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Full Length Article

VTOL site location considering obstacle clearance during approach and departure



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ABSTRACT

Urban air mobility (UAM) extends urban transportation to low-altitude airspace using electric vertical take-off and landing (eVTOL) vehicle to reduce traffic congestion. The vertical take-off and landing (VTOL) site connecting ground and air transport is the critical infrastructure of the UAM. Determining its locations is essential for the design and operation of the air route. This study focuses on the problem of the location of the VTOL site, using Shenzhen as the study area, and establishes an integer programming model with the objective of maximizing travel cost savings to identify the optimal locations of the VTOL sites. This study is different from existing ones in that it explicitly considers the three-dimensional spatial availability of VTOL sites. Geographic information system (GIS) tools are used to identify locations that satisfy two-dimensional (2D) planar availability, and an obstacle assessment model of the approach/departure and transitional surfaces of the VTOL site is built to further screen the locations. The selected potential sites are used as input to the integer programming model, ensuring that the locations identified to establish the VTOL site are optimal. The impact of the number of VTOL sites, the user's transfer time at the VTOL sites, and the eVTOL pricing on the model solution is also discussed. Although this study uses Shenzhen as a research object, the proposed methodology is generalized and applicable to any other city or region, providing recommendations and references for initial planning and related operations of the UAM in selected areas.

1. Introduction

Traffic congestion presents a significant challenge in the majority metropolitan areas around the world, causing substantial economic loss and considerable impact on society. Among the 10 most congested cities in the world, the average commuter wastes more than 150 h of additional time on the roads each year (Friedman, 2020), and when this figure exceeds 35 h, it signifies a negative impact on the economy (Badger, 2013). In addition to impeding economic development, traffic congestion leads to additional travel time, resulting in reduced efficiency and loss of productivity. Motor vehicles moving on congested roads spend longer periods at low speeds, leading to inadequate fuel combustion due to reduced speed and higher levels of harmful substances such as nitrogen

oxides in the exhaust. Furthermore, extended travel time contribute to increased pollutants emissions, leading to air pollution and climate change. This, in turn, affects physical well-being and poses significant challenges to public health (Nadrian et al., 2019, 2020).

To address the problem of traffic congestion, researchers are exploring various new technologies and methods (Jan et al., 2019; Sills, 2018; Wang et al., 2020). With the emergence of unmanned aerial vehicles (UAVs), efforts are being made to extend urban transportation from the ground to the air (Qu et al., 2022). The concept of Advanced Air Mobility (AAM) has been jointly proposed by the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) in USA, with the aim of developing an aviation transportation system that uses electric aircraft to transport passengers and

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cargo (Federal Aviation Administration (FAA), 2020). Urban Air Mobility (UAM) is a subset of AAM that includes a set of rules, procedures, and technologies that enable the operation of airborne passenger and cargo traffic in urban environments. Extensive research efforts have already focused on various aspects of UAM, leading to significant advances in airspace planning (Bauranov and Rakas, 2021), market demand assessment (Long et al., 2023), and aircraft design (Piccinini et al., 2020).

In 2016, Uber released a white paper that provides a comprehensive outline of the use of vertical electric take-off and landing aircraft (eVTOL) to transport passengers within urban environment (Holden and Goel, 2016). The document explicitly outlined the main challenges facing the implementation of eVTOL operations, one of them being the establishment of vertical take-off and landing (VTOL) infrastructure. In 2023, the FAA issued the “Advanced Air Mobility Implementation Plan”, aiming to achieve the required infrastructure elements and procedural measures, including the VTOL infrastructure setup, necessary for scaled AAM operations by 2028 (FAA, 2023a). A recent study has compared the UAM systems in the metropolitan areas in USA and China (Wang et al., 2023). VTOL infrastructure serves as the ground-based foundation for eVTOL operations, encompassing activities such as takeoffs, landings, passenger embarkation, and charging. Given the constraints posed by intensive land use in urban areas, community acceptance, and construction costs, establishing densely distributed VTOL facilities to facilitate door-to-door eVTOL operations is not feasible. Consequently, a single journey UAM comprises three distinct segments, as shown in Fig. 1. Sequentially, these segments consist of ground transportation from the position of departure to the VTOL take-off site (commonly referred to as the “first mile”), airborne transportation from the VTOL take-off site to the VTOL landing site, and finally, ground transportation from the VTOL landing site to the destination (commonly referred to as the “last mile”). As such, strategic placement of the VTOL infrastructure profoundly impacts the safe, efficient, and orderly operation of eVTOLs within the urban environment. The location of the VTOL infrastructure is also fundamental for research on eVTOL flight routes. Therefore, a well-distributed network of VTOL infrastructure is of great significance for the continued advancement of UAM.

According to Amap’s “China Major City Traffic Analysis Report Q2 2022”, Shenzhen ranks first in suboptimal urban traffic health (AutoNavi, 2022). The “Ratio of Mileage in Frequently Congested Road Sections” index is relatively high in Shenzhen. On the Xiangmi Lake Road (south to north) during workdays, the accumulated severe congestion time reached 144 h, equivalent to an average daily severe congestion of 2.3 h. Follow closely along Henan Road (east to west) with a cumulative severe congestion time of 127 h. In 2023, Shenzhen, for the first time in its government work report, introduced the concept of developing the “low-altitude economy”, with the aim of establishing a center for the low-altitude economy and creating a civil UAV test zone. Multiple UAV companies are collaborating to facilitate the high-quality development of Shenzhen’s low-altitude economy. For example, Shanghai Peak Fly Aviation Technology Co., Ltd. plans to inaugurate the world’s first eVTOL route in Shenzhen in October 2023 (Shenzhen China, 2023). Although

there have been numerous studies on the selection of VTOL sites, few have considered whether designated locations meet the required clearances for safe eVTOL takeoffs and landings. Although eVTOLs can take off and land vertically. For safety reasons, normal departure and arrival procedures for passenger-carrying eVTOLs or large eVTOLs require transitional surfaces. A NASA report on various aspects of vertiports has highlighted that the initial step in physical considerations should be identifying the obstacle clearance of existing structures for takeoff and landing (Mendonca et al., 2022). Here, we propose a novel method to determine optimal locations within the city of Shenzhen to establish VTOL sites. Specifically, our research incorporates considerations of three-dimensional airspace availability when choosing VTOL site locations. Within a two-dimensional (2D) space, we leverage GIS tools to initially exclude drone-restricted areas within Shenzhen, ensuring that eVTOL operations comply with regulatory regulations. Subsequently, we exclude occupied areas, such as buildings and zones unsuitable for VTOL site construction, such as parks, and identify remaining areas suitable for VTOL site construction. Uber has also highlighted the possibility of establishing VTOL sites on building rooftops; thus, we identify locations with sufficiently large rooftop surfaces. Subsequently, we established an obstacle assessment model for the VTOL site approach, departure, and transitional surfaces. Using location sites that satisfy 2D planar availability, we further refine our selection. The model outputs VTOL site locations that meet requirements for obstacle clearance during approach and departure, along with corresponding angles for approach and departure trajectories. Finally, we establish an integer programming model, incorporating the identified alternate locations and our processed UAM candidate routes. The model ultimately determines the optimal locations of the VTOL sites, the number of UAM trips, and the mode of transport for the access of passengers to and from the VTOL sites.

The remainder of this paper is organized as follows. Section 2 reviews the relevant studies on the VTOL site location problem; Section 3 describes the assumptions, parameters, and modeling process of the study; Section 4 shows the results of our model and the sensitivity analysis of the relevant parameters; Section 5 explores the effects of three key factors on the modeling results: the number of VTOL sites, the transfer time, and the cost of eVTOL; and Section 6 concludes the study and discusses the direction of future research.

2. Literature review

There is increasing interest in the study of the location of VTOL sites. In Lim and Hwang (2019), the authors focused on the three most congested commuter routes in the Seoul metropolitan area. A *k*-means clustering algorithm was developed based on commuting data represented by latitude and longitude coordinates, and the centroids of the resulting clusters are as VTOL site locations. A UAM traffic demand analysis for commuters across the bay in the San Francisco Bay Area is presented in Bulusu et al. (2021). Rational constraints for the cost of constructing additional VTOL sites and capacity limits were developed to determine the upper and lower limits for the number of VTOL sites.

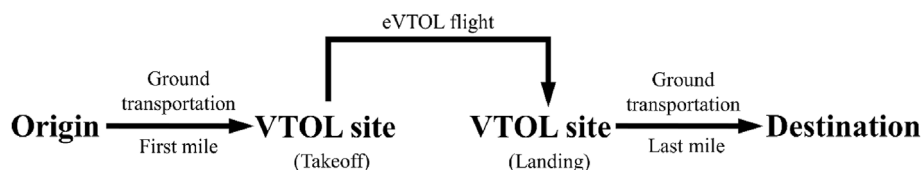


Fig. 1. Illustration of a UAM trip.

Iteratively, a k -means cluster was applied to identify the distribution of the VTOL site that maximizes passenger volume while adhering to time-saving thresholds. The work in [Rath and Chow \(2022\)](#) addressed the selection of landing points for aerial taxis bound for the three major airports of New York City. A Revenue Distance Ratio (RDR) model was formulated that aimed to maximize the flow of passengers from aircraft taxis and an REV (revenue) model aimed at maximizing the income of aircraft taxis. Three pricing scenarios were established, and the optimal locations of the VTOL sites were computed on the basis of these models and objectives. The results indicated that the locations of the VTOL sites exhibit high sensitivity to different pricing scenarios. The REV model provided a more fair distribution of the demand for and income allocation of the VTOL sites. Each of the aforementioned studies aimed to determine rational locations of the VTOL sites to meet specific needs or within localized regions. They also considered various associated parameters in their analyses.

In another line of research, researchers have investigated the locations of VTOL sites from other perspectives. For example, it is assumed that the UAM demand is distributed across an entire metropolitan area. The entire region is then modeled as a grid and VTOL sites can be established in each cell of the grid ([Chen et al., 2022](#)). A subset of p VTOL sites from these cells has been selected as hubs to minimize overall transportation costs. The Weighted Linear Combination (WLC) method is used to select suitable areas for UAM ground infrastructure in combination with Geographic Information Systems information ([Fadhil, 2018](#)). The weights for WLC were determined through expert interviews and the analytical hierarchy process-Delphi method. In [Daskilewicz et al. \(2018\)](#), the demand for UAM is estimated using the American Community Survey and household employment statistics, and an integer programming model is formulated to set the locations of the VTOL sites that maximize time savings compared to car travel. A hub location model is developed that considers the risk of air collisions when determining optimal VTOL site locations and demand distribution for an aerial taxi transport network ([Sinha and Rajendran, 2023](#)). The model aimed to minimize the total cost composed of travel, facility, and collision risk costs. Based on previous studies on aerial taxi demand, the study in [Sinha and Rajendran \(2022\)](#) used the Clustering LARge Applications (CLARA) algorithm to identify 14 VTOL locations. These VTOL locations were gradually opened in multiple stages that are optimized by an integer programming model considering parameters such as rental costs and road facility convenience. In [Wang et al. \(2022\)](#), UAM demand is generated by scaling taxi demand to study the vertiport planning problem. An adaptive discretization approach was developed to find the optimal solution of the model.

VTOL site selection can be modeled as an enhanced single-allocation p -hub median location problem ([Willey and Salmon, 2021](#)). Subgraph isomorphism can be used to identify optimal VTOL site locations considering vehicle constraints and operational strategies, especially for trips involving more than two aerial ports. In [Ploetner et al. \(2020\)](#), the Munich metropolitan area agent-based microsimulation model (MITO) is used to estimate the 2030 traffic demand. A total of three possible demand scenarios are proposed that represent high, medium, and low density demand. The three associated VTOL site networks consisting of 130, 74, and 24 VTOL sites were developed, respectively ([Willey and Salmon, 2021](#)). In [Rajendran and Zack \(2019\)](#), a two-stage approach is proposed to solve the problem of the location of the aerial taxi infrastructure. The authors first filtered conventional taxi customers as potential aerial taxi users and used an iterative k -means clustering algorithm to identify the locations of the VTOL site. To improve the quality of initial seed solutions in k -means, the fitness of candidate sites is

first calculated based on the percentage of satisfied customer demands, and the top ten candidate locations are used as input for the k -means algorithm. Compared to traditional k -means, this algorithm runs efficiently by generating a significantly fewer number of clusters, thus limiting the number of VTOL site locations. A later work extended the work in [Rajendran and Zack \(2019\)](#) from a single-objective decision to include five socioeconomic factors ([Sinha and Rajendran, 2022](#)). A group of potential sites were ranked using a weighted average, and the top five sites with the highest total scores were used as initial inputs for the k -means algorithm. The results showed better performance with smaller Davies–Bouldin index (DBI) values, indicating better clustering with smaller intra-cluster distances and larger inter-cluster distances. An interesting study can be found in [Peng et al. \(2022\)](#), in which a k -medoids clustering algorithm is developed to divide potential UAM user origin-destination pairs into completely connected main zones. The number of main zones is the maximum of zones that meet all UAM aggregated time constraints. The number of VTOL sites in each main zone was increased until capacity limits were met. Then an integer programming model was formulated, combining a constrained clustering of k -medoids to allocate demand to VTOL sites and determine their locations. This method yielded a network consisting of 6 main zones and 116 VTOL sites in the San Francisco Bay Area. Of the 16,308 UAM trips selected, 78% saved travel time, with an average time savings of 27 min compared to driving.

These studies extended single-demand scenarios to include various demands, resulting in VTOL site networks that can adapt to a wide range of travel needs. However, it is important to note that the locations of the VTOL sites derived from these studies are results of mathematical models. Despite considering the geographical restrictions of the real world in 2D space, the suitability of potential vertiports for take-off and landing has not been evaluated.

There are studies that have considered the availability of space when selecting VTOL site locations. In [Jeong et al. \(2021\)](#), the authors used the iteration of k -means to determine the positions of the VTOL sites and used satellite imagery to assess the results of each grouping. If a chosen location is in a restricted area such as a green zone, the clustering process is repeated until all positions suitable for VTOL site construction are found. In [Brühl et al. \(2023\)](#), the authors calculated the total area required to establish a VTOL site based on the quantity and area of facilities, equipment, and road surfaces. Whether the location has sufficient area has to be determined. Then a hub-and-spoke network of VTOL sites will be devised based on eVTOL operational characteristics. In [Wu and Zhang \(2021\)](#), the authors used laser radar data and land usage information as input for the network design model and found the basis for identifying available ground areas for the recognition of the VTOL site. These studies considered ground availability when determining the location of the VTOL site, enabling research results to be more aligned with practical operations.

However, VTOL sites serve as the link between road-side passengers and aerial eVTOL operations. In addition to satisfying the availability in the 2D space, the airspace at the chosen location must also provide eVTOL approach and departure routes that meet obstacle clearance requirements, ensuring safe takeoff and landing. Therefore, determining the locations of the VTOL sites that fulfill three-dimensional spatial availability deserves further research efforts.

Since taxis are greatly affected by ground traffic congestion, we focused on taxi users as the primary candidates for transitioning to UAM services. Therefore, the travel demand for UAM is derived from the operational data of the taxi. The data set obtained covers all time periods within a day and spans the entire geographic range of Shenzhen, covering

various travel purposes such as commuting, leisure, and medical needs. We utilized GIS tools to identify potential 2D locations for the VTOL site, and establish an obstacle assessment model for the VTOL site approach and departure paths. This model aided in further refinement of the selection of potential site locations. We incorporate the potential locations into the input of an integer programming model to determine the final locations for the establishment of the VTOL sites. The established network not only captures diverse travel demands, but also meets three-dimensional spatial availability at each VTOL site location. We conducted sensitivity analyzes on the number of VTOL sites, transfer time, and eVTOL pricing, discussing the impacts on the location and design of the VTOL site. The approach presented in the document improves the feasibility of urban air traffic and provides a reference for the preliminary planning of UAM in a designated area.

3. Methodology

3.1. Assumptions

The following assumptions are made.

- (1) Only taxi passengers are considered as potential customers who may shift to UAM services. This is because UAM trips are chosen to reduce the negative impacts of traffic congestion. Among the various modes of public transportation, buses have dedicated lanes, shared electric vehicles, shared bicycles, and subways are almost unaffected by traffic congestion, only taxis are most affected by road conditions.
- (2) This study assumes that each UAM trip involves only two VTOL sites used, respectively, for take-off and landing, and does not consider inserting an additional VTOL site between them for transfer. Passengers choose UAM because it is time-saving, while additional transfer will increase the time of UAM trips. Additionally, in the early stages of establishing a new mode of transportation, an overly complex infrastructure network is not recommended.
- (3) Four transport modes are considered for each ground segment of a UAM trip: taxi, shared electric bike, shared bicycle, and walking. The speed of each mode is assumed to be constant and is not affected by traffic condition.
- (4) In this study, the range and endurance limitations of eVTOL are not considered. Since the geographic scope of this study is within the city of Shenzhen, the flight distance between any two VTOL sites is relatively short. Thus, the endurance of eVTOL is sufficient to perform any single flight mission. The range and flight-time limitations should be considered in a larger area, such as the cross-city operation of eVTOL.
- (5) This study does not consider the capacity constraints of the VTOL site and the limitations of the eVTOL fleet size.

3.2. Determination of potential UAM trips

According to Assumption (1), this study only considers passengers traveling by taxi as potential customers who can use UAM services. The taxi data used in this study is from a study by Wang et al. (2019), which provides all the Global Positioning System GPS(GPS) data of taxis in Shenzhen on a certain day. Each piece of data includes information such as taxi ID, time, latitude, longitude, and passenger-carrying status. The raw data are processed as a passenger-carrying trip, which is presented in the format of vehicle identification, origin latitude and longitude, destination latitude and longitude, and travel time. Although the

airborne flight segment of UAV services is characterized by high speed and free from traffic congestion, the total time involved in UAM services includes both the ground transport of approaching and departing from VTOL sites, as well as the transfer time. As a result, passengers who experience longer taxi travel times are more likely to consider switching to UAM services. Here, we set a threshold of 30 min. Taxi trips with a duration shorter than the threshold are considered unlikely to opt for eVTOL travel. Ultimately, a total of 46,537 taxi trips were retained as potential UAM journeys.

In fact, the Assumption (1) is a very strong one on the potential UAM passengers. There are other methods to generate UAM demands, such as the grid-based method (Chen et al., 2022). To relax this assumption, we used a similar approach in Wang et al. (2022). To capture the demand for UAM, we must supplement existing data. Since origin-destination (OD) data are not uniformly distributed in terms of space and time, the data we generate should match the distribution of the real data. Here, we employ the Copulas statistical method, which allows us to generate new samples that match the actual data patterns. First, Copulas collects and analyzes real OD data to determine the marginal distribution and the correlation structure between them. Then, the marginal distributions and correlation structures are modeled. The Copulas model considers the dependencies between the variables, which allows the generated data to retain the correlation patterns of the original data. Once the copulas model is built, we can use this model to generate synthetic OD data. The generated data will retain marginal distributions and correlation structures similar to those of the real data, thus statistically matching the real data. We use this method to expand the original volume of taxi data by various multiples (that is, twice, three times, four times, and five times the current taxi data) to simulate the demand for all modes of transportation.

3.3. Determination of potential locations for VTOL sites

3.3.1. Location availability in 2D space

A VTOL site consists of a collection of buildings and facilities, designated for eVTOL takeoff and landing, passenger embarkation and disembarkation, as well as all related operations within a specific area. The feasibility of establishing a VTOL site in a given area depends primarily on the availability of suitable space. To filter potential VTOL areas, we collected shapefiles containing spatial data for Shenzhen's administrative boundaries, buildings, road networks, water bodies, parks, scenic areas, no-fly zones for drones, etc. To establish ground-based VTOL pads, GIS tools were used to exclude areas already occupied, such as buildings, and locations not suitable for VTOL site establishment, such as no-fly zones for drones within Shenzhen. According to FAA guidelines, a regular hexagon with a short diagonal of 500 feet can provide sufficient space available for a VTOL site (Wu and Zhang, 2021). Thus, the remaining areas were densely covered with hexagons, and the centroids of these hexagons were chosen as candidate VTOL site locations. We also explored the potential of constructing VTOL sites on rooftops, inspired by Uber's concept.

3.3.2. Location filtering for three-dimensional (3D) spatial availability

VTOL sites serve as the location for the take-off and landing of eVTOL aircraft. Therefore, establishing suitable VTOL site locations requires not only available planar space, but also three-dimensional conditions that satisfy the obstacle avoidance requirements for eVTOL take-off and landing operations. In particular, according to the China Skyscraper City Ranking as of April 2023, Shenzhen ranks first nationwide in terms of the number of buildings taller than 200 and 300 m. Therefore, it is essential to consider the aerial conditions for the establishment of the VTOL sites in Shenzhen. A recent publication by the FAA outlines the design

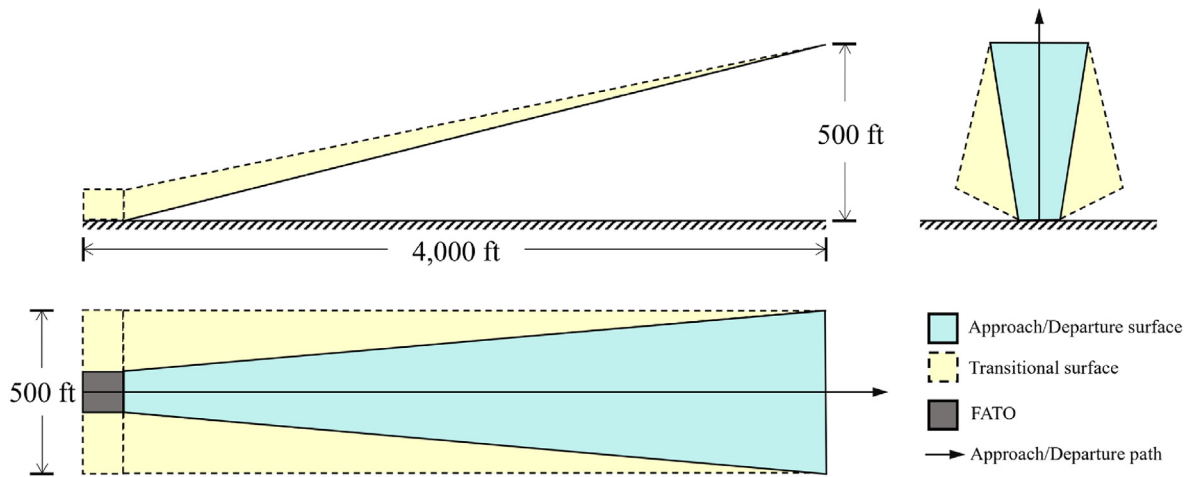
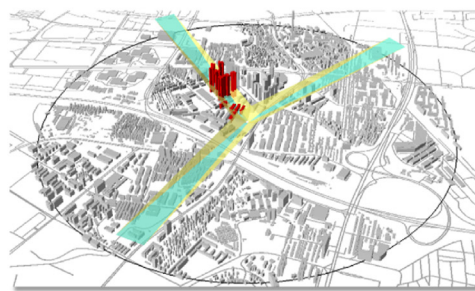


Fig. 2. Vertiport approach/departure and transitional surface.

(a) Process of assessment



(b) Assessment result



(c) Zoom in

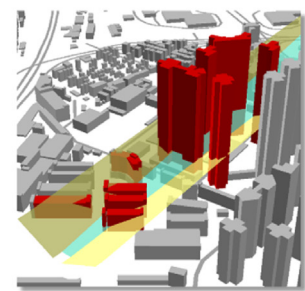


Fig. 3. Assessing potential VTOL site.

standards for VTOL sites, encompassing the geometry and dimensions of the surface and area used for eVTOL takeoff and landing, as well as approach and departure paths, along with requirements for markings, lighting, and navigational aids (FAA, 2023b). In particular, the dimensions of the Touchdown and Liftoff Area (TLOF), the Final Approach and Takeoff Area (FATO) and the Safety Area are based on the control dimension D (diameter of a circle that encompasses the entire aircraft) of the reference eVTOL. They are squares whose geometric centers coincide and measured with dimensions of $1D$, $2D$, and $3D$, respectively. The design requirements for the approach/departure and transitional surface are illustrated in three views in Fig. 2, with the main view, left view, legend and top view in clockwise from the top left. Each FATO should have at least two obstacles-free approach/departure paths, maintaining a minimum separation of 135° between them.

Following FAA regulations, we developed a VTOL site approach and departure path obstacle assessment model. The geometric center of the FATO, obtained from the locations identified in Section 3.3.1, was used as input for the model. Combining it with shapefile data containing elevation information for all buildings in Shenzhen, we evaluated whether the FATO associated with each location had unobstructed approach and departure paths as well as transition areas. The model output consisted of locations that satisfied eVTOL take-off and landing obstacle clearance requirements, along with the orientations of the approach and departure trajectories that met obstacle clearance criteria.

The reference eVTOL chosen for this analysis was the unmanned EH216-S aircraft. Based on the “Special Conditions for the EHang EH216-S Unmanned Aircraft System” issued by the Civil Aviation Administration of China (CAAC), the control dimension D of the EH216-S aircraft is 5.63 m (Civil Aviation Administration of China (CAAC), 2022). This information was used to ensure that the designed FATO could accommodate the reference aircraft without violating safety regulations.

As shown below, Algorithm 1 is a pseudo code for the proposed obstacle assessment model. Fig. 3(a) illustrates the assessment process for a specific location: the black dashed lines represent the initial approach/departure and transitional surfaces. The buildings being evaluated (in deep orange) are shown below the surfaces. By continuously rotating the three-dimensional model clockwise, the remaining buildings to be checked (in light yellow) are evaluated until the criteria for completing the assessment of that location are met. In Fig. 3(b), the top left part illustrates an example of approach and departure paths and transition areas with obstructions (highlighted in red). This is further magnified from another angle in Fig. 3(c). It is evident that eVTOL cannot approach or depart in that direction due to the penetrated obstacles. Since there are no obstacles blocking the path and the angle between the left bottom and right top faces in Fig. 3(b) is greater than 135° . Thus, this point satisfies the three-dimensional spatial availability and can be considered as a potential candidate location to establish a vertical landing and takeoff site.

Algorithm 1. Location filtering for 3D spatial availability

Data: locations satisfying 2D planar availability L_{2D} , shapefiles of all buildings in Shenzhen, FAA vertiport approach/departure and transitional surfaces dimensions

Result: locations satisfying 3D spatial availability L_{3D}

```

1  for  $l \in L_{2D}$  do
2     $DA \leftarrow \emptyset$  // all available approach/departure orientations of  $l$ 
3    for  $deg = 0$  to  $360$  do
4      construct the 3D model  $M$  of the approach/departure and transitional surfaces at  $l$  oriented
        towards  $deg$ 
5      identify all buildings  $B_M$  covered by  $M$ 
6      for  $i \in B_M$  do
7        if  $i$  obstructs  $M$  then
8          break
9        end
10     end
11     else
12        $DA \leftarrow DA \cup deg$ 
13     for  $j \in DA$  do
14       if  $deg - j > 135$  and  $j + 360 - deg > 135$  then
15          $L_{3D} \leftarrow L_{3D} \cup l$ 
16          $next = \text{True}$  //skip the remaining steps, assess next location
17       break
18     end
19     end
20     if  $next$  then
21       Break
22     else
23       continue
24     end
25     end
26     continue
27   end
28 end

```

By integrating the starting and ending points of the UAM candidate trips from Section 3.2, we noticed that some of the locations identified by the model are situated in areas with extremely low or no travel demand, such as Nei Lingding Island and the southern part of Dapeng New District. Given that UAM services are demand driven, we opted to eliminate these locations. Additionally, we closely merged points within a small region among the remaining locations to avoid an excessive number of candidate positions, which could lead to unnecessary computations in subsequent research. As a result, we ultimately selected 37 potential VTOL site locations that satisfy three-dimensional spatial availability.

3.4. VTOL site locations determining model

The Hub Location Problem (HLP) is an extension of facility location problems and has found extensive applications in the field of aviation research (Farahani et al., 2013). Hubs are facilities that are used for transshipment between the origin and destination points in transportation. The HLP is typically framed under the condition that direct connections between transportation nodes are not allowed. It aims to determine optimal hub locations and their corresponding allocations to non-hub nodes, often using a discount factor α to reduce transportation costs between hubs (Alumur and Kara, 2008). Here, we consider the origin and destination points of trips as transportation nodes. Locations that satisfy three-dimensional spatial availability are considered candidate hub nodes. Our model is an adaptation of the traditional HLP, which aims to determine the optimal locations of the VTOL site. In this model,

passengers choose transportation modes based on travel costs.

3.4.1. Parameter setting

The travel cost considered in this study comprises two main components: the monetary cost and the time cost. The monetary cost refers to the money paid based on the pricing of transportation modes. The Pricing Schemes for Taxis, Shared Electric Bikes, and Shared Bicycles are derived from actual operational data in Shenzhen. In addition to the monetary cost, travel time is another potential cost incurred by passengers. Prolonged travel time due to traffic congestion can negatively affect passengers, so we introduce the concept of time cost and monetize travel time. According to the Shenzhen Statistical Yearbook (Statistics Bureau of Shenzhen Municipality, 2023), we obtained the average annual wage

Table 1
Pricing and speed of each mode of transportation.

Transportation mode	Pricing	Speed
eVTOL	Starting pricing 40 yuan with mileage fee 3 yuan/km	130 km·h ⁻¹
Taxi	10 yuan within 2 km, 2.7 yuan/km beyond 2 km	36.7 km·h ⁻¹
Shared electric bicycle	2 yuan within 10 min with 1 yuan/min beyond	15 km·h ⁻¹
Shared bicycle	1.5 yuan within 15 min with 1 yuan/min beyond	10 km·h ⁻¹
Walk	—	5 km·h ⁻¹

of urban employees, which is 155,563 yuan. Dividing this by the general annual working time of 2,080 h, we derive a unit time cost of 78.7 yuan per hour for each traveler.

The speed settings for various transportation modes are reasonable values with common sense. The 36.7 km/h car speed is calculated from the Shenzhen Road Traffic Operation Index System by continuously sampling the average speed of the road at 1-h intervals from 06:00 to 24:00 over a week (Transport Bureau of Shenzhen Municipality, 2023). The cruise speed of eVTOL is from the ‘‘Special Conditions for the EH216-S Unmanned Aerial Vehicle System’’ (CAAC, 2022). The travel cost and speed parameters for each transportation mode are summarized in Table 1.

3.4.2. Decision variables

Let P be the set of origins and destinations for potential UAM trips. R is the set of potential UAM trips, and each trip r in R contains a pair of origin and destination (o, d) , $\forall o, d \in P$. S is the set of 37 potential locations of VTOL sites and M is the set of transport modes that can be used to access the VTOL sites. The decision variables are binary variables $v_i, g^r, u_{ij}^r, a_{mi}^r, e_{nj}^r$. The meanings of each variable are given below.

$$v_i = \begin{cases} 1, \text{ establish a VTOL site at location } i \\ 0, \text{ no VTOL site established at location } i \end{cases} \quad (1)$$

$$g^r = \begin{cases} 1, \text{ trip } r \text{ is completed by ground transportation} \\ 0, \text{ trip } r \text{ is completed by UAM} \end{cases} \quad (2)$$

$$u_{ij}^r = \begin{cases} 1, r \text{ is a UAM trip with the takeoff VTOL site } i \text{ and landing VTOL site } j \\ 0, \text{ otherwise} \end{cases} \quad (3)$$

$$a_{mi}^r = \begin{cases} 1, \text{ trip } r \text{ arrives takeoff VTOL site } i \text{ via ground transportation mode } m \\ 0, \text{ otherwise} \end{cases} \quad (4)$$

$$e_{nj}^r = \begin{cases} 1, \text{ trip } r \text{ departs landing VTOL site } j \text{ via ground transportation mode } n \\ 0, \text{ otherwise} \end{cases} \quad (5)$$

3.4.3. Constraints

Since there are costs associated with the construction of VTOL sites, any UAM planning scheme must have a reasonable value for the number of VTOL sites to be built. In this study, the number of VTOL sites is set to N_{VTOL} , and the constraint 6 represents the limitation on the number of VTOL sites.

$$\sum_{i \in S} v_i = N_{VTOL}, \forall i \in S \quad (6)$$

Passengers must choose one of the two modes, either ground or UAM, to complete their trip, therefore:

$$g^r + \sum_i \sum_{j \neq i} u_{ij}^r = 1, \forall r \in R \quad (7)$$

If a UAM trip involves potential location i , a VTOL site must be constructed at i :

$$\sum_{i \in S, j \neq i} u_{ij}^r + \sum_{j \in S, i \neq j} u_{ji}^r \leq v_i, \forall i \in S, \forall r \in R \quad (8)$$

Regarding the choice of transportation mode for passengers entering and exiting the VTOL sites, it is assumed that each segment for entering and leaving the VTOL site is exclusively associated with one mode of transportation. Equation (9) indicates that if a trip involves UAM travel, a specific mode of transportation must be chosen to enter the VTOL site i :

$$\sum_i \sum_{j \neq i} u_{ij}^r = \sum_m \sum_i a_{mi}^r, \forall r \in R \quad (9)$$

Similarly, the UAM trip r must select a transportation mode to leave the landing VTOL site j :

$$\sum_i \sum_{j \neq i} u_{ij}^r = \sum_n \sum_j e_{nj}^r, \forall r \in R \quad (10)$$

Equations (9) and (10) only ensure that a mode of transport has been chosen to enter the take-off VTOL site i and a mode of transportation has been chosen to leave the landing VTOL site j . However, they do not ensure that they correspond to the trip $r: o \rightarrow i \rightarrow j \rightarrow d$. Therefore, Eq. (11) is added to ensure that the chosen modes of entering and exiting the VTOL sites accurately correspond to this UAM trip r :

$$2u_{ij}^r \leq \sum_m a_{mi}^r + \sum_n e_{nj}^r, \forall i, j \neq i, \forall r \in R \quad (11)$$

Passengers choose the mode of travel that minimizes their travel cost. The travel cost consists of monetary cost and the time cost. Let $f_{air}^r, t_{air}^r, f_{ground}^r$ and t_{ground}^r represent the UAM monetary cost, UAM travel time, ground transportation monetary cost, and ground transportation time for trip r , respectively. p is the unit time value (78.7 yuan/h). f_{ij}^r and t_{ij}^r denote the monetary cost and time to travel by eVTOL from the takeoff VTOL site i to the landing VTOL site j , where t_{ij}^r is composed of the cruise time and the take-off/landing time. It is assumed that the time for a take-off and a landing operation is totally 10 min. Let f_{mi}^r and t_{mi}^r represent the monetary cost and time for passengers to travel to the takeoff VTOL site i for the trip r using the transportation mode m , f_{nj}^r and t_{nj}^r represent the monetary cost and time for passengers to travel from the landing VTOL site j for the trip r using the transportation mode n . $t_{transfer}^r$ represents the transfer time for the trip r when using UAM travel, including the time from leaving ground transportation to boarding the eVTOL at the take-off VTOL site t_{gr}^r and the time from the landing VTOL site to transferring to ground transportation t_{lg}^r . In our study, transfer is set to 20 min. Travel cost is represented by $f + t \cdot p$. Passengers will choose the mode with the lowest travel cost. Therefore, passengers who satisfy the inequality 12 will move from ground transportation to UAM travel:

$$f_{air}^r + t_{air}^r \cdot p < f_{ground}^r + t_{ground}^r \cdot p \quad (12)$$

among which,

$$f_{air}^r = f_{mi}^r + f_{ij}^r + f_{nj}^r \quad (13)$$

$$t_{air}^r = t_{mi}^r + t_{ij}^r + t_{nj}^r + t_{transfer}^r \quad (14)$$

We use the Haversine formula to calculate the flight distance of the eVTOL. The Haversine formula is used to calculate the distance between two locations in a great circle, and given the coordinates of the takeoff VTOL site ($lat 1, lon 1$), the coordinates of the landing VTOL site ($lat 2, lon 2$), and the radius of the Earth $R_E = 6378.137$ km, the distance D_{air} between them is

$$D_{air} = 2 \arcsin \sqrt{\sin^2 \frac{(lat1 - lat2)}{2} + \cos(lat1) \cdot \cos(lat2) \cdot \sin^2 \frac{(lon1 - lon2)}{2}} \cdot R_E \quad (15)$$

For the ground segments of entering and leaving the VTOL sites, we use the Manhattan distance as the driving distance for taxis. We consider 1.25 times the Euclidean distance as the riding distance for shared electric bikes and shared bicycles, and 1.2 times the walking distance. Since the ground segments to and from the VTOL sites are usually short, the error introduced by using the above methods instead of actual distances can be negligible. The airborne time for eVTOL flights and the time for entering and leaving VTOL sites using various modes are calculated based on Eq. (15) and the speed parameters in Section 3.4.1.

For pure ground trips, the pure ground transportation time for each trip r is provided by the data in Section 3.2, and the distance for each trip is calculated using Networkx based on the Shenzhen road network data obtained from OpenStreetMap (Boeing, 2017), an open source map and geodatabase that can be freely used and edited according to the protocol. Osmnx and Networkx are Python extension packages that are used to obtain road network data and calculate the distance between two points in a complex network, respectively.

Due to the NP-hard nature of large-scale hub location problems, there are no known polynomial-time methods to solve them. Only smaller-scale instances can yield exact solutions. To address this challenge, we propose two additional constraints based on the analysis of the characteristics of the UAM. These constraints significantly reduce the problem's size and the number of variables, allowing the model to be solved in a short time.

First, based on the passenger mode choice criteria, we can identify those trips that, regardless of how the VTOL site combinations for take-off and landing are configured, cannot lower their travel costs. These trips will inevitably choose pure ground transportation over UAM. Thus, using inequality 16, we exclude these trips from the total set of trips, focusing on the remaining trips that have the potential to change direction towards UAM.

$$f_{mi}^r + f_{ij}^r + f_{nj}^r + (t_{mi}^r + t_{ij}^r + t_{nj}^r + t_{transfer}^r) \cdot p > f_{ground}^r + t_{ground}^r \cdot p, \forall r \in R, \forall i, j \in S \quad (16)$$

Furthermore, when distributing two VTOL sites i and j in a single trip, if a passenger chooses to use i and j for eVTOL travel, they will invariably select the site closer to the departure point as the take-off VTOL site and the one closer to the destination point as the landing VTOL site. Assuming that VTOL site i is closer to the starting point of the trip o and VTOL site j is closer to the destination point of the trip d , a passenger's UAM journey will always follow the sequence $o \rightarrow i \rightarrow j \rightarrow d$, rather than $o \rightarrow j \rightarrow i \rightarrow d$. Therefore, using the inequality 17, we can eliminate the variables associated with the sequence $o \rightarrow j \rightarrow i \rightarrow d$ from consideration.

$$d_{mi}^r + d_{nj}^r \leq d_{mj}^r + d_{ni}^r, \forall r \in R, \forall i, j \in S \quad (17)$$

Eventually, the set G of study objects is reduced to

$$G = \left\{ (r, i, j, m, n) \mid f_{air}^r + t_{air}^r \cdot p < f_{ground}^r + t_{ground}^r \cdot p, d_{mi}^r + d_{nj}^r \leq d_{mj}^r + d_{ni}^r \right\} \quad (18)$$

3.4.4. Objective function

The objective of the model is to maximize travel cost savings for all trips that may shift to UAM:

$$\max \sum_{r \in R} \left\{ \sum_i \sum_{j \neq i} [f_{ground}^r + t_{ground}^r \cdot p - (f_{ij}^r + t_{ij}^r \cdot p)] \cdot u_{ij}^r - \sum_m \sum_i [f_{mi}^r + (t_{mi}^r + t_{gt}^r) \cdot p] \cdot a_{mi}^r - \sum_n \sum_j [f_{nj}^r + (t_{nj}^r + t_{gt}^r) \cdot p] \cdot e_{nj}^r \right\} \quad (19)$$

where $v_i, g^r, v_{ij}^r, a_{mi}^r, e_{nj}^r \in \{0, 1\}$, $(r, i, j, m, n) \in G$.

4. Results

4.1. Data and settings

Our model has two main inputs, namely, the potential UAM trips that are given in Section 3.2, and the potential locations of the VTOL site in Section 3.3. The importance of the VTOL sites is illustrated in Fig. 4, with the size of each site indicating its significance. This will be discussed in more detail in Section 4.3. The speed and pricing parameters of various modes of transportation are shown in Table 1. The calculation of the distance and time of transportation is given in Section 3.4.1. Based on these data and settings, the model we built was solved using Python and the Gurobi solver, to determine the locations of the VTOL sites in Shenzhen, along with the number of UAM trips and the mode of transportation of each trip that arrived and left the VTOL sites.

4.2. VTOL sites and UAM benefits under current UAM demands

We aim to save as much travel cost and capture as much demand as possible under the premise that the number of VTOL sites is reasonable.

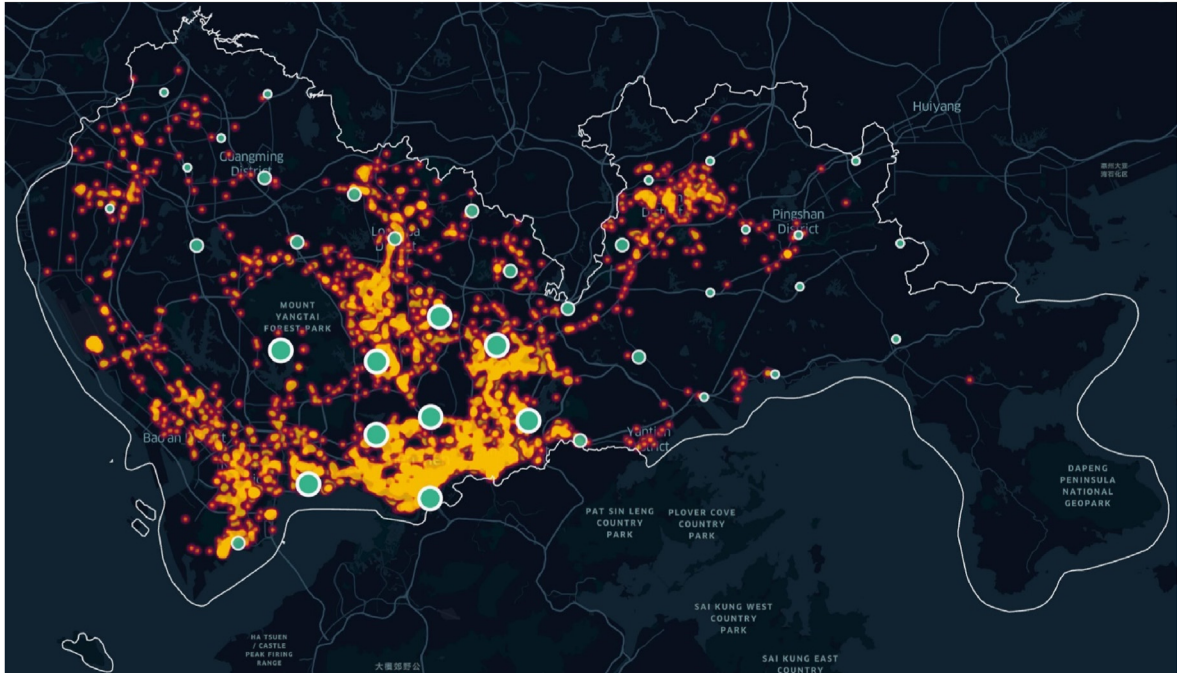
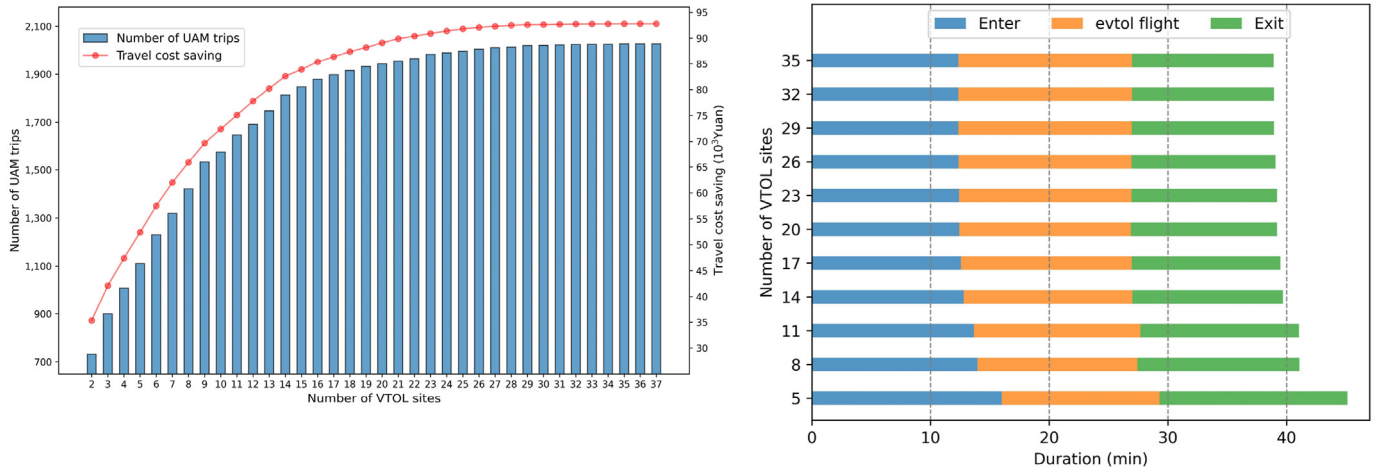
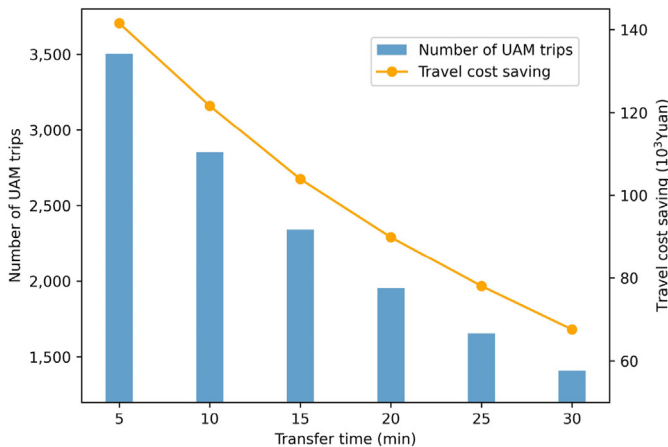


Fig. 4. UAM demands and the locations of VTOL site (<https://kepler.gl>).

(a) UAM trips and cost saving under different number of VTOL sites (b) Time spent on each segment with different number of VTOL sites



(c) Transfer time



(d) eVTOL pricing

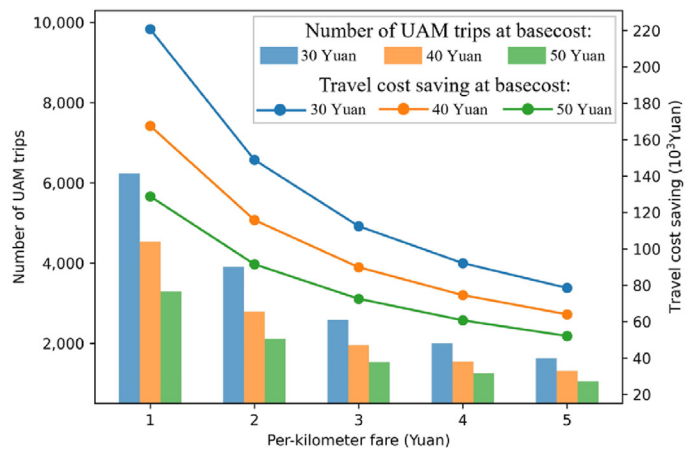


Fig. 5. Different number of VTOL sites and takeoffs and landings at the site.

To determine the number of VTOL sites to be established, we solved the UAM trips and travel cost savings corresponding to the number of VTOL sites from 2 to 37, and the result is shown in Fig. 5(a). When the number of VTOL sites exceeds 21, the incremental number of UAM trips resulting from building an additional VTOL site is less than 10 and the incremental travel cost savings is less than 800 yuan. This suggests that when the number of VTOL sites reaches 21, the ability of the infrastructure network to save travel costs and capture demand is approaching saturation, and the effect of saving more travel costs and attracting more riders to UAM by building more VTOL sites becomes less pronounced. Therefore, we have determined that the number of VTOL sites to be established is 21.

Regarding the ground transportation modes for passengers entering the VTOL sites, 1,331 trips choose shared electric bikes, 620 trips opt for taxis, and 3 trips involve walking. These percentages are 68.12%, 31.73%, and 0.15%, respectively, of the total of 1,954 UAM trips. For departing VTOL sites, 1,385 trips are on shared electric bikes, 562 trips in taxis, and 7 trips on foot. These percentages are 70.88%, 28.76%, and

0.36%, respectively. It is apparent that shared electric bikes are the predominant mode of transportation for ground segments between VTOL sites. The distribution of UAM trip time allocation among the VTOL site segments that enter, the eVTOL flight segments, and the VTOL site segments that exit are shown in Fig. 6(a). Segments entering and exiting the VTOL sites account for around 40% of the total UAM trip time, indicating room for further time reduction in the ground segments. This can be achieved by planning and designing the infrastructure network more rationally to improve the accessibility of the VTOL site. Fig. 6(b) illustrates the time savings by choosing the UAM option over the original taxi option. From Fig. 6(b), it is evident that opting for UAM travel leads to significant time savings. The most substantial time savings fall within 30–50 min intervals, with 10-min intervals. The time saved by choosing UAM travel is up to 3 h in some cases.

4.3. VTOL sites and UAM benefits under scaled UAM demands

To further explore the location of VTOL sites and the potential

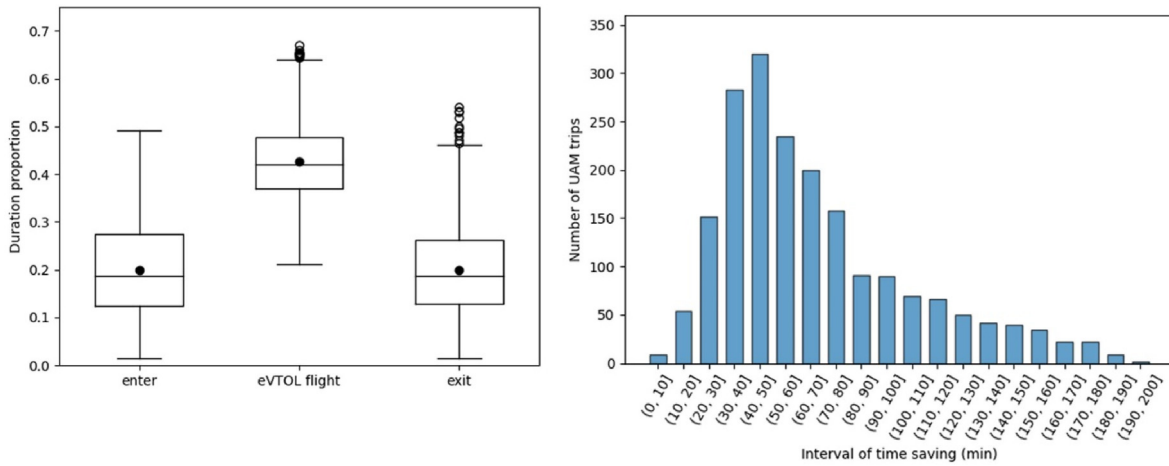
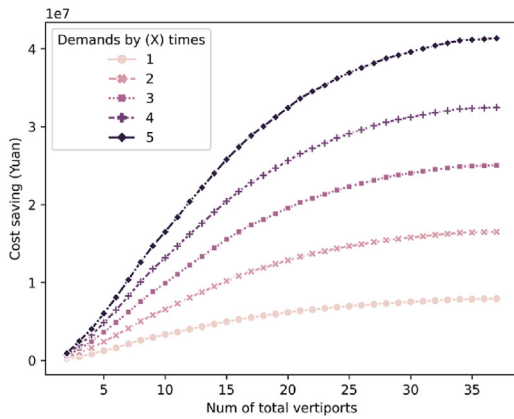


Fig. 6. Statistical results on time spent on each segment and time savings.

(a) Cost saving



(b) Scaled number of trips at each VTOL site

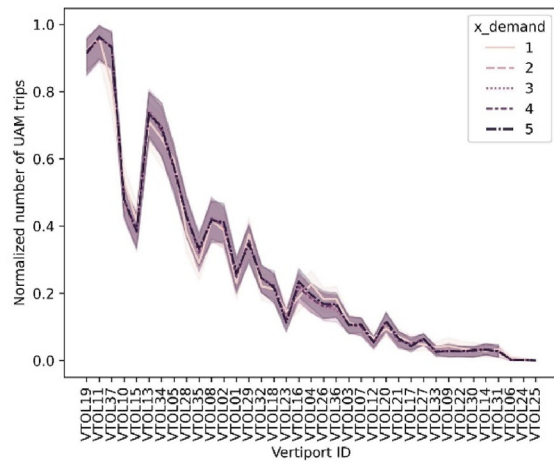


Fig. 7. Cost savings and the number of UAM trips at VTOL site under different demands.

advantages of UAM, we employ a similar approach to that of Wang et al. (2022) to generate UAM requests based on existing taxi requests. Future UAM demand is set to be 2, 3, 4, 5 times of current demand. The economic advantages of UAM become more pronounced as demand increases (Fig. 7(a)). In particular, the cost savings between different levels of UAM demand are more pronounced when the number of VTOL sites is greater than 10. The total number of UAM trips provided by each VTOL site is determined based on the UAM demand and the number of VTOLs (N_{VTOL}). The number of trips is then normalized using the MinMaxScaler algorithm from Scikit learn. We plot the normalized trips at each site in Fig. 7. VTOL sites can be divided into three categories: Group I (#trips ≥ 0.4), Group II ($0.2 \leq \#trips < 0.4$), and Group III (#trips < 0.2). The size of the markers in Fig. 4 also indicates three groups of VTOL sites. The most important ones, i.e., Group I sites, are located in the center of the city, where the demand for UAM is higher than other areas. If the resources for constructing VTOL sites are limited, these sites should be given priority.

5. Discussions

The establishment of VTOL sites is a key factor in the successful implementation of UAM to improve the efficiency of urban transportation. Three elements can have an effect on the results of our model:

the number of VTOL sites, the transfer time, and the cost of eVTOL. In this section, we will explore the potential influence of these factors on the determination and development of VTOL sites.

- Impact of the number of the VTOL Sites: As shown in Fig. 5(b), with an increase in the number of VTOL sites, the proportion of time spent on the ground segments entering/exiting the VTOL pads and the eVTOL flight segments stabilizes around 13 min, while the overall time remains approximately 40 min. This suggests that the total travel time becomes relatively stable with a larger number of VTOL sites.
- Effect of transfer time: We observed the impact of transfer time at the VTOL sites on total cost and UAM trip counts. Transfer time represents the convenience of transitioning from ground transportation to boarding an eVTOL, reflecting the operational efficiency of VTOL sites. Passengers choose UAM for its time savings, and when the transfer time increases from 5 to 30 min, as shown in Fig. 5(c), UAM trips decrease from 3,504 to 1,410, with 59.76% of UAM passengers switching to pure ground transportation. This indicates that as the transfer time increases, the advantage of time savings with UAM is offset, leading to a significant reduction in UAM users and diminishing the efficiency and competitiveness of UAM in the transportation market.

- Influence of eVTOL price: Sensitivity analysis of the price of eVTOL demonstrates a certain impact on UAM trip counts and travel cost savings. By adjusting model parameters based on different eVTOL prices, we can observe changes in UAM trip counts and travel cost savings. The result of the analysis revealed that the demand for UAM is highly sensitive to the pricing structure of eVTOL. In Fig. 5(d), when the initial fare is set at 30 yuan and the per kilometer fare is 1 yuan, the UAM trips exceed 6,000, but with an initial fare of 50 yuan and a per kilometer fare of 5 yuan, the UAM trips decrease to around 1,000. When the initial fare is lower, the demand for UAM is more sensitive to changes in the per kilometer fare. For instance, when the initial fare is 30 yuan, an increase in the per kilometer fare from 1 to 5 yuan results in a decrease in UAM trips from 6,200 to 1,600. However, with an initial fare of 50 yuan, the same change in the per-km fare leads to a reduction in UAM trips from 3,200 to 1,000. The trend in travel cost savings follows a similar pattern. UAM operators should consider the relationship between eVTOL pricing and UAM demand more thoroughly, taking into account factors such as market dynamics, the size of the eVTOL fleet, and additional operational and management costs, while setting UAM prices.

These analyzes help us better understand the influence of different parameters on the model results, facilitating the optimization of UAM network design and planning strategies.

6. Conclusions

This study presents a comprehensive process and methodology for determining the locations of VTOL sites in Shenzhen. Due to the significant impact of traffic congestion on taxi rides among various public transportation modes, this study considers taxi passengers as potential users to transfer to UAM. We use GIS tools to identify locations that satisfy 2D plane availability and establish an obstacle assessment model to further filter locations that satisfy 3D spatial availability. By adapting the traditional HLP based on UAM characteristics, an integer programming model is developed to locate the VTOL sites. The model takes potential UAM trips derived from processed taxi trip data, potential locations of the VTOL site determined using GIS and obstacle assessment, and relevant parameter settings as input. Maximize travel cost savings and solve for the locations of the VTOL sites, the number of UAM trips and the choice of transportation modes for each trip that enters and leaves the ground segments of the VTOL sites. Considering 3D spatial availability of locations ensures that each VTOL site's location not only represents the mathematical optimum but also meets safety requirements for eVTOL take-off, departure climb, final approach, and landing phases. The methodology, model, and conclusions can provide decision support for urban planners in the initial stages of UAM planning.

However, a limitation of this research is the lack of detailed income data, which led to setting the time value parameter based on average annual wages. In reality, everyone's time value varies, and different time values significantly impact UAM demand. Those with lower time value may opt for cheaper transportation modes, having greater tolerance for traffic congestion, whereas those with higher time value are more likely to choose time-saving UAM. The high time value suggests that they might be willing to pay several times more than ground transportation prices to save time by taking eVTOL. Considering VTOL site capacity limits and eVTOL fleet size limits presents another avenue for improvement. Capacity restrictions might lead to eVTOL ground waiting or hovering due to high demand, while adding eVTOL fleet size limitations could result in passengers waiting despite being at the VTOL site, reducing UAM's time-saving benefits. Moreover, factors such as the introduction of ride-sharing services for eVTOL similar to taxi pooling, considering uncertainties arising from congestion when entering and leaving VTOL site ground segments, and adding noise when selecting VTOL site locations, can be explored as future research directions.

Replication and data sharing

The data and codes that support the findings of this study are available at <https://doi.org/10.26599/ETSD.2023.9190024>.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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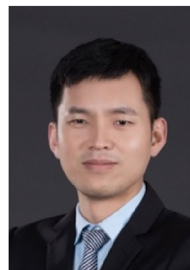
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