for flyability.

The next Section provides motivation for this research. The following two Sections III and IV describe the modeling tool and the simulation system used for this approach. The site suitability conducted with the modeling tool are described in Section V, and the feasibility of flight between selected vertiport locations are presented in Section VI. The reported case studies are for the Los Angeles, CA, and Columbus, OH regions, The paper ends with some final remarks.

II. Motivation

In the UAM Vision Concept of Operations [1], the UAM Organizational Framework and Barriers are described. The Community Integration barrier addresses the Supporting Infrastructure and Operational Integration aspect. The barriers of airspace and fleet operations management, airspace system design and implementation, and aircraft development and production, address the aspects of safe, efficient, and scalable airspace operations; airspace design and operational rules and procedures; and aircraft noise and weather-tolerant aircraft. The desire to overcome those barriers is one motivation for this research.

From the Operations Research and Computational Geometry community, a facility location problem has been looked at as the optimal placement of facilities to minimize transportation costs while considering factors like avoiding placing hazardous materials near housing, and competitors' facilities [5]. The facility location problems are optimization problems and are often solved with mixed-integer programming methods. There are infeasibility of solutions and computational efficiency issues with these methods. Several articles are available in literature for selecting location of vertiports [6], [7], addressing the location based on the passenger travel demand models. The location of the vertiports is determined depending on where most of the trips originate and where they end [8], [9]. Also, these efforts are focused on specific local regions only (San Francisco/Bay Area, Chicago, Tampa, etc.). Thus, another motivation is to find fast and guaranteed solutions for siting of vertiports across the entire country.

The adoption of widespread use of AAM vehicles will necessitate a network of vertiports located throughout a geographical region. A vertiport is a physical structure for the departure, arrival, and parking/storage of AAM vehicles. There were three questions that this research started to address. First was, where can a vertiport be placed in a given region? The second was, if a location seemed good from several considerations, how can one determine its suitability for constructing a vertiport there? Lastly, once some locations have been deemed acceptable, would flight of vehicles between them be feasible? These questions also motivated this research.

With that background and motivation, NASA has developed VAMOS! It consists of two capabilities: a Regional Modeling Tool (RMT) and a Regional Simulation System (RSS). Even though each of these environments works on one local region at a time, they have a national scope and are both capable of performing evaluations anywhere in the contiguous United States, and conceivably the whole world, if the required data (see Section V) are available.

III. VAMOS! Regional Modeling Tool

The Regional Modeling Tool (RMT) enables the user to identify and compare geographical locations suitable for placing a vertiport or for assessing suitability of pre-selected locations. It accomplishes this in five basic steps. In step one, RMT incorporates data from a local region where a vertiport is desired [10]. These attributes could be location-based (e.g., proximity to mass transit stations), level-based (e.g., noise levels), characteristic-based (e.g., residential zoning), and time-based (e.g., demand). These data include reward attributes and penalty attributes. Reward attributes are useful resources in the vicinity of the location under consideration, e.g., public transportation and public safety. Penalty attributes are potential hazards or risks in proximity of the location under consideration, e.g., parks and power lines. Step two defines the criteria for proximity and the weights for relative importance of attributes. For example, if a train station is desired in the vicinity of the vertiport, how far could it be for its utility to be felt? Its utility would be higher if it were adjacent to the vertiport than if it were located two miles away. RMT enables the user to characterize such relationships in the form of an expression, which can be customized if priorities change. In this step, weights are also specified for each of the attributes, to describe their relative importance. For example, how important is it to have a fire station in the vicinity of a vertiport (say, 5, on a scale of 0 to 5), compared to a convention center (say, 2, on the same scale). The criteria and weights are defined for each attribute, whether a reward or a penalty. In step three, the RMT creates a composite suitability color-coded gradient or a "heat map" on a grid defined for the region and overlays it on a map of the region. The method for computing the composite suitability, along with sample reward and penalty criteria, are described in Appendix A. Using the suitability map (which is interactive), the user may select a vertiport location by clicking on the map/grid, presumably in an area where the colors are warmer, indicating that the composite suitability is higher. The corresponding value of composite suitability at the chosen location is displayed, along with the suitability of each of reward and penalty attribute based on their proximity to the chosen location. More discussion on this is presented in the Regional Modeling Tool Case Studies (Section V).

IV. VAMOS! Regional Simulation System

Once the user determines a desired set of vertiport locations for a given region using RMT, these locations are provided to the Regional Simulation System (RSS). The RSS is built upon the NASA-developed WorldWind open-source virtual globe API [11]. The trajectory engine and basic infrastructure are implemented with the NASA-developed Future ATM (Air Traffic Management) Concepts Evaluation Tool (FACET) software [12]. Many manufacturers are developing designs for different purposes and building the larger AAM vehicles. Reference [13] provides almost 800 vectored thrust (any thruster for lift or cruise), Lift+Cruise (separate thrusters for lift and cruise), wingless (no thruster for cruise, thrusters for lift only), personal flying devices (pilot in saddle or standing), and electric rotorcraft (e-helicopter or e-autogyro) models from concept design to technology demonstrators from around the world. NASA has also developed several models [14], [15], and [16].

The RSS has the ability to model various e-VTOL vehicle trajectories in fast-time simulation utilizing aircraft performance models developed at NASA. Currently, NASA-developed performance models for two quadrotors are available within the system [14]. Based on the location of the vertiports and the desired route structure/flight plan. a traffic scenario is generated by the user by defining origin/destination (OD) pairs. The RSS simulates flight of the vehicles between the OD pairs according to a user-defined schedule, and the impact of those flights can be assessed. The RSS computes and displays metrics that characterize the impacts, including feasibility of flight from a performance perspective, noise impact, and battery monitoring, all in the presence of modeled wind and weather. The user can refine the candidate vertiport locations based upon his/her consideration of the presented metrics for the feasibility of flight between them. More discussion on this is presented in the Regional Simulation System Results (Section VI).

The simulation component of the VAMOS! technology displays, in real time, the simulated operational behavior of AAM vehicles along their projected flight paths combined with data dynamically obtained from live sources. These data sources can be from the Federal Aviation Administration (FAA) or other private or public governing bodies, from one or more AAM vehicles in flight, and from weather sources.

V. The Regional Modeling Tool (RMT) Case Studies

Figure 1 depicts a composite suitability map for the downtown Los Angeles region. The results are computed on a grid which is 7x7 miles. It has 200 cells in each direction, totaling 40,000 cells. Therefore, each cell represents roughly 55 meters or 185 ft square. The warm (reddish) and the cool (bluish) colors represent higher and lower suitability values, respectively. By clicking on any region, one can "place" a vertiport at that location. The corresponding parameters of suitability of all attributes at that location are provided to the user on a panel on the right side of the display. This process can be repeated by selecting multiple vertiports within this grid or by moving the grid to nearby locations, like cities of Anaheim, or Newport Beach, or Woodland Hills in the Los Angeles Basin. A similar process can be followed to place vertiports in other parts of the country, by moving the basic grid at the desired location (from the graphical user interface). The same task can be achieved by creating adaptations of those specific regions, e.g., San Francisco, Chicago. The tool is designed to incorporate reward and penalty data from any location in the country, and roughly 70% of the data are automatically downloaded from publicly available sources. Table 1 below shows a list of 28 attributes in the Los Angeles case study. Some attributes have a letter "y" or "n" associated with it. It conveys whether NASA was able to download the data from publicly available sources. If not, then the partner provided those data.

NASA worked with several regional partners to develop and validate this capability. With the help of the Los Angeles Department of Transportation (DOT), the City of Los Angeles Planning Department, the Ohio DOT, the City of Columbus Planning Department, the Hillsborough County Transportation Planning Organization, and the Michigan DOT, a few preliminary vertiport site locations have been evaluated using the VAMOS! RMT. These were deemed as good locations, and some users in advanced stages of planning, suggested that they could proceed with the required process for assessing siting vertiports at those locations. Considering the sensitivities associated with the data from these entities and the locations under consideration, these results will be presented in a subsequent publication as a user evaluation report.

Table 1: List of attributes and their availability for the Los Angeles case study. (y) or (n) indicate if the data were available from public sources.

Attribute	Attribute	Attribute
Airport hazards (n)	Fire stations (y)	Ports (y)
Airports (y)	Future GPLU§ (n)	Power grid (y)
Airspace (y)	Heliports (y)	Powerplants (y)
Bicycle stations (y)	Large obstacles (y)	Rail stations (y)
Buildings (n)	Medical centers (y)	Schools (n)
Bus stations (y)	Medium obstacles (y)	Sports venues (y)
Convention centers (y)	Parking lots (y)	Vacant lots (n)
Dams (y)	Parks (n)	Zoning (n)
Daycare centers (y)	Places of worship (y)	
DOD† facilities (y)	Police stations (y)	

†DOD = Department of Defense, §GPLU = Generalized Planned Land Use

Even though the RMT functions across any region throughout the US, there are several differences across these areas. The zoning description for each location is different and the community partners had to provide those data, along with the corresponding weights and criteria for each zoning attribute (e.g., residential, manufacturing zones). Other attributes like existing/future planned land use data and detailed building heights (for each partner), study areas (assessment for development in Hillsborough County, FL), airspace hazards (in Los Angeles, CA), economic zones (opportunity and reinvestment zones in Franklin County, OH), etc. had to be provided by each community. These data were available with the communities and were relatively straightforward to incorporate in RMT. There was some tuning of the weights and criteria based on their experience within the local region. For example, the criteria for fire stations were different with each partner. Each of the attributes with their weights and criteria were carefully analyzed once, and preference files with all the settings were saved for future use.

With the Regional Modeling Tool, several features are available for the user to make decisions about placement of vertiports. Other than incorporating the desired data, there is also the possibility to provide user-specified potential vertiport regions grid data. Through this data set, the user can eliminate any sensitive locations (e.g., underground water pipes), so that the tool will compute acceptable solutions for vertiport locations on the acceptable grid data only. The ambient noise data are available and so a user can perform additional assessment for noise impact based on the location of a particular vertiport. RMT allows the user to visualize increase in noise at a specific location with a $1/r^2$ dissipation model, and additionally, more than 1.5 dBA increase in noise at that location. A user can provide 3D structure data (e.g., building in a downtown area) and locate vertiports on top of buildings or parking structures. Then, based on the FAA's current suggestion of utilizing approach/departure path surfaces, similar to those described in FAA Advisory Circular 150_5390_2c for heliports, the user can assess obstruction to these paths due to surrounding tall structures. Figure 2 (a) displays the LIDAR structural elevation data [17] for the Columbus, OH downtown area. As can be seen, the vertiport approach/departure flight path is obstructed by several building structures in the vicinity of the "placed" vertiport.

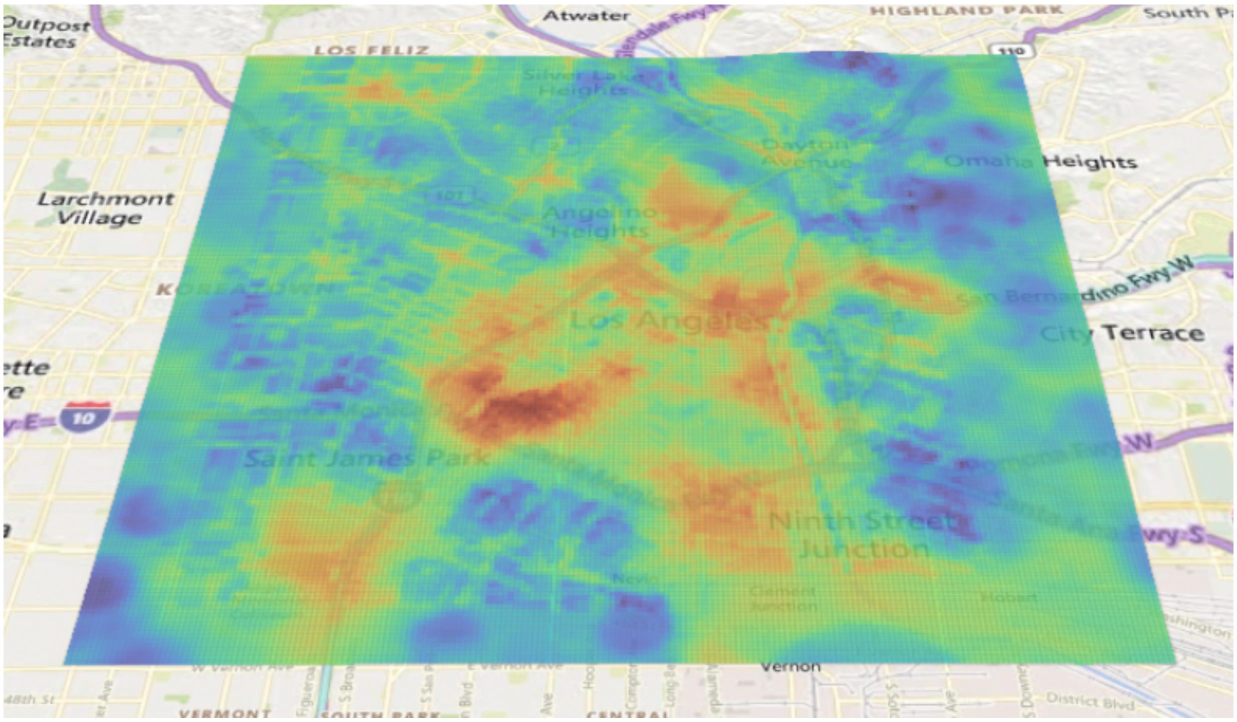


Figure 1[†]: Composite suitability for the downtown Los Angeles region. Warm colors represent more suitable locations and cool colors represent less suitable locations.

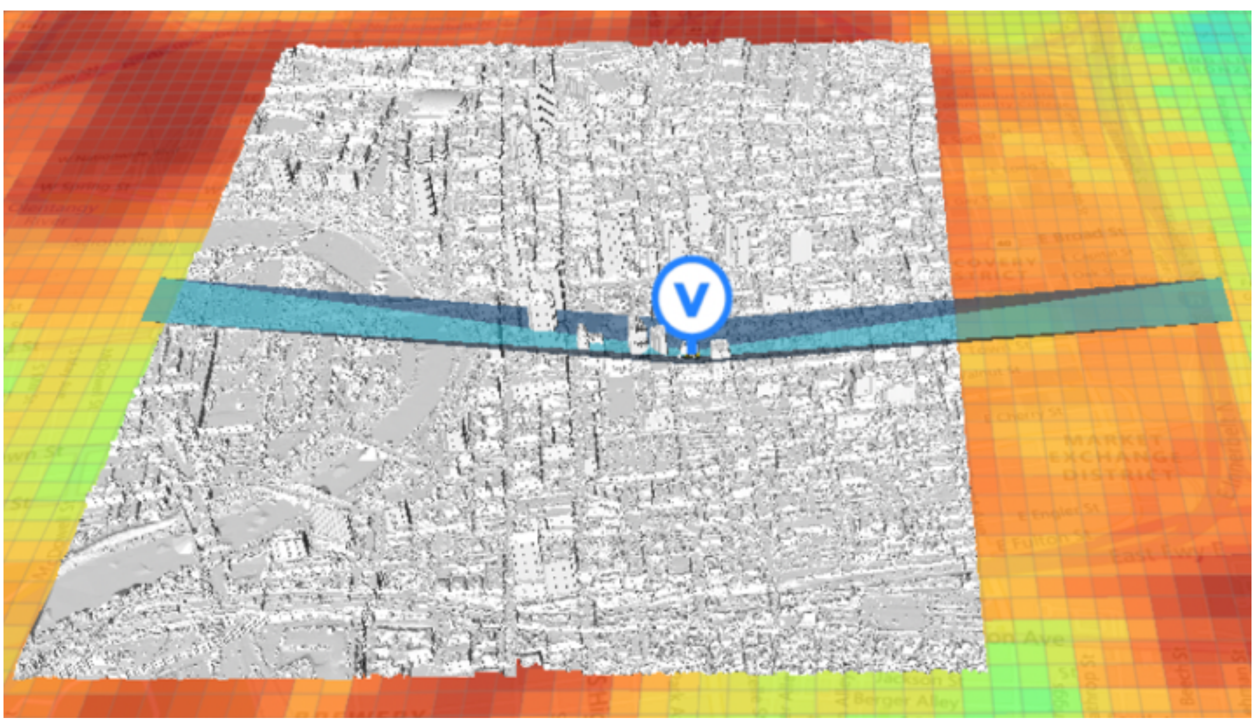


Figure 2[†] (a): City of Columbus, OH, building heights from LIDAR data, and the approach and departure surfaces.

[†] Underlying map data is © OpenStreetMap contributors. https://www.openstreetmap.org/copyright.

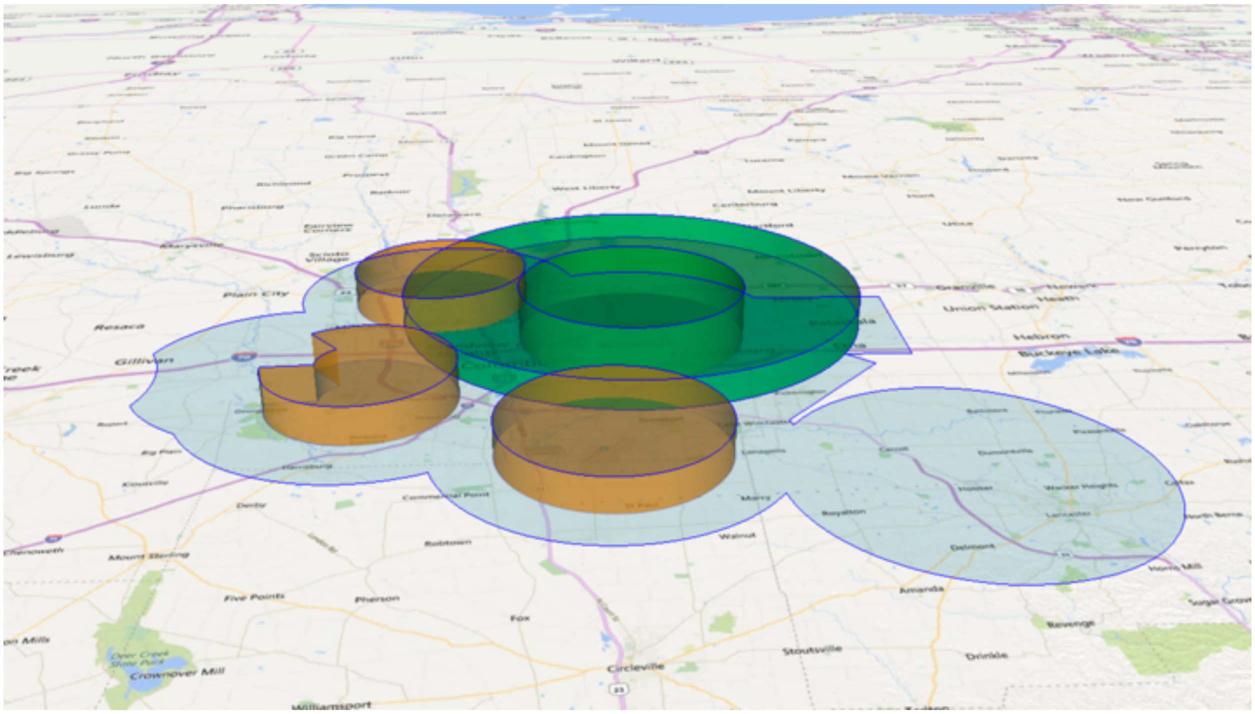


Figure 2 (b) [†]: Various classes of airspace over the larger Columbus region.

Figure 2: (a) LIDAR data and a vertiport location in the downtown Columbus area, and (b) C (green), D (brown), and E (cyan) Classes of airspace over the larger Columbus region.

The 3D airspace, including FAA-designated Class C, D, and E airspace over the larger Columbus area and the highway structure that the automobiles use is shown in Fig. 2 (b). These will be discussed more in the results for the Regional Simulation System (Section VI next).

VI. The Regional Simulation System (RSS) Results

Once the vertiport locations were selected in the Los Angeles region using the RMT heat map, these locations were provided manually to the simulation component of VAMOS, the RSS. A scenario schedule was generated with a computer script between these vertiport locations. The departure times, the origin/destination location of vertiports, the flight routes, and the cruise altitude of vehicles were input. RSS then modeled these e-VTOL vehicle trajectories according to the scenario schedule and the available vehicle performance models [15]. The simulation software also simulates hover or airborne holding, as needed while waiting for clearance to enter a corridor (designed for safety and airspace deconfliction), clearance for landing, aligning with the approach path (seen in Fig. 2 (a)), or just before touchdown.

One of the use cases for VAMOS RSS is to help assess the route structure for these e-VTOL vehicles between multiple origin/destination pairs. Figure 3[†] displays a simulation snapshot featuring 20 vehicles in the Los Angeles Basin. The scenario consisted of two types of vehicles (16 of the smaller-sized yellow Model 1 and 4 of the larger-sized black Model 2) flying along direct routes between five selected vertiport locations. These five locations were at Warner Center at Woodland Hills, near Los Angeles (LA) International Airport (LAX), near City Hall in downtown Los Angeles, the Anaheim Convention Center parking lot, and parking structure near Fashion Island Mall in Newport Beach. Highlighted just north of Santa Monica on the map is the noise footprint of NASA7, the quadcopter Model 1 cruising at 2000 ft from Woodland Hills to LAX. Noise footprints are precomputed based on the trajectory of the vehicles and are time-tagged for synchronization within RSS. Noise footprints from different vehicles are convolved by RSS to accurately model the noise impact on the ground.

[†] Underlying map data is © OpenStreetMap contributors. https://www.openstreetmap.org/copyright.

Each of the vehicles is modeled with a battery indicator that shows percent of battery remaining, as the vehicle flies along its path towards its destination. The two vehicle performance models have a fixed initial charge and a fixed depletion rate. These are used to model the battery state of charge as the vehicle goes through its climb, cruise, and descent phases. This is analogous to fuel consumption models for conventional aircraft. The electric battery charge depletion model used by RSS, is under development at NASA.

There are three types of routes available within the RSS. Figure 4 illustrates examples of each route type in the state of Ohio. Each of the Figure 4 (a, b, and c) parts show 30 flights with 24 smaller Model 1 (yellow) and 6 larger Model 2 (black) vehicles. They fly routes between Toledo (top left), Cleveland (top right), Columbus (middle right), and Dayton (middle left), with Cincinnati (bottom left) and Canton/Akron to the right of the Cleveland/Columbus corridor. First, there are direct routes from origin to destination (shown in Figure 3 for the LA region and described earlier). Figure 4 (a) displays these routes for the Ohio region. Second, there are routes that mimic/overfly established highways for surface transportation, such as highways, waterways, or railroads. Figure 4 (b) shows examples in the State of Ohio (e.g., I-71 going from Cleveland to Cincinnati via Columbus). Third, there are obstacle-avoidance routes, derived by deviating from a flight plan route to avoid due to weather or other polygons of FAA-designated constrained airspace. Figure 4 (c) shows the same image as Figure 4 (b) but with two obstacles and the simulated paths for NASA3/4 and NASA5/6 around the static obstacles. Notice that NASA6 deviates to the west side of the obstacle while NASA5 deviates to the east side. Both NASA3 and NASA4 to the east, based on an RSS optimization for minimum deviation distance.

The computed metrics are distance and time of flight, noise footprints, and battery consumption between origin and destination vertiports. When noise models become available for production aircraft, and when static and dynamic models become available for obstacles like Special Use Airspace and dynamic weather, respectively, additional metrics could be computed. These metrics (e.g., noise impact on the ground) could inform decisions to consider alternate sites for a particular vertiport. They could also suggest establishing additional vertiports along the path. In Figure 3 the nominal distance from Newport Beach (bottom) to Woodland Hills (top left) is about 65 miles, which may not be feasible for a shorter-range vehicle when considering the need to avoid the LAX arrival/departure paths and climb to clear the Topanga State Park hills. Such considerations may motivate city planners to consider more vertiports along that route, say, in Torrance or Compton.

Currently, the FAA Concept of Operations [2] refers to the notion of using airspace corridors to arrive at and depart from the vertiports, especially in areas where there may be other conventional aircraft flying within the airspace classes depicted in Figure 2 (b). It also talks about the use of heliport like approach/departure surfaces shown in Figure 2 (a). The RSS has incorporated a notional corridor along the highway I-71 traversing from Cleveland, OH to Cincinnati, OH. Such corridors can be established for assessing additional flight time and battery requirements with and without winds. The corridor definition should be extended to include the final approach segment of the arriving flight using the approach surface to the vertiport touchdown and lift-off area.

The statistics of time based on Direct routes (Fig. 4 (a)), and highway-based routes (Fig. 4 (b)), and Obstacle Avoidance routes (Fig. 4 (c)), with and without winds are shown in Table 2 below. The flight time corresponding to the flight between Cleveland (CLE) and Cincinnati (CIN) (in either direction) with no winds (W0) is shown in the second column. The battery state of charge is shown in the third column. Columns 4 and 5 show the flight time and battery data where the first and second numbers in each column, are for the flight from CLE to CIN and CIN to CLE, respectively. These results are obtained when the flights are subject to prevalent winds W1. The W1 winds are described on a 40-km grid and comprised of predominantly southerly winds. Similarly, columns 6 and 7 show same data when subject to winds W2. The W2 winds are presented on a 13-kim grid and comprised of predominantly northwesterly winds. Both wind models had maximum speeds of 30 knots prevailing for all flights with slight variation in the direction of incident winds. The RSS does not yet handle obstacle avoidance with higher resolution (13-km) winds, so flight time and battery data are not available for that case. It is work in progress.

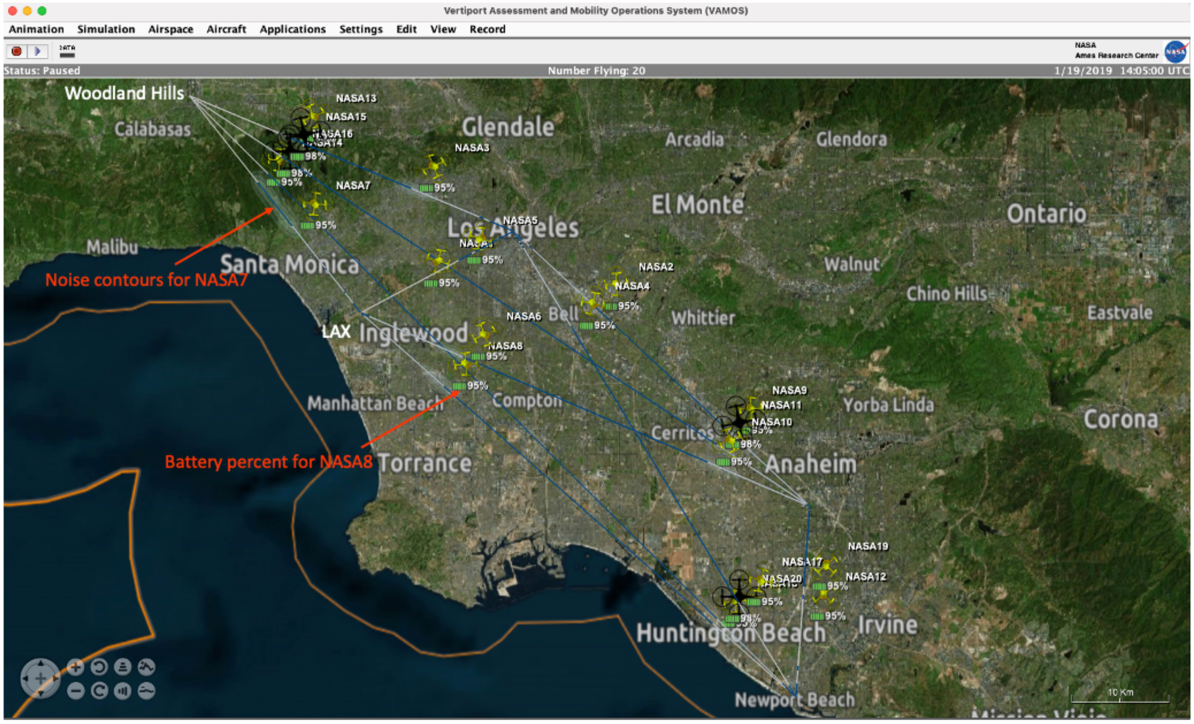


Figure 3: Display of 20 flights between five vertiports in the Los Angeles Basin.

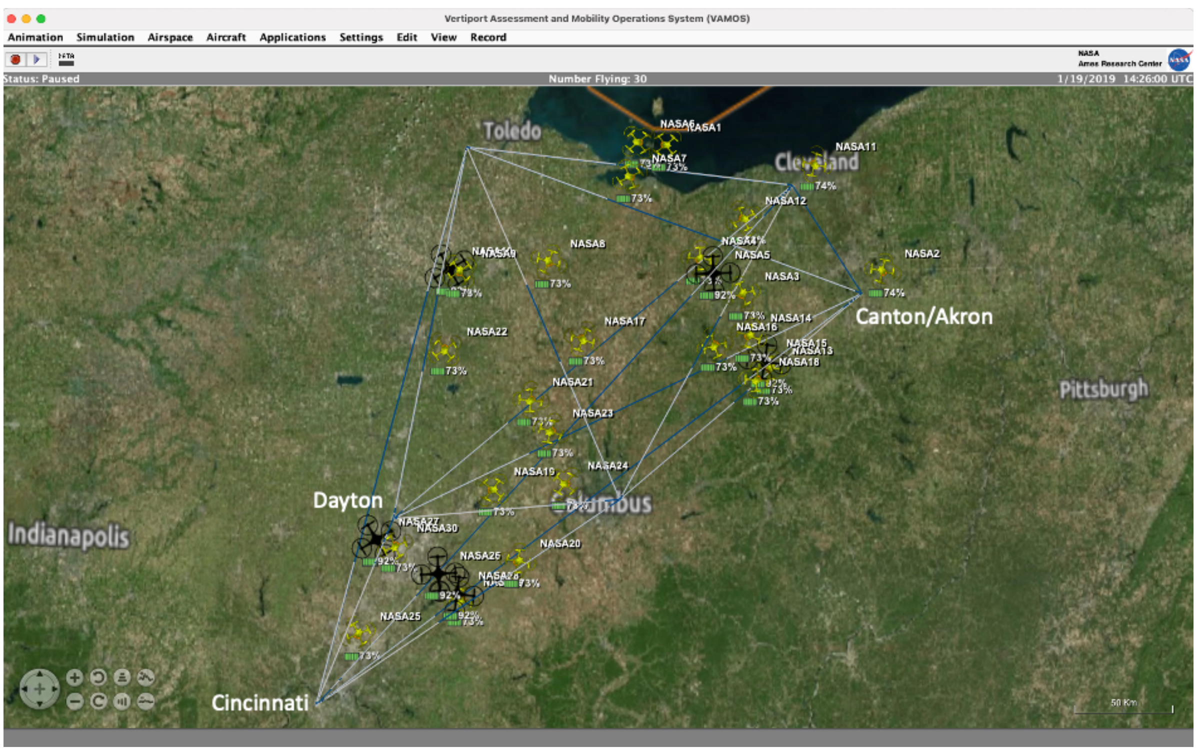


Figure 4 (a): Direct routes.

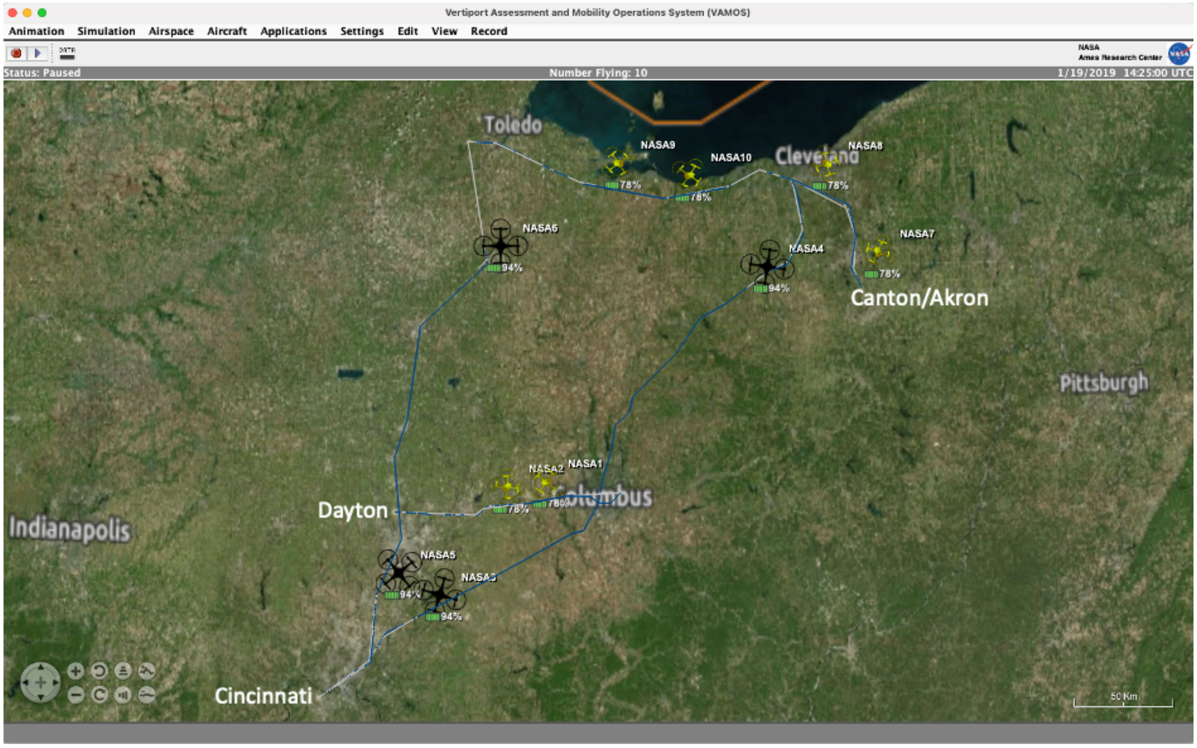


Figure 4 (b): Highway-structured flight routes.

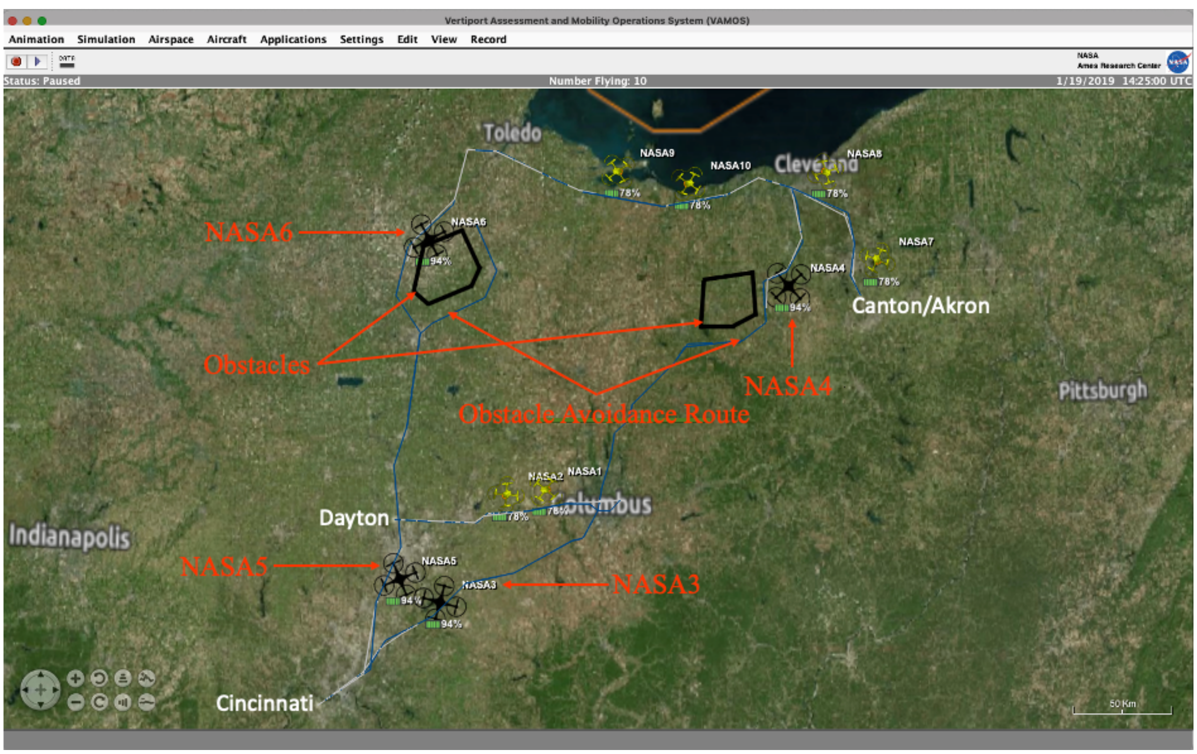


Figure 4 (c): Highway-structured flight routes with obstacle avoidance.

Figure 4: Different route structures in the Ohio region.

Interesting results from Table 2 can be observed the flights along the highways shown in Fig. 4 (b) above. The first and second numbers in Columns 4-7 are for flights from Cleveland to Cincinnati, and Cincinnati to Cleveland, respectively. First numbers in Row 3 (Highways) show that due to different winds (W1 and W2), one could have an additional 20-minute (150 for W1 vs 130 for W2) flight time and an additional battery use of 4 percent (72 for W2 vs 68 for W1). For the CIN to CLE flight, the differences are even more pronounced. The flight time shows an additional 42 minutes (167-125) while the additional battery use is 8 percent (73-65). Similar results can be observed for Direct Routes as well. Winds can play a significant role in the AAM operations, for schedule conformity and battery usage, resulting in additional safety considerations.

Table 2: Time and battery values for the three route structures with and without winds. The numbers shown are for the longest route between Cleveland and Cincinnati.

Route	Time: W0 (minutes)	Battery (percent left)	Time: W1 (minutes)	Battery: W1 (percent left)	Time: W2 (minutes)	Battery: W2 (percent left)
Direct	120	72	139/150	69/68	135/126	68/70
Highways	140	70	150/125	68/73	130/167	72/65
Obstacle Avoidance	143	70	150/155	68/67	-	-

VII. Future Work

VAMOS! is a work in progress. Feedback from the user community will continue to improve its feature set and modeling accuracy. There is a patent pending for this technology, and it will be made available to the community for input and improvement.

It should be noted that there are several factors included for the development of Regional Modeling Tool (RMT) and Regional Simulation System (RSS) that need to be refined for higher-fidelity decisions.

- The current RMT grid is a square grid for evaluation of composite suitability. In the future, a rectangular or arbitrary-shaped grid to fit the evaluation region better, with adaptive cell size, could be implemented for the computation.
- The noise data are used in RMT to provide impact from the vehicles, but the models are not refined for actual operations and the tempo (frequency and density) of traffic. For the RSS, the noise footprints are precomputed, but incorporation of noise modeling data along with the trajectory generation model would be more representative.
- The time-varying demand and traffic congestion data incorporated in the RMT need to have higher resolution.
- Currently, for the RSS, only flight routes along highways are explored. There are other possibilities like routes along railroad tracks or creeks that have not been explored and may provide lower-risk solutions.
- Also, for the RSS, the winds used are at lower resolution than the potential AAM vehicles require for trajectory modeling. The wind data should be higher resolution (meters instead of kilometers laterally, and tens of feet instead of hundreds of feet vertically) for the local region under consideration. Also, the impact of low-altitude weather (perhaps rain, convective activity, etc.) could be included in the form of airspace constraints. RSS is able to route vehicles around these constraints. However, as noted earlier, the obstacle avoidance algorithm needs work to function with higher-resolution winds.
- The model used for battery consumption in the RSS is preliminary and under development. It is intended that the models will evolve over time and will be incorporated in the simulation system.
- The vehicle performance models in the RSS are approximations of generic quadrotors. A Lift+Cruise and a Side-by-Side electric air vehicle models are already developed at NASA. These models are yet to be incorporated in the RSS for assessing diverse operations. Once the models for production vehicles are available from commercial companies, those could be integrated into the simulation.
- Lastly, the RMT and RSS need to be integrated in an environment like the NASA-developed TestBed [18]. A scenario generation software is needed so that the VAMOS! technology can seamlessly be operated by a user.

VIII. Final Remarks

The concept of Advanced Air Mobility (AAM) and the flight of electric Vertical Take-Off and Landing (e-VTOL) vehicles is gaining momentum. This paper introduced a patent-pending technology called VAMOS! to support city planners in evaluating the suitability of given vertiport locations and the feasibility of flight routes between them. VAMOS! is comprised of a Regional Modeling Tool (RMT) and a Regional Simulation System (RSS).

Based on the selected values of the suitability, one or more vertiport locations can be assessed. Once these locations are determined with the RMT, the RSS is invoked, which simulates the flight of vehicles between them. The vehicles are flown to assess metrics of performance and suitability of the selected vertiports. The modeling and simulation tools will be integrated in the future using the NASA-developed TestBed infrastructure, with a user in the loop. With the integrated software, and partnership with regional communities, the vertiport location aspect for AAM infrastructure can be addressed and used by vertiport developers and operators. Several meetings and joint discussions indicated that there is interest in this technology from the FAA. NASA worked with regional partners to evaluate VAMOS! for its utility in assessing the suitability of chosen vertiport locations in a specific region. Initial results for computed composite suitability indicated that RMT-generated suitability scores correlated well with subject-matter expert opinion.

Appendix A: Suitability Computation

This Appendix describes the algorithm for computing the composite suitability value. Given a region such as a city or a county, some locations may be more or less suitable for placement of vertiport infrastructure due to either beneficial or penalizing impacts on the surrounding area. The following description allows the user to evaluate each grid location to make comparisons for deciding where to place vertiport on the user-defined grid.

The suitability value is computed at each grid location. For example, in the default set, the grid is defined to be 7 miles by 7 miles square, with 200 cells in each direction, making it a 40,000-cell grid. For each grid location under consideration, a suitability value is defined to take a value over the range -1 to +1, where a value of -1 indicates “not at all suitable,” and +1 indicates “fully suitable.” The values in between indicate some intermediate level of suitability between “not at all” and “fully” suitable. A suitability value of 0 is then a “neutral” point, indicating that either there is no information available to make a positive or negative assessment or there is information available, but the positive and negative contributions cancel out.

Composite Suitability

The algorithm to compute the composite suitability for a grid location is defined as follows:

1. Identify attributes that contribute to the suitability of a location. For example, attributes considered include zoning, planned land use, fire stations, noise, and time-varying attributes like traffic congestion and passenger-trip demand. Note: the dynamic attributes are discrete and are treated as static (like any other static attribute like train stations) at each time slice. The composite suitability is also defined, then, at those time slices. The purpose of computing the composite suitability at all those time slices, is to assess if there would be high demand or high congestion during high tempo of air traffic operations, and how would that impact the area (maybe within a few blocks) in the vicinity of that vertiport, from the city/county perspective.
2. For each attribute, compute the individual suitability independent of all other attributes at the given grid location.
3. Identify the relative importance of each attribute and combine the computed independent suitability values to obtain a composite suitability value at the given grid location.

The algorithm depends on the following definitions. Let N_a be the number of attributes and let $s_{k,i}$ be the individual-attribute suitability at each grid location i for attribute k, where $k \in 1,2,\dots,N_a$. Each $s_{k,i}$ is within the range $[-1,+1]$. Let w_k be the weight of attribute k, expressing the relative importance compared to all other attributes. It is required that $0 \geq w_k \leq 5 \ \forall \ k$ and $w_k > 0$ for at least one k. Then, define $s(i)$ as the composite suitability value at a grid location i, where:

$$s(i) = \frac{\sum_{k=1}^{N_a} w_k s_{k,i}}{\sum_{k=1}^{N_a} w_k} \tag{1}$$

The denominator ensures the composite suitability is normalized to stay within the valid range $[-1,+1]$ and the weights w_k themselves need not be normalized to 1. See Figure 1 above for the composite suitability in the downtown Los Angeles region.

Individual-Attribute Suitability

Computing each individual-attribute suitability is dependent on the data used. There may be individual attributes which have multiple data points (features) in the vicinity of a particular grid cell. For example, it was observed that daycare centers and places of worship were quite dense datasets in many locations. The following two sub-sections deal with situations where there is only a single data point (one school) versus multiple features (many schools) in the vicinity of a grid cell.

<u>Single Feature Suitability</u>

An attribute contributing to the composite suitability value of a grid location could be its proximity to a point feature such as a school building. It could be either beneficial or detrimental to be close to certain types of features. For simplicity, these features are modeled as points on the map, with the assumption that the scale on which the suitability is assessed is large relative to the size of a school building. Two cases are illustrated below. One represents a reward attribute, and the other, a penalty.

Example: Proximity to a Reward (A Hospital)

Having a hospital near a vertiport is beneficial because it facilitates access to medical services. Suppose there is one hospital near the grid location under consideration and let $s_{k,i}$ represent the individual-attribute suitability related to proximity to this hospital. A mathematical function is developed to quantify the value of $s_{k,i}$.

First, identify values of s_k at known locations. At the exact position of the hospital, $s_{k,i}$ is defined as +1, indicating maximal suitability. As distance (the criterion) is increased from the hospital, $s_{k,i}$ should decrease, as the value of having a hospital in the vicinity decreases. It should be noted that this criterion can be in terms of time as well and doesn't have to be distance-based. Once the position is greater than a maximum distance d_{max} from the hospital, it is unaffected by the presence of the hospital and so neither positive nor negative impact is assessed on the suitability due to the hospital ($s_{k,i} = 0$). (Note: there may be attributes where the criterion may be defined such that beyond a certain crossover distance, the impact may flip the sign to be opposite of what it was (+1), at the exact location of the hospital. For example, it may be that for hospitals, after say an intermediate distance of $d_{crossover}$, the suitability may tend linearly to -1 at d_{max}). Then, a criterion $c_{\text{reward}}(d)$ of some distance d is defined that takes these known values, and for simplicity, linearly interpolates between them:

$$c_{\text{reward}}(d) = \text{x}_{[0,+1]}\left(1 - \frac{d}{d_{max}}\right), \tag{2}$$

where the saturate function, ξ, is defined as:

$$\xi_{[a,b]}(x) = \min(\max(x, a), b) \tag{3}$$

If $d_{\text{hospital}}(i)$ is the distance from the hospital to the grid location i, then let

$$s_{k,i} = c_{\text{reward}}(d_{\text{hospital}}(i)) \tag{4}$$

as an individual-attribute (hospital) contribution to the composite suitability. The $s_{k,i}$ computed here is plugged into Eq. 1 above. See Figure 5 (a) for the distance criterion for hospitals (reward, Score is +1 for x-value of 0) in the Los Angeles region, and Figure 5 (c) for the single attribute reward suitability for hospitals.

Note that while the suitability score can vary across the full interval $[-1, +1]$, $c_{\text{reward}}(d)$ varies strictly in $[0, +1]$ because it is assumed that positions far from the hospital are not impacted. Alternatively, it is assumed that positions should be explicitly penalized if they are too far from a hospital, in which case we would modify c_{reward} to decrease to a negative suitability value. The next section provides an example of an attribute that would have a clear, penalizing effect on the suitability value.

Example: Proximity to a Penalty (A Park)

Having a vertiport nearby a peaceful, quiet park is unfavorable because the vertiport might create a noise disturbance due to vehicle operations and it might cause an increase in vehicle traffic along nearby roads. Similar to

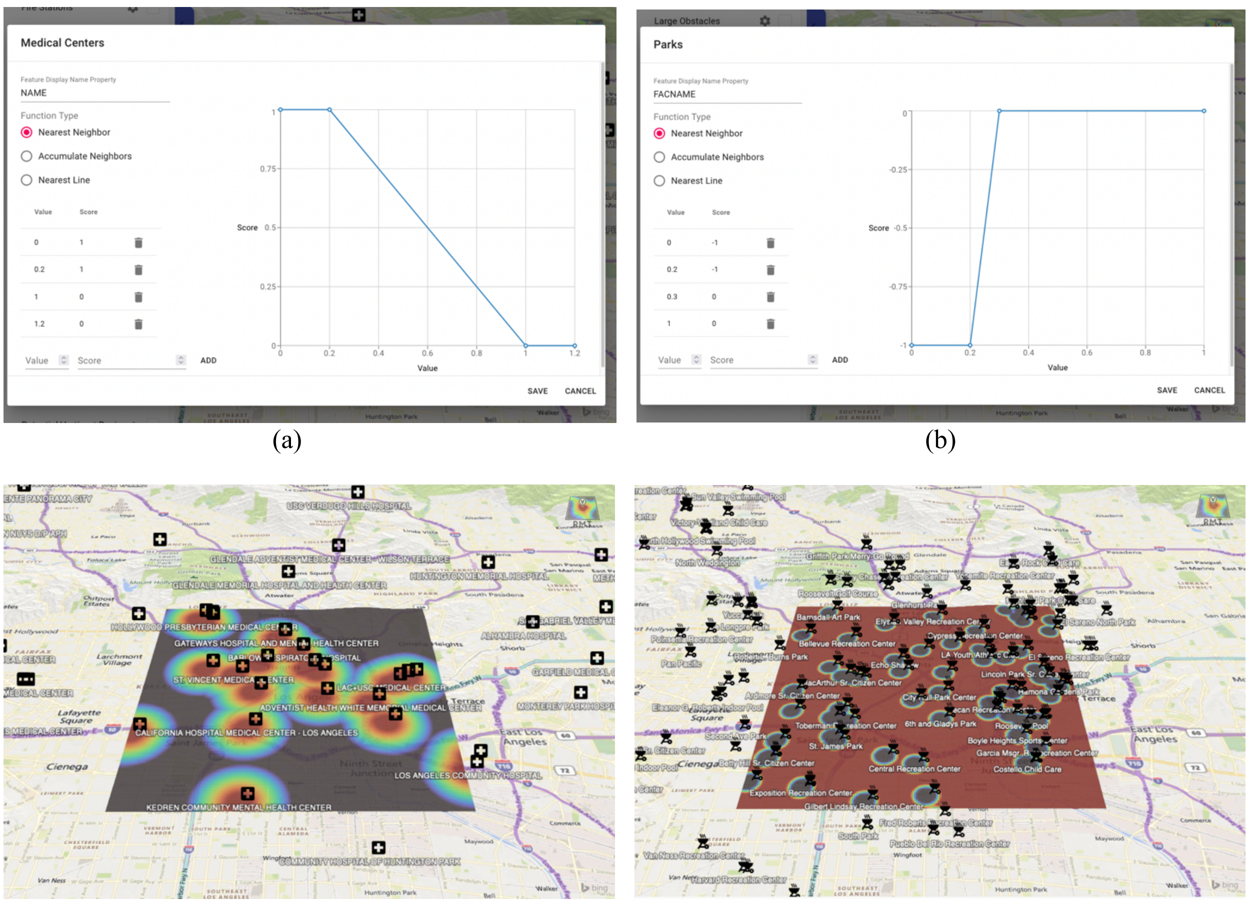
$c_{\text{reward}}(d)$, define a function $c_{\text{penalty}}(d)$ to capture an increase in penalty as a function of decreasing distance from the park as:

$$c_{\text{penalty}}(d) = \text{x}_{[-1,0]}\left(\frac{d}{d_{max}} - 1\right). \tag{5}$$

If $d_{\text{park}}(i)$ is the distance from the park to grid location i, then let

$$s_{k,i} = c_{\text{penalty}}(d_{\text{park}}(i)) \tag{6}$$

as an individual-attribute (park) contribution to the composite suitability. The $s_{k,i}$ computed here is plugged into Eq. 1 above. See Figure 5 (b) for the distance criterion for parks (penalty, Score is -1 for x-value of 0) in the Los Angeles region, and Figure 5 (d) for the single attribute penalty suitability for parks. Again, it should be noted that the criterion can be in terms of time as well and doesn't have to be distance-based.



(a) (b)

(c) (d)

Figure 5: Distance criterion for hospitals as a reward (a), distance criterion for parks as a penalty (b), reward function suitability for hospitals (c), and penalty function suitability for parks (d).

It should be noted that there may be specific attributes which need to be treated as hard constraints. There is a functionality available to read in a 'Potential Vertiport Regions' data file (described in Section V), for the chosen grid size. The file has grid cells eliminated where vertiports cannot be placed. Reading that file permits the modeling tool to compute composite suitability only on grid cells present.

Additionally, the colormap used in Figs. 5 (c) and 5 (d) have a *range* of colors from black (least suitable) to red (most suitable). There are colormaps available where these colors could be based on user's preference. If a user is color-blind, there are single color-gradient maps available. Alternately, if one wishes, just a red-yellow-black colormap can be used for suitability value ranges, say 0-0.35 as black, 0.36-0.65 as yellow, and 0.66-1.0 as red.

Multiple Feature Suitability

Another example of a suitability attribute could be proximity to multiple point features, for instance, proximity to multiple hospitals in the region.

While each feature can be assigned to its own attribute, where each attribute would quantify proximity to each feature (using the approach discussed in the previous section), this does not capture all desired behavior. For example, if there were two hospitals treated as a separate attribute, and the individual-attribute suitability values were 0.8 and 0.4 respectively, then an equal weighting between the two attributes would result in a composite suitability of (0.8 + 0.4)/2 = 0.6. However, one would expect that the composite suitability would be *at least* 0.8, i.e., that there is some *added* benefit of having the second hospital also in the vicinity. Here, instead treating *each hospital uniquely*, where one might care specifically about proximity to hospital A versus proximity to hospital B. There may be applications for this, say, if each hospital offers unique medical services from the other, but then they should be provided as two datasets, for example, one for cancer treatment and one for trauma center.

In general, there is a need to quantify whether a position is close to *any* of an identical set of features, and if so, *how many*. A means of accumulating the contributions from each point feature in the set is developed, into a single value for the entire set.

Similar to the previous discussion on Single Feature Suitability for one feature, values for s_k to take at known locations are identified. Considering the previous examples of hospitals and parks, when no hospitals are nearby, the grid location i has neither positive nor negative suitability, and as more hospitals are present nearby, the suitability increases and eventually saturates at the maximum value +1. When no parks are nearby, the location i has neither positive nor negative suitability, and as more parks are present nearby, the suitability decreases and eventually saturates at the minimum value -1.

In general, for a set of identical point features, let M_k represent the number of features in the region, and let $d_j(i)$ be the distance from grid location i to feature $j \in 1, 2, \ldots, M_k$. Then, let $c_0 \in [-1, +1]$ be a constant value for the suitability of a position if there were no point features nearby (either there are none in the entire region or are none within any distance to be of any influence). Also, let $c(d) \in [-1, +1]$ be a value function to assess the impact of a single point feature based on its distance d from the cell location.

Then, the following function for $s_{k,i}$ quantifies the effect of multiple identical point features as:

$$s_{k,i} = \xi_{[-1,+1]}\left(c_0 + \sum_{j=1}^{M_k} c\left(d_j(i)\right)\right). \tag{7}$$

Where, if $c_0 = 0$ and $c(d) \in [-1, 0]$, then as M_k increases, $s_{k,i}$ trends to -1 (for increasing penalty features), and if $c_0 = 0$ and $c(d) \in [0, +1]$, then as M_k increases, $s_{k,i}$ trends to $+1$ (for increasing reward features). The constant c_0 is often set to zero, however, it adds flexibility for cases when the absence of a nearby type of feature would make a position inherently suitable or unsuitable. An example of that would be utility tower poles, which if not present, would inherently make the locations suitable. The $s_{k,i}$ computed here is plugged into Eq. 1 above.

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