Development of optimal scheduling strategy and approach control model of multicopter VTOL aircraft for urban air mobility (UAM) operation*

多旋翼垂直起降 (VTOL) 飞机在城市空中出行 (UAM) 运营中的最优调度策略与逼近控制模型开发 *

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摘要

Urban air mobility (UAM) is emerging as a new alternative to solve the traffic problem in the metropolitan area. Industries and government agencies are preparing for the future UAM system and operation. A new ATC (Air Traffic Control) strategy or aircraft separation method that reflects flight characteristics of multicopter VTOL (Vertical Take-off and Landing) aircraft is required. Particularly, approach control around the vertiport is one of the essential issues for the safe and efficient operation of UAM, and strict safety standards are required for service in populated urban areas. In this study, the concept of holding points where multicopter aircraft can hover is introduced, and three scheduling strategies for arriving aircraft are developed and evaluated by comparing the on-time performance (OTP) with hovering time and ground time. BQA (Branch Queuing Approach), SBA (Sequence-based Approach) and, SBAM (sequence-based approach with moving circles) models are proposed and compared. BQA model prioritizes airspace safety by limiting the aircraft's travel path; SBA model allows the aircraft to move freely within the airspace and prioritizes aircraft's arrival sequence; and finally, SBAM adds the moving circle concept to the SBA model. For each model, OTP and loss of separation (LOS) risk of the proposed models are found and they are compared by simulations. The simulation result shows that SBA and BQA have similar punctuality performance and BQA model with no LOS risk is the most efficient approach control model for multicopter VTOL aircraft of UAM.

城市空中出行 (UAM) 作为一种新的解决方案，正在兴起以解决大都市区域的交通问题。工业界和政府机构正在为未来的 UAM 系统和运营做准备。需要一种新的空中交通管制 (ATC) 策略或飞机间隔方法，以反映多旋翼垂直起降 (VTOL) 飞机的飞行特性。特别是，围绕直升机场的进近控制是 UAM 安全高效运营的关键问题之一，并且在人口密集的城区提供服务需要严格的安全标准。在本研究中，引入了多旋翼飞机可以悬停的等待点的概念，并开发了三种到达飞机的调度策略，通过比较悬停时间和地面时间与准点性能 (OTP) 来评估这些策略。提出了分支排队方法 (BQA)、基于序列的方法 (SBA) 和带有移动圆的基于序列方法 (SBAM) 模型，并进行了比较。BQA 模型通过限制飞机的飞行路径优先考虑空域安全；SBA 模型允许飞机在空域内自由移动，并优先考虑飞机的到达顺序；最后，SBAM 模型在 SBA 模型中增加了移动圆的概念。对于每种模型，都找到了提出模型的 OTP 和间隔损失 (LOS) 风险，并通过模拟进行了比较。模拟结果显示，SBA 和 BQA 具有相似的准点性能，且无 LOS 风险的 BQA 模型是对 UAM 的多旋翼 VTOL 飞机最有效的进近控制模型。

1. Introduction

1. 引言

As the UN "World Urbanization Prospects" reports, the urbanization is rapidly progressing around the world. As of 2018, approximately 55% of the world's population resides in urban areas, and the global urbanization rate is expected to reach 68% by 2050 (UN Department of Economic Social Affairs, 2018). Urban concentration causes various problems such as traffic, noise, pollution, and lack of infrastructure. It also creates social problems such as heavy traffic jams resulting in substantial social and economic losses in major cities, including New York, London, Tokyo, and Seoul (Rath and Chow, 1904). Inrix, a global traffic analysis agency, reports that Americans waste, on average,97 h a year due to the traffic jams, which equals an economic loss of $1,348 a year. Moreover,

根据联合国《世界城市化展望》报告，全球城市化正在迅速推进。截至 2018 年，世界上大约 55% 的人口居住在城市地区，预计到 2050 年全球城市化率将达到 68%(联合国经济与社会事务部，2018 年)。城市集中导致了各种问题，如交通、噪音、污染和基础设施不足。它还造成了社会问题，如严重的交通堵塞，在纽约、伦敦、东京和首尔等大城市造成了巨大的社会和经济损失 (Rath 和 Chow，1904 年)。全球交通分析机构 Inrix 报告称，美国人平均每年因交通堵塞浪费 97 小时，这等于每年 $1,348 的经济损失。此外，

Nomenclature

$AETA_i$ adjusted estimated time of arrival of VTOL aircraft i

ATA_i actual time of arrival of VTOL aircraft i

ETA_i estimated time of arrival of VTOL aircraft i

ETD_i estimated time of departure of VTOL aircrafti

GT_i ground time of VTOL aircraft i

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HT_i hovering time of VTOL aircraft i
ΔL minimum landing separation time
MGT minimum ground time
N_V the total number of VTOL aircraft
p on-time arrival criteria
S_c cruise speed of approach
S_i landing sequence of the VTOL aircrafti
S_v vertical speed of approach
STA_i scheduled time of arrival of VTOL aircrafti
TD_i scheduled time of departure of VTOL aircraft i
t current time
W_i early operation weight

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metropolitan cities' drivers waste, on average, 80 h a year due to the traffic jams, which accounts for 15% of their total driving time (INRIX, 2019). Various researches on the measures to alleviate traffic congestion and their introduction to real-life are steadily progressing. For instance, traditional methods such as high-occupancy vehicle lanes, traffic signal coordination, and ramp metering are extensively used in many countries. Recently, along with the development of information and communication technologies, the development of shared mobility, unmanned vehicles, and AI-based traffic control are in the spotlight. However, these techniques or systems cannot surpass the capacity of land transportation systems. Lately, innovative attempts are being made to change the mobility industry's paradigm; the introduction of urban air mobility (UAM) is actively discussed worldwide to transform the urban mobility from the existing 2D to a 3D space.

大城市的驾驶员平均每年因交通堵塞而浪费 80 h 小时，这占他们总驾驶时间的 15% (INRIX，2019)。关于缓解交通拥堵的措施及其在现实生活中的应用的研究正在稳步进展。例如，高承载车道、交通信号协调和匝道计量等传统方法在许多国家被广泛使用。最近，随着信息通信技术的发展，共享出行、无人驾驶车辆和基于 AI 的交通控制受到了关注。然而，这些技术或系统无法超越陆地运输系统的容量。近期，创新的尝试正在改变出行行业的范式；城市空中出行 (UAM) 的引入在全球范围内被积极讨论，以将城市出行从现有的二维空间转变为三维空间。

1.1. Related work and research motivation

1.1. 相关工作与研究动机

In August 2018, the National Aeronautics and Space Administration (NASA) announced the UAM, a concept of next-generation urban mobility, and defined it as "safe and efficient air traffic operations in a metropolitan area for manned aircraft and unmanned aircraft systems" (Thipphavong, et al., 2018). In 2016, Uber unveiled Uber Elevate service plan and published a white paper with concepts, feasibility, and market research for air taxi operations (Uber, 2016). Uber collaborated with Aurora, Bell, Joby Aviation, and Hyundai to develop a number of vehicles in the form of Vertical Take-off and Landing (VTOL) for air taxi service, which are planned to be launched commercially in Melbourne, Los Angeles, and Dallas in 2023 (Uber, 2020). In fact, it is understood that the current state of VTOL development for UAM is close to realizing air taxi service with many models such as Airbus' "Vahana," Ehang's "Ehang 184," and Boeing's NeXt's "PAV." They have succeeded in the test flight, and they are expected to enter the commercialization phase (AIRBUS, 2019; EHANG, 2020; BOEING, 2019; Siewert et al., 2019; Reiche et al., 2019). For the successful operation of UAM, both the development of VTOL vehicles and the establishment of systems and social infrastructure for UAM operations are critical. The United States is establishing social foundations for UAM by readjusting related laws and systems, including the air traffic control (ATC) under the leadership of related authorities such as NASA and the Federal Aviation Administration (FAA). In 2013, NASA first presented the Conceptual Framework of Unmanned Aircraft Systems (UAS) Traffic Management (UTM) (FAA, 2020). Then, in 2016, the UTM RTT (Research Transition Team) was jointly organized with the FAA to conduct full-scale research on UTM development and implementation. (FAA, 2017). As part of this effort, "14 CFR Part 107" was enacted in 2016, including Commercial Drone Operation Standard, Pilot Qualification, and operation limits for drone (FAA, 2016). In 2018, UTM ConOps (Concept of Operations) was published, which included UTM's vision and operational concepts and UTM development requirements (FAA, 2018). Moreover, a small number of academic studies on UAM have been conducted since 2018. Several conceptual studies are conducted, including the integrated operation method of the airspace for the introduction of UAM and the communication concept for ATC (Thipphavong, et al., 2018); (Balac, 2018); (Lascara et al., 2019). There are many studies related to the trajectories and the collision avoidance of individual aircraft for the operation of UAM. Katz et al. presented an encounter model for developing UAM collision avoidance system (Katz et al., 2019), and Euclides et al. developed the simulation framework for the trajectory based UAM operations (Euclides et al., 2019). Furthermore, several meaningful studies are conducted on the computational guidance algorithm for free flight aircraft on a route under UAM environment (Yang and Wei, 2018, 2020; Yang et al., 2019, 2020; Bertram et al., 2019) and the algorithms for the scheduling of arriving aircraft of on-demand UAM (Pradeep and Wei, 2018; Kleinbekman et al., 2018, 2020; Kim, Aug., 2020). Existing studies are primarily on the area control level during the ATC phase such as individual aircraft trajectories and collision avoidance. Although some researches have dealt with arrival sequencing and scheduling, there is a lack of ATC perspectives such as approach control around the vertiport. However, as noted in the Boeing's commercial airplane accounting statistics (Boeing, "Statistical Summary of Commercial Jet Airplane Accidents," http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/statsum.pdf, 2019), approach control is a crucial component in the actual operation of aircraft, with 54.9% of fatal accidents occurring in descent, approach, and landing phases. Different from the airports which are usually located on the city's outskirts, the vertiport in UAM is to be located in the densely populated urban area. Moreover, a new ATC strategy or aircraft separation method for UAM is required due to its different flight characteristics from the conventional commercial airplane such as the vertical takeoff and landing of the VTOL and hovering around the vertiport for landing. Recently, Betram et al. conducted a research by conceptualizing airspace around vertiport composed of several rings in which the aircraft can continue to rotate (Bertram and Wei, 2020). In this case, the aircraft starts the landing procedure at the outermost ring and moves slowly towards the inner ring to enter the final approach phase. This study is similar to our research in which the ATC is applied around the vertiport. However, there are differences in the airspace design method, the concept of approach control phases, and aircraft separation methods.

2018 年 8 月，美国国家航空航天局 (NASA) 宣布了 UAM(下一代城市机动性概念)，并将其定义为“大都市区域内载人飞机和无人飞机系统的安全高效空中交通运行”(Thipphavong 等人，2018 年)。2016 年，Uber 公布了 Uber Elevate 服务计划，并发布了一份关于空中出租车运营的概念、可行性和市场研究的白皮书 (Uber，2016 年)。Uber 与 Aurora、Bell、Joby Aviation 和 Hyundai 合作，开发了几款垂直起降 (VTOL) 形式的空中出租车服务车辆，计划于 2023 年在墨尔本、洛杉矶和达拉斯商业推出 (Uber，2020 年)。实际上，据了解，目前 UAM 的 VTOL 开发状态已经接近实现空中出租车服务，有许多型号如空客的“Vahana”、亿航的“Ehang 184”和波音 NeXt 的“PAV”。它们已经成功完成了试飞，预计将进入商业化阶段 (AIRBUS，2019 年；EHANG，2020 年；BOEING，2019 年；Siewert 等人，2019 年；Reiche 等人，2019 年)。为了 UAM 的成功运营，VTOL 车辆的开发以及 UAM 运营系统和社交基础设施的建立都至关重要。美国正在通过调整相关法律和系统，包括在 NASA 和联邦航空管理局 (FAA) 等相关部门的领导下，建立空中交通管制 (ATC) 的社会基础。2013 年，NASA 首次提出了无人机系统 (UAS) 交通管理 (UTM) 的概念框架 (FAA，2020 年)。然后，在 2016 年，FAA 与 UTM RTT(研究过渡团队) 共同组织，对 UTM 开发和实施进行大规模研究 (FAA，2017 年)。作为这项努力的一部分，2016 年颁布了“14 CFR 第 107 部分”，包括商业无人机操作标准、飞行员资格和无人机操作限制 (FAA，2016 年)。2018 年，发布了 UTM 操作概念 (ConOps)，其中包含了 UTM 的愿景、操作概念和 UTM 开发要求 (FAA，2018 年)。此外，自 2018 年以来，已经进行了一些关于 UAM 的学术研究。进行了一些概念性研究，包括 UAM 引入的空域综合操作方法和 ATC 的通信概念 (Thipphavong 等人，2018 年)；(Balac，2018 年)；(Lascara 等人，2019 年)。有许多关于 UAM 运营中单架飞机轨迹和避碰的研究。Katz 等人提出了用于开发 UAM 避碰系统的遭遇模型 (Katz 等人，2019 年)，Euclides 等人开发了基于轨迹的 UAM 运营的仿真框架 (Euclides 等人，2019 年)。此外，还进行了一些关于在 UAM 环境下自由飞行飞机的路线计算导航算法的有意义研究 (Yang 和 Wei，2018 年、2020 年；Yang 等人，2019 年、2020 年；Bertram 等人，2019 年) 以及按需 UAM 到达飞机的调度算法 (Pradeep 和 Wei，2018 年；Kleinbekman 等人，2018 年、2020 年；Kim，2020 年 8 月)。现有研究主要集中在对 ATC 阶段的区域控制级别进行研究，如单架飞机轨迹和避碰。尽管一些研究已经涉及到达序列和调度，但缺乏关于机场附近进近控制的 ATC 视角。然而，正如波音商业飞机事故统计所示 (Boeing，“商业喷气飞机事故统计摘要”，http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/stat-sum.pdf，2019 年)，进近控制在实际飞机运行中是一个关键组成部分，有 54.9% 的致命事故发生在下降、进近和着陆阶段。与通常位于城市郊区的机场不同，UAM 的起降场将位于人口密集的市区。此外，由于 VTOL 的垂直起降和起降场周围的悬停等不同于传统商用飞机的飞行特性，UAM 需要新的 ATC 策略或飞机间隔方法。最近，Betram 等人通过将起降场周围的空域概念化为由几个环组成的区域，飞机可以在其中继续旋转 (Bertram 和 Wei，2020 年)。在这种情况下，飞机从最外层的环开始着陆程序，缓慢向内环移动以进入最后进近阶段。这项研究与我们的研究类似，都是在起降场周围应用 ATC。然而，在空域设计方法、

进近控制阶段概念和飞机间隔方法上存在差异。

In this study, the type of aircraft used for UAM is a multicopter VTOL of small category such as the EHang 184, EHang 216, and Volocopter 2x which can accommodate 1 or 2 passengers. Uber's UAM mainly considers Vectored Thrust VTOL to increase cruise speed. However, this is more practical in countries that require long-distance travel, such as the United States and Canada, and is more suitable for public transport such as Air Metro. However, multicopter VTOL is more suitable considering the short-distance travel within the congested city center, door-to-door air Taxi or individually owned and used PAV (A. Bacchini, xxxx).

在本研究中，用于城市空中出行 (UAM) 的飞行器类型为小型多旋翼垂直起降 (VTOL) 飞机，例如 EHang 184、EHang 216 和 Volocopter 2x，这些飞机能够搭载 1 或 2 名乘客。优步的 UAM 主要考虑使用矢量推力 VTOL 以提高巡航速度。然而，这在需要长途旅行的国家，如美国和加拿大，更为实用，并且更适合于如空中地铁这样的公共交通。但是，考虑到拥挤市中心内的短途旅行，多旋翼 VTOL 更加合适，适用于门到门的空中出租车或个人拥有和使用的个人空中交通工具 (PAV)(A. Bacchini，xxxx)。

This research has considered UAM as a novel transportation mode can replace personal vehicles in the long term, not as a concept of air metro which will be operate in near future; and was conducted from the perspective of approach control of PAV which may be driven in densely populated areas such as residential areas or commercial areas. Therefore, it is considered possible to construct a safe UAM environment by reducing unnecessary circular flight nearby vertiport for holding. Although multicopter VTOL has low cruise speed, it has an ability for stable hovering which makes it suitable for short distance traveling within urban district, considered in this study. Also, in terms of energy consumption, it is more efficient to reduce hovering (Silva et al., 2018). But as it increases the possibility of collision for dense flights to do continued circular flight in the city center, this study has been conducted in the more conservative way where hovering of aircraft takes place near vertiports.

该研究将 UAM 视为一种新型的交通方式，从长远来看可以替代私人车辆，而不是即将运营的空中地铁的概念；并且是从可能在人口密集区域如住宅区或商业区驾驶 PAV 的角度进行的。因此，通过减少附近垂直起降场的不必要的圆形飞行以等待，认为有可能构建一个安全的 UAM 环境。尽管多旋翼 VTOL 的巡航速度较低，但它具有稳定的悬停能力，使其适合在城市区域内的短途旅行，本研究予以考虑。此外，在能源消耗方面，减少悬停更为高效 (Silva et al.，2018)。但由于在城市中心进行连续圆形飞行增加了碰撞的可能性，本研究采取了更为保守的方式，即飞机在垂直起降场附近悬停。

1.2. Contributions and outline of the paper

1.2. 论文贡献与概述

This study contributes to the research literature as follows:

本研究对研究文献的贡献如下:

1) An optimal scheduling strategy suitable for UAM approach control is established. Three different scheduling strategies are computed by applying general algorithm (GA), and the scheduling strategies for UAM are selected by comparing the results.

1) 建立了一种适合 UAM 接近控制的最佳调度策略。通过应用通用算法 (GA)，计算了三种不同的调度策略，并通过比较结果来选择 UAM 的调度策略。

2) Three new approach control models which can be applied to UAM are presented. First, holding points that a VTOL aircraft can hover is introduced. Then, BQA that prioritizes the safety of airspace is proposed, as well as the SBA and SBAM models, which prioritizes aircraft arrival sequence.

2) 提出了三种新的控制模型，这些模型可以应用于城市空中交通 (UAM)。首先，介绍了 VTOL 飞机可以悬停的保持点。然后，提出了优先考虑空域安全的 BQA 模型，以及优先考虑飞机到达顺序的 SBA 和 SBAM 模型。

3) OTP and LOS risks of each model are calculated through simulation; based on the results, the most suitable approach control model for UAM is presented.

3) 通过模拟计算了每种模型的 OTP 和 LOS 风险；基于结果，提出了最适合 UAM 的接近控制模型。

This paper is organized as follows. In Section II, the optimal scheduling strategy of arrival flights is described. In Section III, three vertiport approach control models are proposed. In Section IV, empirical results obtained through the simulation are described, and discussion of the results and future work are covered in Section V, followed by the conclusion.

本文的组织结构如下。在第二部分，描述了到达航班的优化调度策略。在第三部分，提出了三种垂直机场的接近控制模型。在第四部分，描述了通过模拟获得的实证结果，并在第五部分讨论了结果和未来的工作，最后是结论。

2. Optimal sequence of arrival flights

2. 到达航班的优化顺序

Determining the order of landing of aircraft arriving at the airport is a fundamental issue in the ATM of commercial aircraft because it is intended to use the airspace capacity efficiently and safely (Eun et al., 2010). However, commercial aircraft must continue to fly along with the holding pattern around the airport. Due to the complicated landing procedures, there exist multiple limitations to enforcing adjusted landing sequences, and current practice of aircraft arrival scheduling is the first-come-first-served (FCFS) approach. However, VTOL vehicles can respond immediately to the traffic controller's landing instructions because they can hover around the vertiport and wait at one point, which makes landing easier by applying the actual adjusted arrival sequence. Moreover, unlike airports, UAM's vertiport is required to use limited urban space; therefore, proper scheduling sequence is required for efficient use of a narrow apron.

确定到达机场的飞机着陆顺序是商业飞机空中交通管理 (ATM) 的基本问题，因为这旨在高效且安全地使用空域容量 (Eun 等人，2010 年)。然而，商业飞机必须继续沿着机场周围的保持模式飞行。由于复杂的着陆程序，存在多个限制以执行调整后的着陆序列，当前飞机到达调度的做法是先到先得 (FCFS) 方法。但是，VTOL 车辆可以立即响应交通控制员的着陆指令，因为它们可以在垂直机场周围悬停并在一个点等待，这使得通过应用实际的调整后到达序列使着陆变得更容易。此外，与机场不同，UAM 的垂直机场需要使用有限的都市空间；因此，为了高效使用狭窄的停机坪，需要适当的调度序列。

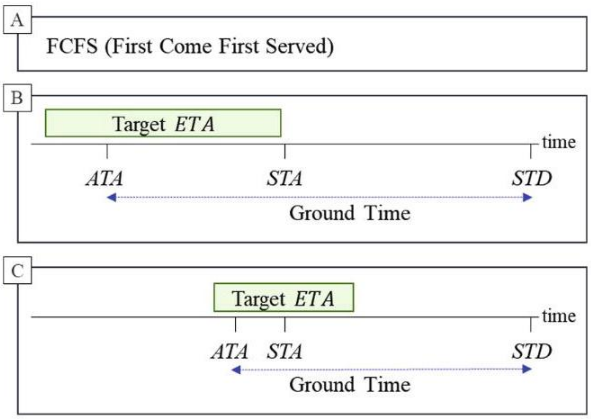


Fig. 1. Scheduling strategy.
图 1. 调度策略。

2.1. Scheduling strategy and problem statement

2.1. 调度策略和问题陈述

In this section, three scheduling strategies are considered to determine the optimal scheduling strategy to be applied to UAM's approach as shown in Fig. 1.

在本节中，考虑了三种调度策略，以确定如图 1 所示的适用于 UAM 接近的最优调度策略。

Strategy A, FCFS, is a universal and classic scheduling scheme that gives the landing priority to vehicles according to the estimated time of arrival (ETA) (Frank and Heinz, 2020). In strategy B and strategy C, the adjusted estimated time of arrival (AETA) of individual vehicle is used:

策略 A，FCFS，是一种通用且经典的调度方案，它根据预计到达时间 (ETA)(Frank 和 Heinz，2020) 给予飞机着陆优先权。在策略 B 和策略 C 中，使用了个别飞机调整后的预计到达时间 (AETA):

$$AETA_i = \mathrm{Max}\left[ETA_i, \Delta\mathrm{L} \times (S_i - 1) + t\right] \tag{1}$$

where ΔL is the minimum landing separation time, $\mathrm{S_i}$ is the landing sequence of the vehicle i , and t is the current time. ATEA is calculated by considering the ETA which is a function of distance-to-go and groundspeed and the waiting time that may occur due to the actual landing sequence. In the scheduling strategy, it is important to consider not only the ETA calculated as the residual distance to the destination of each aircraft, but also the estimated landing time delayed due to the landing sequence. Therefore, AETA is applied in this study. Strategy B and C each sets the cost function as per the strategy. As the strategy B allows early arrival, the cost function is given as follows:

其中 ΔL 是最小着陆间隔时间，S_i 是飞机 i 的着陆顺序，t 是当前时间。ATEA 是通过考虑 ETA(这是一个取决于剩余距离和地速的函数) 以及可能由于实际着陆顺序而产生的等待时间来计算的。在调度策略中，重要的是不仅要考虑作为每架飞机到达目的地剩余距离的 ETA，还要考虑由于着陆顺序而延迟的预计着陆时间。因此，本研究中应用了 AETA。策略 B 和 C 各自根据策略设定成本函数。由于策略 B 允许提前到达，成本函数如下所示:

$$f\left(AETA_i, STA_i\right) = \sum_{i=1}^{N_V} \left(AETA_i - STA_i\right) \times W_i, \tag{2}$$

where W_i is early operation weight.

其中 W_i 是早期操作权重。

However, strategy C sets the cost function to minimize the deviation of the AETA from the scheduled time of arrival (STA) as follows:

然而，策略 C 设定成本函数以最小化 AETA 与计划到达时间 (STA) 的偏差，如下所示:

$$f\left(AETA_i, STA_i\right) = \sum_{i=1}^{N_V} \left|AETA_i - STA_i\right| \times W_i. \tag{3}$$

As shown in Fig. 1, strategy C is a scheduling strategy that can increase the efficiency of vertiport use by minimizing the ground time (GT). GT refers to the time period that begins when a VTOL aircraft lands and ends when an aircraft takes off in the vertiport. However, it has a disadvantage in that the hovering time (HT) is prolonged by waiting in the air until the point close to the STA without giving priority to landing to early arrival vehicles. In Eqs. (2) and (3), i is the vehicle identifier, and N_V means the total number of vehicles. W_i can be expressed as follows, as the early operation weight.

如图 1 所示，策略 C 是一种调度策略，通过最小化地面时间 (GT) 来提高垂直起降场的使用效率。GT 指的是从 VTOL 飞机在垂直起降场着陆开始到飞机起飞结束的时间段。然而，它在以下方面存在缺点: 由于在空中等待直到接近 STA 的时间，不优先考虑提前到达的飞机着陆，导致悬停时间 (HT) 延长。在公式 (2) 和 (3) 中，i 是飞机识别符，N_V 表示飞机总数。W_i 可以表示为早期操作权重，如下所示。

$$W_i = \begin{cases} \alpha, \text{ if VTOLaircraftarriveearlierthantheschedule } \left(AETA_i \leq STA_i\right) \\ 1-\alpha, \text{ otherwise } \left(AETA_i > STA_i\right) \end{cases}, \tag{4}$$

here, α could be defined as a value between 0 and 1 . As the value of α gets smaller, it indicates that the vehicles arrived earlier than the schedule at the environs of the vertiport, is given the priority for an early landing. Thus, selection of an appropriate value of α , which relates to the decision of early operation weight (W_i) are crucial in the scheduling strategy for UAM. This is discussed in detail in Section 2.4.

在这里，α 可以定义为介于 0 和 1 之间的值。随着 α 值的减小，它表明在机场附近的车辆比预定时间提前到达，并被优先安排提前着陆。因此，选择一个适当的 α 值，它与早期操作权重 (W_i) 的决定相关，对于城市空中交通 (UAM) 的调度策略至关重要。这一点在 2.4 节中进行了详细讨论。

The objective function of the arriving aircraft's scheduling optimization problem is to minimize the cost for each strategy, as shown in Eq. (5) below:

如下式 (5) 所示，到达飞机调度优化问题的目标函数是最小化每种策略的成本:

$$\begin{gathered} \text{Min } f\left(AETA_i, STA_i\right) \\ \text{s.t } \left|AETA_i - AETA_j\right| \geq \Delta L \text{ for } i, j \in \{1, 2, \ldots, N_V\} \\ AETA_i = \text{Max}\left[ETA_i, \Delta L \times \left(S_i - 1\right) + t\right] \text{ for } i, j \in \{1, 2, \cdots, N_V\}\ , \\ S_i \in \mathbb{Z}, 1 = \min\left(S_i\right) \leq S_i \leq \max\left(S_i\right) \text{ for } i, \in \{1, 2, \cdots, N_V\} \end{gathered} \tag{5}$$

2.2. Methodology

2.2. 方法论

The scheduling optimization problem of arriving aircraft is a typical NP-Hard problem (Psaraftis, 1978), and it is difficult to solve because it requires long computation time to determine the exact solution. Therefore, in this study, a representative meta-heuristic technique, genetic algorithm (GA), is used. GA is extensively used in the field of ordered combination optimization as the genetic calculation process such as crossover, mutation, and displacement is not standardized and can be redesigned by researchers to suit individual research characteristics (Whitley, 1994). On the other hand, it is important to reduce the variability of solutions that can occur with genetic operators in sequence optimization problems. By reflecting this in the genetic operation process, unnecessary repeated operations can be reduced, and feasible solutions can be searched efficiently. Fig. 2 shows the flowchart of the optimal scheduling algorithm using GA.

到达飞机的调度优化问题是典型的 NP-难问题 (Psaraftis，1978)，由于其需要长时间计算以确定确切解，因此难以解决。因此，在本研究中，使用了一种代表性的元启发式技术——遗传算法 (GA)。GA 在有序组合优化领域得到了广泛应用，因为遗传计算过程如交叉、变异和位移并未标准化，研究人员可以根据个人研究特点重新设计 (Whitley，1994)。另一方面，减少序列优化问题中由于遗传操作产生的解的变异性也很重要。通过在遗传操作过程中反映这一点，可以减少不必要的重复操作，并且有效地搜索可行解。图 2 显示了使用 GA 的最优调度算法的流程图。

To compare scheduling strategies, we generated 100 sets of flight data. Unlike commercial aircraft, UAM requires generating virtual flight data as there is no actual flight data, which is performed on the same basis as shown in Table 1. Relatively congested flight schedule is assumed as 50 VTOL aircraft are considered to arrive within 20 min , and ETA assumed 85% of OTP situations on a two-minute basis. It means that 85% of the aircraft in flight can arrive within 2 min time window of the STA. Most airliners around the world manage OTP standard as 5 min . This means when airplanes arrive in 5 min after STA, they are considered as on time flight. As UAM is not a long-distance international flight like normal airliner, it's inappropriate to set OTP as 5 min. This study assumes that UAM is a short distance urban mobility and accordingly, an OTP of 2 min is set. Therefore, it is assumed that ETA is normally distributed with a mean of the vehicle' s STA and standard deviation of $\frac{p}{\Phi^{-1}(OTP)}$ derived from the inverse of the standard normal cumulative distribution function (cdf) and on-time arrival criteria(p). Also, the STD is set to secure ground time between 10 and 15 min , assuming the minimum ground time (MGT) required for charging and servicing the vehicles is 10 min . For this, it is assumed that the STD is calculated by summing the MGT and ω_i which is a uniform random value between 0 and 5 min , to the STA.

为了比较调度策略，我们生成了 100 组航班数据。与商业飞机不同，由于没有实际飞行数据，UAM 需要生成虚拟飞行数据，这与方法如表 1 所示相同。假设相对拥挤的飞行计划为 50 架 VTOL 飞机在 20 min 内到达，预计到达时间 85% 假设为 OTP 情况下的两分钟。这意味着 85% 的飞行中的飞机可以在预计起飞时间 2 min 的时间窗口内到达。世界上大多数航空公司将 OTP 标准设定为 5 min 。这意味着当飞机在预计起飞时间 5 min 之后到达时，它们被认为是准点航班。由于 UAM 不是像正常航班那样的长途国际航班，因此将 OTP 设定为 5 分钟是不合适的。本研究假设 UAM 是短途的城市出行，因此，将 OTP 设定为 2 分钟。因此，假设预计到达时间服从以车辆预计起飞时间为均值，标准差为 $\frac{p}{\Phi^{-1}(OTP)}$ 的正态分布，该标准差是从标准正态累积分布函数 (cdf) 的逆函数和准点到达标准 (p) 得出的。同时，假设标准差 (STD) 设置为在 10 和 15 min 之间确保地面时间，假设为充电和维修车辆所需的最小地面时间 (MGT) 为 10 min 。为此，假设标准差 (STD) 是通过将最小地面时间 (MGT) 和 ω_i 相加到预计起飞时间 (STA) 上计算得出的，其中 ω_i 是介于 0 和 5 min 之间的均匀随机值。

2.3. Comparison of scheduling strategies

2.3. 调度策略比较

The optimal landing schedule for arriving aircraft is determined by applying GA to arbitrary flight data. Fig. 3 shows the scheduling result found by the three strategies with Dataset 1 . It is assumed that there is no delay in landing due to the lack of vertiport's landing pad, and at the same time, only one VTOL is considered to be capable of takeoff or landing.

到达飞机的最佳着陆时间表是通过将遗传算法应用于任意飞行数据来确定的。图 3 显示了使用数据集 1 时三种策略找到的时间安排结果。假设由于缺乏垂直机场的着陆垫，着陆没有延迟，同时，仅考虑一个

VTOL 能够进行起飞或着陆。

In Strategy A, regardless of the STA, vehicles with fast ETA can be seen landing in sequence while maintaining the minimum landing separation time. Moreover, the results for the vehicles with fast ETA (ETA < STA) in strategies B and C, show that the landing sequence is affected by the STA, and the landing sequence is changed. In particular, the range of difference between ETA and ATA can be clearly seen in Strategy C. In Strategy B, if there is a vehicle that arrives earlier than the STA, the vehicle lands without waiting within the range that does not limit the next vehicle's landing. However, strategy C shows a pattern in which the vehicle with fast ETA awaits in the air before landing to reduce deviation with the STA. Based on the scheduling result, the GT waiting in the vertiport until the landing vehicle takes off again and the HT waiting in the air until receiving the landing order around the vertiport can be calculated. At this time, the estimated time of departure (ETD) assumes no delay in departure due to factors such as vehicle maintenance, battery charging, weather conditions, and GT and HT are then calculated as follows:

在策略 A 中，无论预计起飞时间 (STA) 如何，具有较快预计到达时间 (ETA) 的车辆可以按顺序着陆，同时保持最小着陆间隔时间。此外，策略 B 和 C 中具有较快预计到达时间 (ETA < STA) 的车辆的结果表明，着陆顺序受到 STA 的影响，并且着陆顺序发生了变化。特别是，在策略 C 中，预计到达时间 (ETA) 与实际到达时间 (ATA) 之间的差异范围可以明显看出。在策略 B 中，如果有车辆比 STA 提前到达，该车辆将在不限制下一辆车着陆的范围内着陆而无需等待。然而，策略 C 显示出一种模式，即具有较快预计到达时间的车辆在着陆前在空中等待，以减少与 STA 的偏差。基于时间安排结果，可以计算出在垂直机场等待着陆车辆再次起飞的地面等待时间 (GT) 和在机场周围等待着陆指令的空中等待时间 (HT)。此时，预计起飞时间 (ETD) 假设由于车辆维护、电池充电、天气条件等因素没有起飞延迟，GT 和 HT 则按以下方式计算:

$$GT_i = ETD_i - ATA_i$$

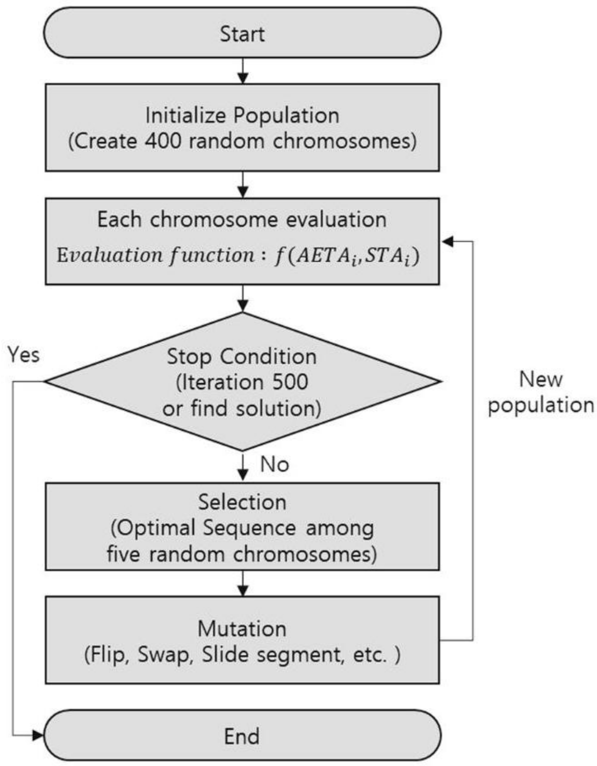


Fig. 2. Flow chart of the GA for arrival sequence.
图 2. 到达顺序遗传算法的流程图。

Table 1
表 1
Data generation criteria.
数据生成标准。

The # of PAVs	$N_V = 50$
Scheduled Time of Arrival (STA)	$STA_i U\,(1, 20)$
Estimated Time of Arrival (ETA)	$ETA_i N\left(STA_i, \left(\frac{p}{\Phi^{-1}(OTP)}\right)^2\right)$ where, $p = 2\,(m)\,, OTP = 85\%$, $\Phi =$ standard n or m at cdf
Scheduled Time of Departure (STD)	$STD_i = STA_i + MGT + \omega_i$, where, $\omega_i U\,(0, 5)\,, MGT = 10\,(m)$

个人空中车辆 (PAV) 的 #	$N_V = 50$
预定到达时间 (STA)	$STA_i U\,(1, 20)$
预计到达时间 (ETA)	$ETA_i N\left(STA_i, \left(\frac{p}{\Phi^{-1}(OTP)}\right)^2\right)$ 其中，$p = 2\,(m)\,, OTP = 85\%$, $\Phi =$ 标准 n 或 m 在 cdf
预定出发时间 (STD)	$STD_i = STA_i + MGT + \omega_i$, 其中，$\omega_i U\,(0, 5)\,, MGT = 10\,(m)$

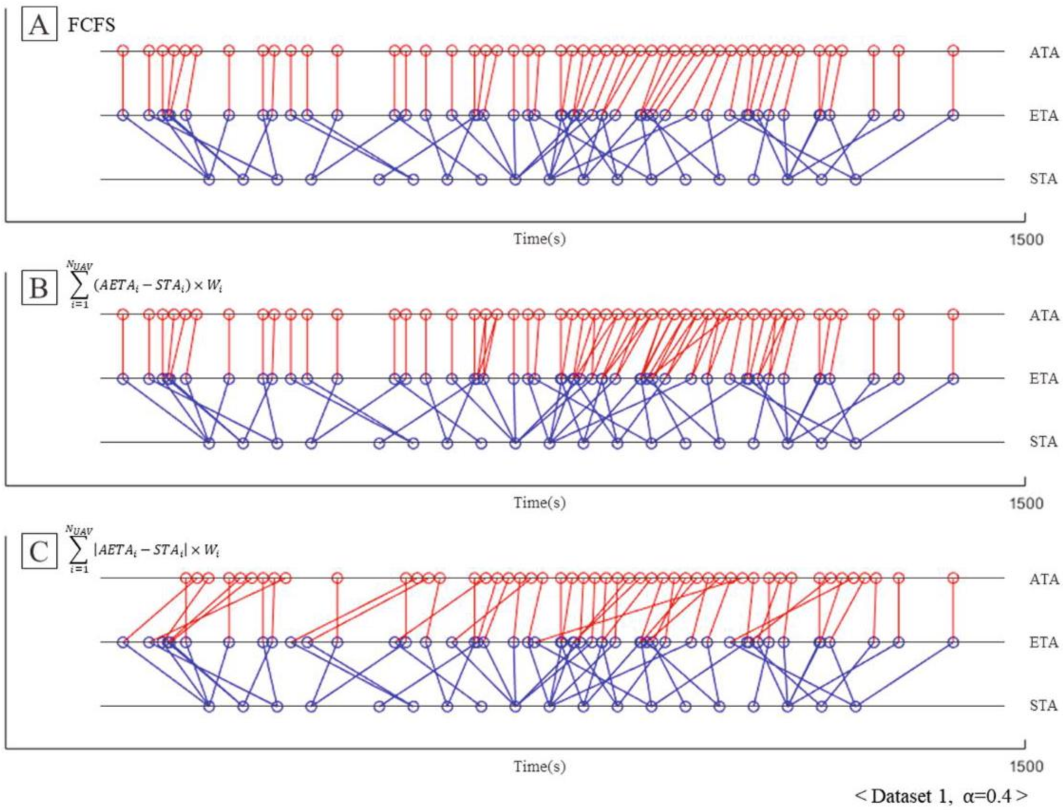


Fig. 3. Scheduling results of three strategies for Dataset 1.
图 3. 三种策略针对数据集 1 的调度结果。
where,
其中，

$$ETD_i = \begin{cases} STD_i, \text{ if } STD_i - ATA_i \geq MGT \\ ATA_i + MGT, \text{ otherwise} \end{cases}, \tag{6}$$

$$HT_i = ATA_i - ETA_i \tag{7}$$

Fig. 4 shows the GT and HT of each vehicle for Dataset 1. By individual aircraft, FCFS strategy's and B strategy's GT and HT are similar. In Strategy B, certain vehicles are subjected to sequence adjustment; however, in a situation where the vehicle to be landed is not concentrated, the sequence variation hardly occurs, and a landing sequence similar to FCFS is found. However, strategy C has a distinctly different pattern of GT and HT from strategies A and B. In general, GT decreases, and HT increases. This phenomenon is because the deviation of STA and ATA is reduced to minimize the unnecessary time spent in the vertiport. Scheduling strategies such as strategy C are thought to be more suitable for arrival scheduling for UAM. Unlike most airport, vertiport uses limited space in the city, which inevitably limits the space where vehicles can stay. Therefore, the VTOL vehicle reflects the characteristics of hovering flight; thus, if the end-of-discharge of the onboard battery pack is not in short supply, even if HT increases, the scheduling strategy of landing close to the STA while waiting in the air is a more suitable method.

图 4 显示了数据集 1 中每辆车的地面时间 (GT) 和悬停时间 (HT)。对于每架飞机，先来先服务 (FCFS) 策略和 B 策略的 GT 和 HT 相似。在 B 策略中，某些车辆受到序列调整的影响；然而，在待降车辆不集中的情况下，序列变化几乎不会发生，并且发现了一个类似于 FCFS 的着陆序列。但是，策略 C 的 GT 和 HT 模式与策略 A 和 B 有显著的不同。通常，GT 减少，而 HT 增加。这种现象是因为将 STA 和 ATA 的偏差减少到最小，以减少在立体港口不必要的停留时间。像策略 C 这样的调度策略被认为更适合于城市空中出行 (UAM) 的到达调度。与大多数机场不同，立体港口在城市中使用了有限的空间，这不可避免地限制了车辆可以停留的空间。因此，VTOL 车辆反映了悬停飞行的特点；因此，如果机载电池组的放电结束并不短缺，即使 HT 增加，在空中等待时接近 STA 的着陆调度策略也是一种更合适的方法。

2.4. Impact of changing early operation weight (W_i)

2.4. 更改早期操作权重的影响 (W_i)

To identify the appropriate value of early operation weight affecting the scheduling result, the scheduling results using 100 sets of

为了确定影响调度结果的早期操作权重的适当值，使用了 100 组

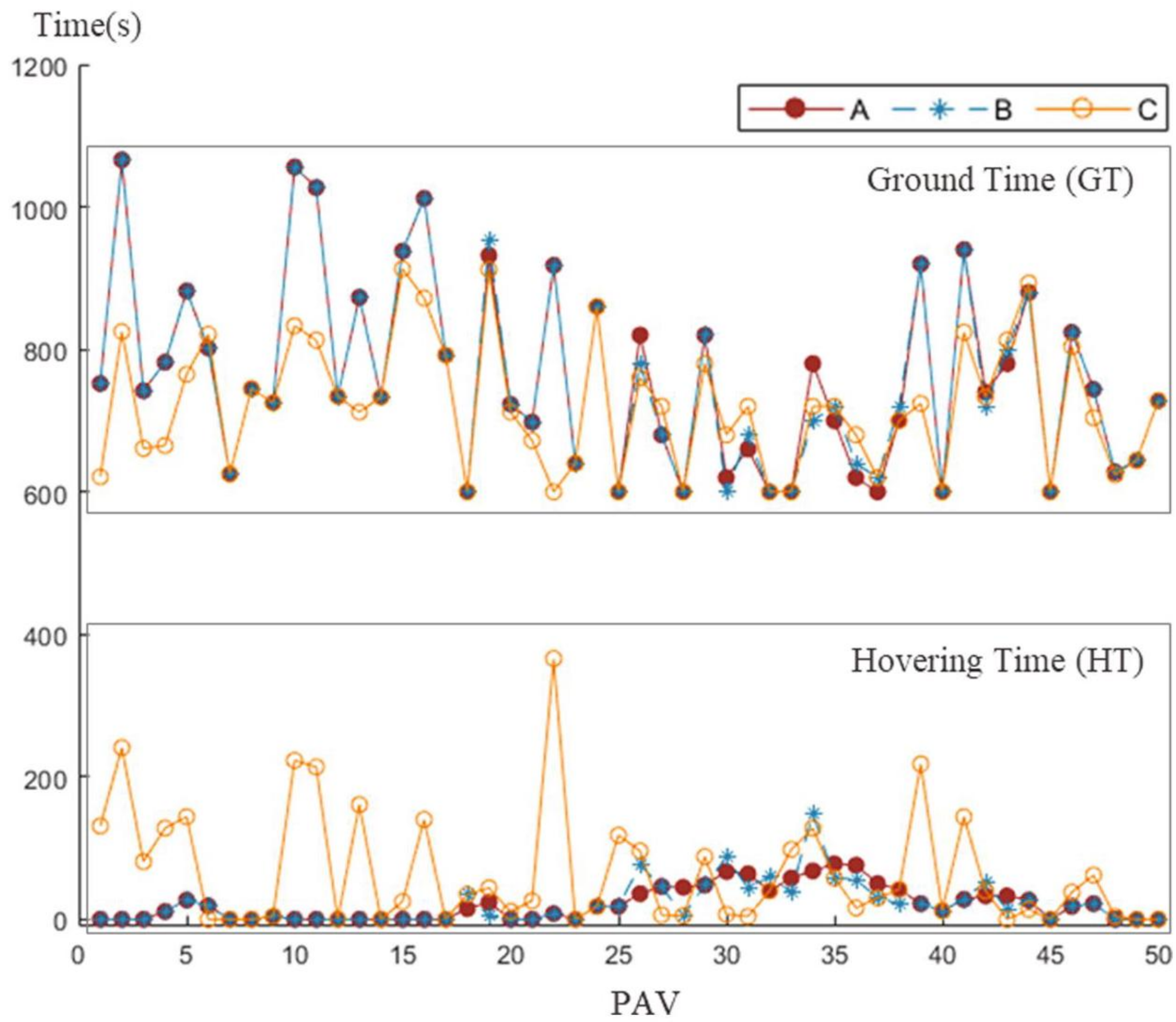


Fig. 4. Ground time (GT), hovering time (HT) for Dataset 1.
图 4。数据集 1 的地面时间 (GT)、悬停时间 (HT)。

flight data are compared. We verified the scheduling results of each dataset based on the OTP, average ground time (AGT), and average hovering time (AHT), which are obtained as follows:

飞行数据来比较调度结果。我们根据 OTP、平均地面时间 (AGT) 和平均悬停时间 (AHT) 验证了每个数据集的调度结果，这些结果如下获得:

$$\text{OnTimePerformance(OTP)} \ = \frac{\sum_{i=1}^{N_V} x_i}{N_V} \times 100 \text{ , where, } x_i = \begin{cases} 1, \text{ if } ATA_i \leq STA_i + p \\ 0, \text{ otherwise} \end{cases} \tag{8}$$

$$\text{AverageGroundTime (AGT)} = \frac{\sum_{i=1}^{N_V} GT_i}{N_V} \tag{9}$$

$$\text{AverageHoveringTime (AHT)} = \frac{\sum_{i=1}^{N_V} HT_i}{N_V} \tag{10}$$

The OTP confirms that individual vehicles arrive within 2 min of the delay standard through scheduling, AGT and AHT are calculated as the average of GT and HT for all vehicles. Fig. 5 shows the scheduling results for 100 datasets

OTP 确认通过调度，单个车辆在 2 min 的延误标准内到达，AGT 和 AHT 是所有车辆 GT 和 HT 的平均值。图 5 显示了 100 个数据集的调度结果。

The average OTP for FCFS is 79%, which is slightly less than 85% for data generation criteria. This is because some delayed vehicles maintain minimum landing separation time, assuming a relatively dense landing scenario in which 50 vehicles land in 20 min. However, OTP results are better than FCFS for α values,0.1 -0.4 in Strategy B, and for α values,0.1 -0.7 in Strategy C. Both AGT and AHT results show that strategy B gives similar results to FCFS without being significantly affected by α values. However, strategy C shows a decrease in AGT, and increase in AHT as α values increase. If GT decreases, then HT increases, which is a natural result of conflicting concepts. Moreover, even if AHT increases, strategy C that can reduce AGT is suitable for UAM's vertiport strategy, and we can see that when α is 0.4, it can maximize the OTP while balancing AHT and AGT.

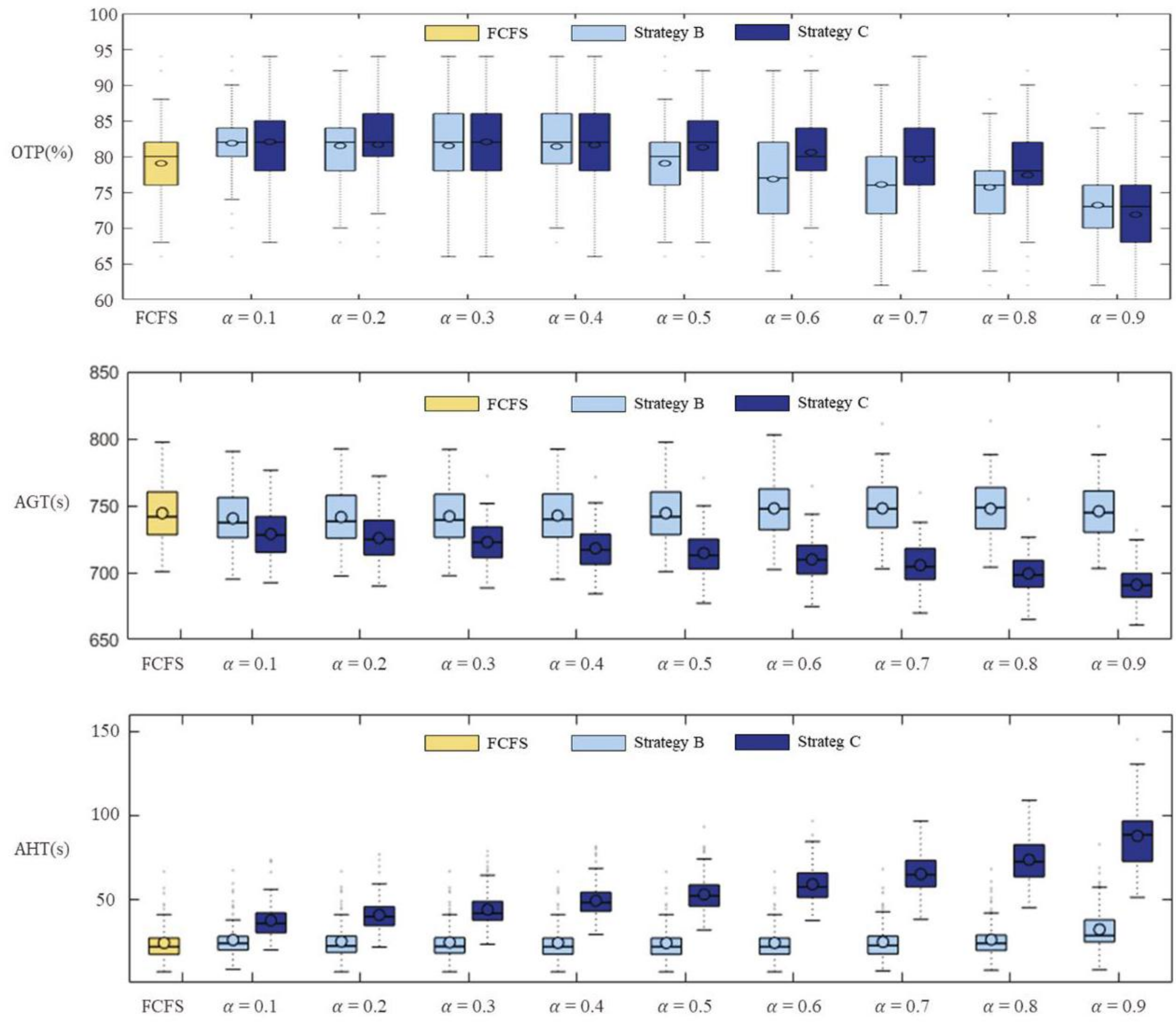
FCFS 的平均 OTP 为 79%，略低于数据生成标准的 85%。这是因为一些延迟的车辆维持了最小着陆间隔时间，假设了一个相对稠密的着陆场景，即 50 辆车在 20 分钟内着陆。然而，OTP 结果在策略 B 的 α 值为 0.1 -0.4 时，以及在策略 C 的 α 值为 0.1 -0.7 时，都优于 FCFS。AGT 和 AHT 的结果都显示，策略 B 在不受到 α 值显著影响的情况下，给出了与 FCFS 相似的结果。然而，策略 C 随着 α 值的增加显示出 AGT 的减少和 AHT 的增加。如果 GT 减少，那么 HT 就会增加，这是冲突概念的天然结果。此外，即使 AHT 增加，能够减少 AGT 的策略 C 适合于 UAM 的垂直港口策略，我们可以看到当 α 为 0.4 时，它可以在平衡 AHT 和 AGT 的同时最大化 OTP。

3. Vertiport approach control model

3. 垂直港口进近控制模型

In previous studies, we proposed a branch queuing approach (BQA) and a sequence-based approach (SBA), which are UAM's

在以前的研究中，我们提出了分支排队方法 (BQA) 和基于序列的方法 (SBA)，这些是 UAM 的



approach control concepts. We also introduced optimal vertiport airspace design results based on (K. Song, xxxx). This section introduces additional concrete models based on the proposed concept in the previous study and we suggest a sequence-based approach with moving circles (SBAM), which is a modified approach control concept of SBA. Fig. 6 shows the three approach control concepts dealt with in this study. The airspace around the vertiport comprises holding points where vehicles can hover at while waiting in the air, and several holding circles connecting these holding points. Individual vehicles entering the approach phase gradually lower their altitude and move to the inner circle. The three models control vehicles in different ways. BQA allows movement only within a predetermined path between the holding points. In Fig. 6, a dotted line indicates a previously determined movement path between the holding points. In both SBA and SBAM, the vehicle with the fastest arrival sequence in the upper holding circle searches for an empty holding point in the lower holding circle without a fixed path. The SBA moves along the straight path between the starting holding point and the arriving holding point, whereas SBAM's moving circle is placed around the holding circle as shown by the solid blue line in Fig. 6. The vehicle moving into the holding circle lowers the altitude and then moves from the moving circle to the holding point.

接近控制概念。我们还介绍了基于 (K. Song, xxxx) 的最优垂直起降场空域设计结果。本节基于前一项研究中提出的概念，引入了额外的具体模型，并提出了一种基于移动圆的序列方法 (SBAM)，这是 SBA 的改进型接近控制概念。图 6 展示了本研究中处理的三个接近控制概念。垂直起降场周围的空域包括一些等待点，飞行器可以在空中悬停等待，以及连接这些等待点的多个等待圈。进入接近阶段的飞行器逐渐降低高度并向内圈移动。这三个模型以不同的方式控制飞行器。BQA 仅允许在等待点之间的预定路径内移动。在图 6 中，虚线表示等待点之间预先确定的移动路径。在 SBA 和 SBAM 中，位于上层等待圈中到达顺序最快的飞行器，在没有固定路径的情况下搜索下层等待圈中的空等待点。SBA 沿着起始等待点与到达等待点之间的直线路径移动，而 SBAM 的移动圆则如图 6 中的实心蓝线所示，放置在等待圈周围。进入等待圈的飞行器降低高度，然后从移动圆移动到等待点。

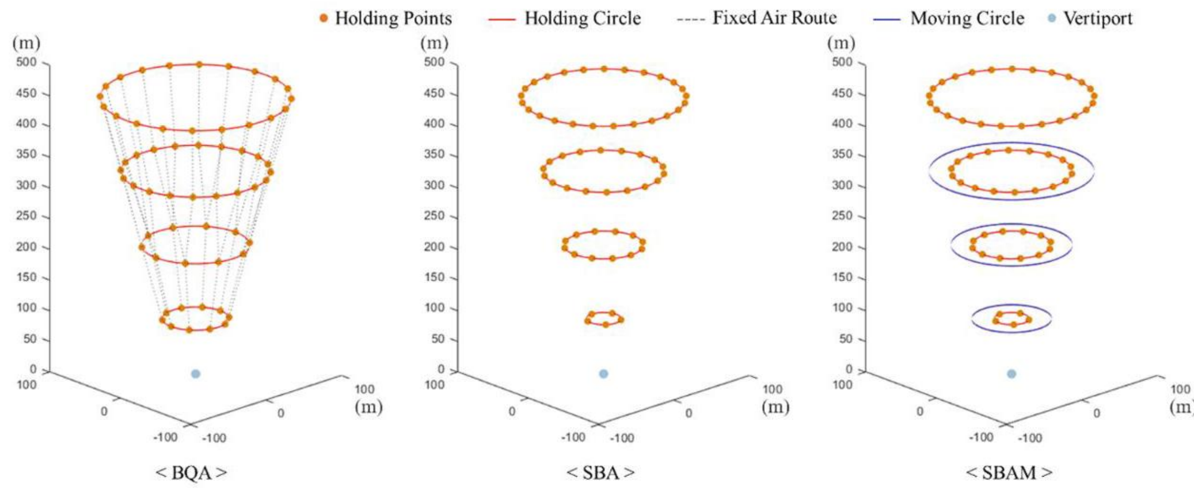


Fig. 6. Three proposed vertiport approach control concepts.
图 6。三种提出的垂直起降场接近控制概念。

3.1. Branch queuing approach (BQA)

3.1. 分支排队方法 (BQA)

BQA model restricts vehicle movement to a minimum in the vertiport airspace. The pair of holding points that can move from the airspace design stage is determined; moreover, vehicles in the control stage receive movement commands only in the specified path. Fig. 7 shows the approximate framework of the BQA model. The BQA model is composed of two stages. The first step is a preparation stage for model implementation, and the process is almost similar for SBA and SBAM, which is described later in the section. In the first step, parameters necessary for airspace design and approach control are the inputs; based on these, the optimal airspace, including the radius of the holding circle, the arrangement of each holding point, and the number of branches, are designed. Moreover, basic initialization for model demonstration is performed such as loading flight data and calculating initial AETA.

BQA 模型将车辆在机场空域内的移动限制在最小范围内。可以从空域设计阶段移动的一对等待点被确定；此外，控制阶段的车辆仅在指定路径上接收移动指令。图 7 展示了 BQA 模型的近似框架。BQA 模型由两个阶段组成。第一步是模型实施的准备阶段，SBA 和 SBAM 的过程几乎相似，这部分将在后面的章节中描述。在第一步中，输入是进行空域设计和进近控制所必需的参数；基于这些参数，设计包括等待圈半径、每个等待点的布局以及分支数量的最优空域。此外，还进行了模型演示的基本初始化，例如加载飞行数据和计算初始预计到达时间 (AETA)。

In the second step, a full-scale approach control is performed. Flight status data includes all information necessary for approach control, such as position coordinates of vehicles, landing sequence, and vehicle occupancy of the holding point and checks, and updates are then performed in real-time. If there are vehicles capable of landing in vertiport and capable of landing in holding circle 1 the innermost circle with the lowest altitude, landing clearance is given to the aircraft with the highest priority in the landing sequence. Moreover, the vehicles in holding circle 2 $\sim$ N located in the same branch queuing, receive moving clearance to the inner holding circle regardless of the sequence as the first vehicle receives the landing clearance. With a 2D plot in the left of Fig. 8, vehicles in the same branch queuing move together along a specified route as indicated by the red shade. Moreover, GA-based optimal scheduling is executed in real-time and updates the landing sequence of the flight status data. The scheduling strategy, strategy B is covered in Section 2 and is performed for vehicles located in the holding circle 1.

在第二步中，进行全规模的进近控制。飞行状态数据包括进行进近控制所需的所有信息，如车辆的位置坐标、着陆顺序以及等待点上的车辆占用情况，并进行实时检查和更新。如果机场内存在能够着陆的车辆，并且位于最低高度的内部等待圈 1(最内圈) 内，则给予在着陆顺序中优先级最高的飞机着陆许可。此外，位于同一分支排队等候的等待圈 2 $\sim$ N 中的车辆，在第一辆车获得着陆许可后，不考虑顺序，都将接收到移动到内部等待圈的许可。在图 8 左侧的 2D 图中，同一分支排队的车辆沿着红色阴影所示的规定路线一起移动。此外，基于遗传算法的最优调度实时执行，并更新飞行状态数据的着陆顺序。调度策略，即策略 B 在第 2 节中有所介绍，并且适用于位于等待圈 1 中的车辆。

3.2. Sequence-Based approach (SBA)

3.2 基于序列的方法 (SBA)

Compared to BQA, the SBA model allows vehicles to move freely in the vertiport airspace. In the SBA model, vehicles do not move to the inner holding circle along the specified route, but search the holding point with the shortest moving path among the empty holding points at the time of receiving moving clearance. Fig. 9 shows the approximate framework of the SBA model. The process performed in the first step is similar to that of BQA. However, at the optimal airspace design stage, there are differences compared to BQA's approach. In the second step, certain procedures are added compared to BQA. For instance, when it is necessary to move to the inner holding circle, the vehicle with the fastest landing sequence in the holding circle is searched. Moreover, as SBA does not move along a specified route, vehicle trajectory is created.

与 BQA 相比，SBA 模型允许车辆在立体港口空域内自由移动。在 SBA 模型中，车辆在接收到移动许可时，不是沿着指定路线移动到内等待圈，而是在空等待点中搜索移动路径最短的等待点。图 9 显示了 SBA 模型的近似框架。第一步执行的过程与 BQA 相似。然而，在最优空域设计阶段，与 BQA 的方法相比存在差异。在第二步中，相比于 BQA 增加了一些程序。例如，当需要移动到内等待圈时，会搜索在等待圈中降落序列最快的车辆。此外，由于 SBA 不沿指定路线移动，因此会创建车辆轨迹。

The most significant difference between SBA and SBAM lies in the process of creating a trajectory. As shown in Fig. 10, SBA creates a simple linear trajectory between the start point and finish point; however, SBAM uses the moving circle to reach the destination point.

SBA 和 SBAM 之间最显著的区别在于创建轨迹的过程。如图 10 所示，SBA 在起点和终点之间创建一个简单的线性轨迹；然而，SBAM 使用移动圆来达到目的地。

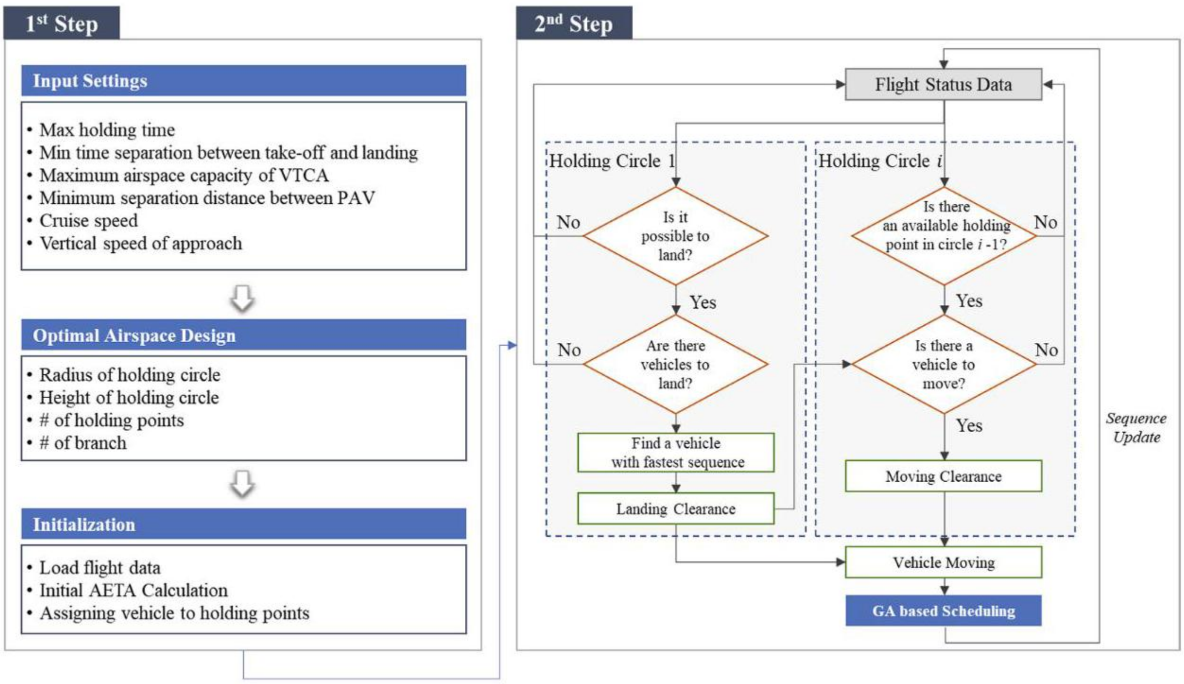


Fig. 7. The framework of BQA model.
图 7. BQA 模型的框架。

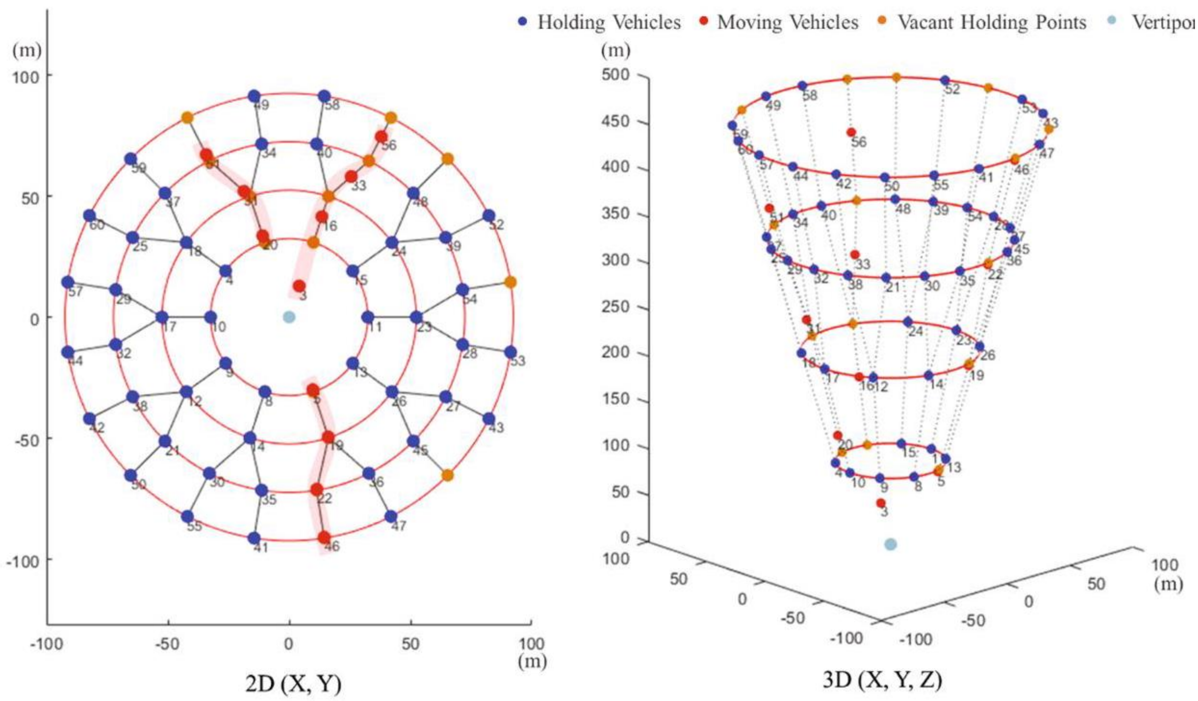


Fig. 8. A sample of BQA model application.
图 8. BQA 模型应用的示例。

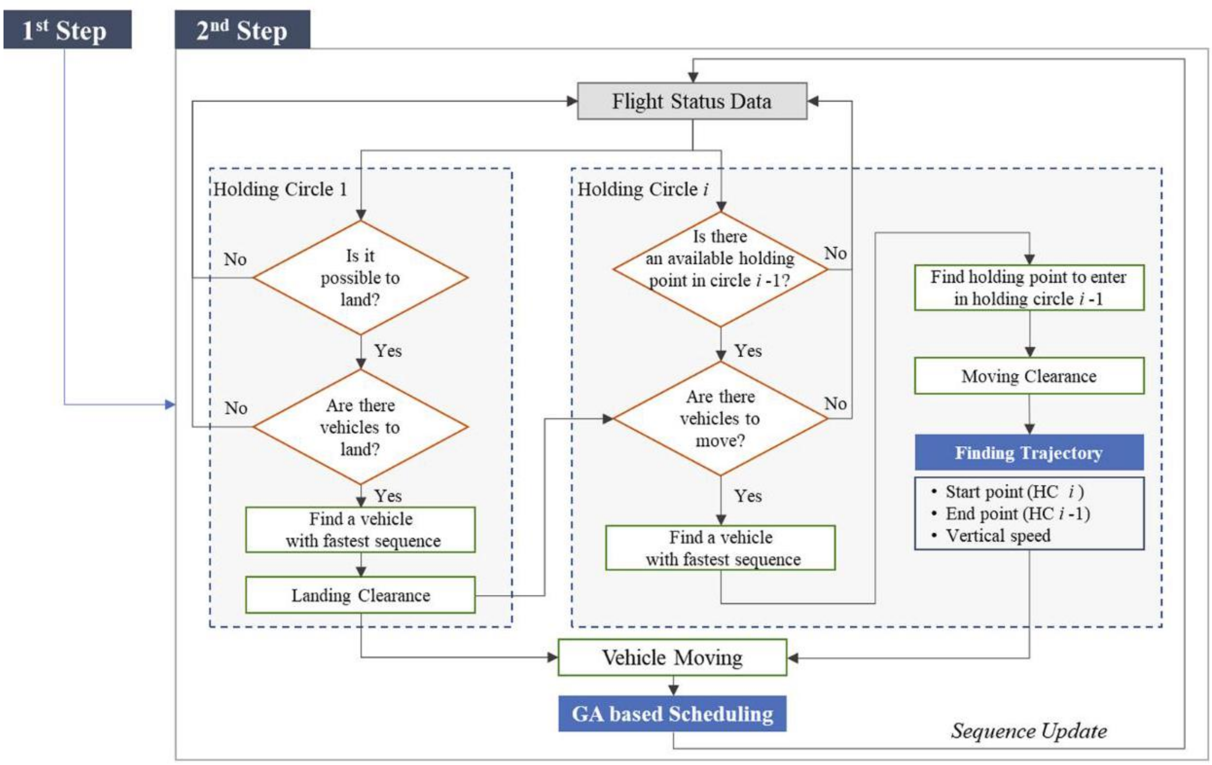


Fig. 9. The framework of SBA model.
图 9. SBA 模型的框架。

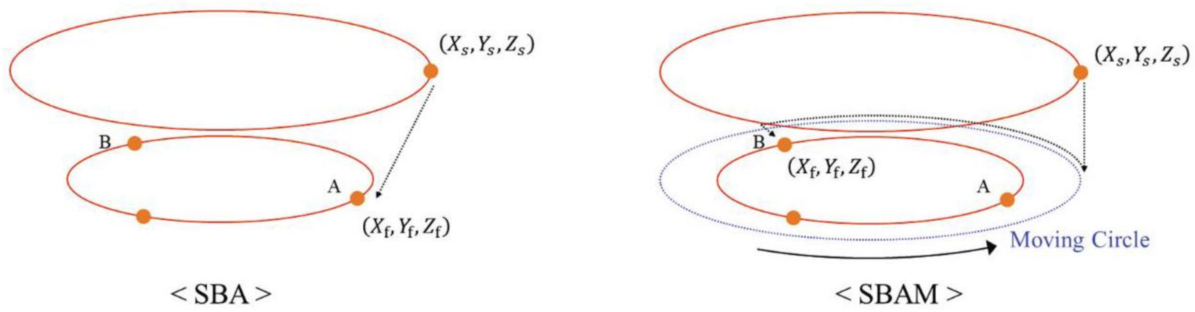


Fig. 10. Trajectory difference between SBA and SBAM.

图 10. SBA 与 SBAM 之间的轨迹差异。

In SBA, the trajectory coordinates of vehicle i after t time, that received moving clearance using the vehicle' s start point (X_s, Y_s, Z_s) , finish point (X_f, Y_f, Z_f) , and vertical speed of approach (S_v) , is calculated as follows:

在 SBA 中，接收到移动许可的车辆 i 在 t 时间后的轨迹坐标，使用车辆的起点 (X_s, Y_s, Z_s) 、终点 (X_f, Y_f, Z_f) 和接近的垂直速度 (S_v) ，计算如下:

$$T_{i,t} = \left(X_s + \frac{X_f - X_s}{\left(\frac{Z_s - Z_f}{S_v}\right)} \times t, Y_s + \frac{Y_f - Y_s}{\left(\frac{Z_s - Z_f}{S_v}\right)} \times t, Z_s - S_v \times t \right) \tag{11}$$

Here, the vehicle's horizontal speed is not considered because the actual travel time is affected by the vertical speed as it takes much time for vertical movement due to the characteristics of the VTOL aircraft.

这里，没有考虑车辆的水平速度，因为实际旅行时间受到垂直速度的影响，由于 VTOL 飞机的特性，垂直移动需要花费更多时间。

3.3. Sequence-based approach with moving circles (SBAM)

3.3. 基于移动圆的序列方法 (SBAM)

First, it descends vertically from the start point (X_s, Y_s, Z_s) and then enters the moving circle. The moving trajectory can be simply obtained as shown in Eq. (12), by altering Eq. (11). As it is a vertical movement from the start point, the horizontal coordinates(X, Y) do not change, only the vertical position changes.

首先，它从起点 (X_s, Y_s, Z_s) 垂直向下移动，然后进入移动圆。移动轨迹可以简单地通过如图所示的式 (12) 获得，通过改变式 (11)。因为它从起点做垂直移动，所以水平坐标 (X, Y) 不发生变化，只有垂直位置发生变化。

$$T_{i,t} = (X_s, Y_s, Z_s - S_v \times t) \tag{12}$$

To develop the moving trajectory in the second step' s moving circle, we need to identify the angle θ on the plane between the start point and the finish point as shown in Fig. 11. To calculate θ , the coordinates of (X_m, Y_m) , which are the points entering the holding circle from the moving circle, are required. This is calculated as Eq. (13) below using the equation of a circle with a radius of r_2 , and the equation of a straight line derived from the center of the circle and the finish point (X_f, Y_f) .

为了在第二步的移动圆中开发移动轨迹，我们需要确定图 11 所示的起点和终点之间的平面角度 θ 。为了计算 θ ，需要知道 (X_m, Y_m) 的坐标，即从移动圆进入保持圆的点。这可以通过使用半径为 r_2 的圆的方程和由圆心到终点的直线方程得到的式 (13) 来计算。

$$X_m = \sqrt{\frac{r_2^2}{\left(1 + \frac{Y_f^2}{X_f^2}\right)}}, Y_m = \frac{Y_f^2}{X_f^2} \times \sqrt{\frac{r_2^2}{\left(1 + \frac{Y_f^2}{X_f^2}\right)}} \tag{13}$$

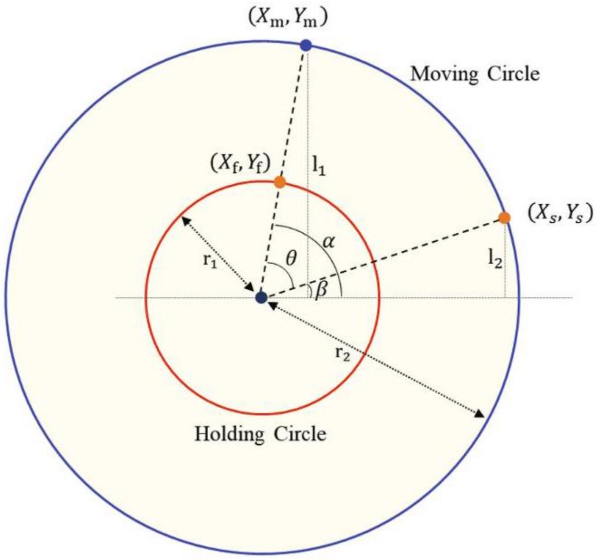


Fig. 11. SBAM trajectory calculation.
图 11。SBAM 轨迹计算。

The angle θ can also be expressed as $\alpha - \beta$ as shown in Fig. 11, and tan θ is equal to (14). The $\sin\theta$ and $\cos\theta$ of Eq. (14) can then be developed into Eqs. (15) and (16) by the addition theorem of trigonometric functions.

图 11 中的角度 θ 也可以表示为 $\alpha - \beta$ ，并且 tan θ 等于式 (14)。式 (14) 中的 $\sin\theta$ 和 $\cos\theta$ 可以通过三角函数的和差化积公式分别展开为式 (15) 和式 (16)。

$$\tan\theta = \frac{\sin\theta}{\cos\theta} \tag{14}$$

$$\sin\theta = \sin(\alpha - \beta)$$

$$= \sin\alpha\cos\beta - \cos\alpha\sin\beta$$

$$= \frac{Y_m}{l_1}\cdot\frac{X_s}{l_2} - \frac{X_m}{l_1}\cdot\frac{Y_s}{l_2}$$

$$= \frac{1}{l_1 \cdot l_2}(Y_m \cdot X_s - X_m \cdot Y_s) \tag{15}$$

$$\cos\theta = \cos(\alpha - \beta)$$

$$= \cos\alpha\cos\beta - \sin\alpha\sin\beta$$

$$= \frac{X_m}{l_1}\cdot\frac{X_s}{l_2} - \frac{Y_m}{l_1}\cdot\frac{Y_s}{l_2}$$

$$= \frac{1}{l_1 \cdot l_2}(X_m \cdot X_s - Y_m \cdot Y_s) \tag{16}$$

Eq. (17) can then be obtained by substituting Eqs. (15) and (16) in Eq. (14), and θ can be calculated as shown in Eq. (18) using the inverse function of the tangent.

然后将式 (15) 和式 (16) 代入式 (14)，可以得到式 (17)，并且如式 (18) 所示，使用正切的反函数可以计算出 θ 。

$$\tan\theta = \frac{Y_m \cdot X_s - X_m \cdot Y_s}{X_m \cdot X_s - Y_m \cdot Y_s} \tag{17}$$

$$\theta = \tan^{-1}\left(\frac{Y_m \cdot X_s - X_m \cdot Y_s}{X_m \cdot X_s - Y_m \cdot Y_s}\right) \tag{18}$$

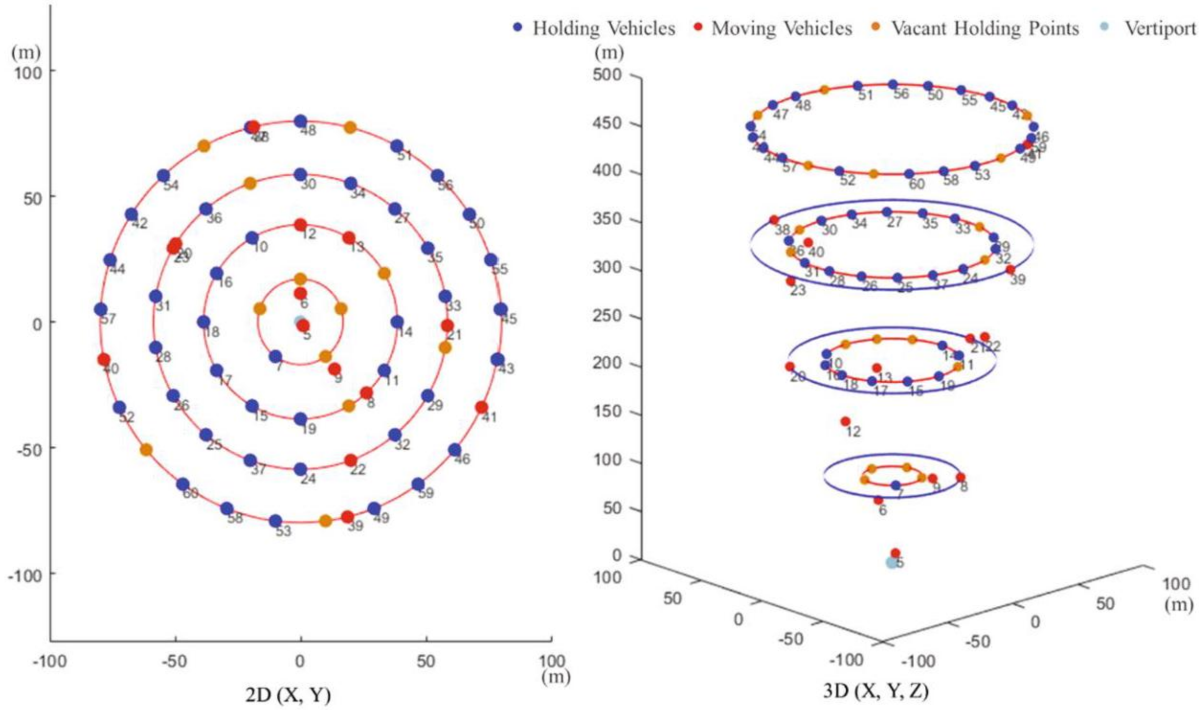


Fig. 12. A sample of SBAM model application.
图 12。SBAM 模型应用示例。

Travel time within a moving circle of the vehicle can be expressed as Eq. (19) using the radius of the moving circle (r_2) and the cruise speed of approach (S_c) . Moreover, the moving angle (θ_t) in the moving circle after t second of the start point can be expressed as Eq. (20) and the trajectory of the vehicle can be expressed as Eq. (21) using θ_t .

车辆在移动圆内的行驶时间可以表示为使用移动圆的半径 (r_2) 和接近巡航速度 (S_c) 的公式 (19)。此外，从起点开始 t 秒后的移动圆中的移动角度 (θ_t) 可以表示为公式 (20)，车辆的轨迹可以表示为使用 θ_t 的公式 (21)。

$$\text{Movingcircle Travel Time } (MTT) = \frac{r_2\theta}{S_c} \tag{19}$$

$$\theta_t = \frac{\theta}{MTT} \times \left(t - \frac{Z_s - Z_f}{S_v}\right) \tag{20}$$

$T_{i,t} = (\cos\theta_t \cdot X_s - \sin\theta_t \cdot Y_s, \sin\theta_t \cdot X_s + \cos\theta_t \cdot Y_s, Z_f)$ (21)

The third step is creating the trajectory of a straight-line for the vehicle that finishes the movement of the moving circle to enter the holding circle. This straight section’s travel time is given by Eq. (22) and the traffic time after t second of the vehicle from the start point is equal to Eq. (23).

第三步是为车辆创建一条直线轨迹，以完成移动圆的运动并进入保持圆。这一直线段的行驶时间由公式 (22) 给出，车辆从起点开始 t 秒后的交通时间等于公式 (23)。

$$\text{EntrysectionTravelTime } (ETT) = \frac{r_2 - r_1}{S_c} \tag{22}$$

$$T_{i,t} = \left(X_m + \frac{X_f - X_m}{(ETT)} \times \left(t - \frac{Z_s - Z_f}{S_v} - \frac{r_2\theta}{S_c}\right), Y_m + \frac{Y_f - Y_m}{(ETT)} \times \left(t - \frac{Z_s - Z_f}{S_v} - \frac{r_2\theta}{S_c}\right), Z_f\right) \tag{23}$$

From Eqs. (12), (20), (21), (22), and (23), the vehicle trajectory in SBAM is derived as follows, and different trajectories are generated according to the range of t . Fig. 12 shows an example of the approach control applying the SBAM model.

由公式 (12)、(20)、(21)、(22) 和 (23) 可得，SBAM 中车辆轨迹推导如下，根据 t 的范围生成不同的轨迹。图 12 展示了应用 SBAM 模型的接近控制示例。

$$
T_{i,t} \begin{cases}
\left(X_s, Y_s, Z_s - S_v + t\right), t \text{ if } \frac{2Z_s - Z_f}{S_v} \\
\Big(\cos \frac{\theta}{Z_s \theta} \times \Big(t - \frac{Z_s - Z_f}{S_v}\Big) \cdot X_s - \sin \frac{\theta}{Z_s \theta} \times \Big(t - \frac{Z_s - Z_f}{S_s}\Big) \cdot Y_s, \Big) \\
\sin \frac{\theta}{Z_s} \times \Big(t - \frac{Z_s - Z_f}{S_s} \cdot X_s + \cos \frac{\theta}{Z_f \theta} \times \Big(t - \frac{Z_s - Z_f}{S_s}\Big) \cdot Y_s, Z_f\Big) \\
\frac{t Z_s - Z_f}{S_s} = t \leq \frac{X_s}{S_s} + \frac{Z_f \theta}{S_f}, \\
\Big(X_m + \frac{Y_g - X_m}{S_s} \times \Big(t - \frac{Z_s - Z_f}{S_s} - \frac{Z_f \theta}{S_f}\Big), Y_m + \Big(t - \frac{Z_s - Z_f}{S_s} - \frac{Z_f \theta}{S_c}\Big), Y_f = Y_m \times \Big(t - \frac{Z_s - Z_f}{S_s} - \frac{Z_f}{S}
\\
(X_s - X_f) = X_s \times \Big(t - \frac{Z_s - Z_f}{S_s} \times \Big(t - \frac{Z_s - Z_f}{S_s} + t - 1\Big), t < \frac{Z_s - Z_f}{S_s} - \frac{Z_f \theta}{S_c}\Big), \\
(X_s - X_f) = X_f \times \Big(t - \frac{Z_s - Z_f}{S_s} \times \Big(t - \frac{Z_s - Z_f}{S_s} + t - 1\Big), t < \frac{Z_s - Z_f}{S_s} \times \Big(t - \frac{Z_s - Z_f}{S_s} + t - 1\Big), t < \frac{Z_s - Z_f}{S_s} \times \Big(t - \frac{Z_s - Z_f}{S_s}
\end{cases} \tag{24}
$$

4. Empirical results

4. 实证结果

A series of simulation experiments are performed to compare the effects of three approach controls proposed above (BQA, SBA and SBAM) in terms of the OTP and airspace safety. One hundred sets of flight data with different flight schedules and scenarios are generated, and a total of 600 simulations are conducted by applying the three models and two scheduling strategies. Then, the derived 36,000 vehicle flight data is analyzed.

进行了一系列仿真实验，以比较上述三种接近控制方法 (BQA、SBA 和 SBAM) 在 OTP 和空域安全方面的效果。生成了具有不同飞行计划和场景的 100 组飞行数据，并应用三种模型和两种调度策略进行了总共 600 次仿真。然后，分析了得出的 36,000 条车辆飞行数据。

4.1. On-Time performance (OTP)

4.1. 准点率 (OTP)

Punctuality is a critical factor in UAM and commercial airlines, so unnecessary ground time in the vertiport must be reduced in UAM as the vertiport is operated in a limited space. When operated by air taxi, more importance is imposed on the arrival punctuality because the connection with other transportation means is important. In this respect, we compared the delay time and the OTP results.

准时性是城市空中出行 (UAM) 和商业航空的关键因素，因此在 UAM 中，必须减少在立体港口的不必要地面时间，因为立体港口是在有限空间内运营的。当由空中出租车运营时，对到达准时性的要求更高，因为与其他交通工具的连接非常重要。在这方面，我们比较了延误时间和准点率 (OTP) 的结果。

Fig. 13 shows a histogram of time delay for each model for 36,000 vehicles obtained through simulation. Here, the delay time is calculated as the difference between the actual time of arrival (ATA) and the scheduled time of arrival (STA), and a negative value means early arrival. The difference in the distribution of time delay for each model is not significant; however, for all three models, the time delay is distributed closer to 0 for using GA-based scheduling compared to FCFS, which does not use the scheduling strategy. This means that the scheduling strategy that minimizes the deviation of STA and ATA is implemented in all three models.

图 13 显示了通过模拟得到的 36,000 辆车的每个模型的时延柱状图。这里的延误时间是指实际到达时间 (ATA) 与计划到达时间 (STA) 之间的差异，负值表示提前到达。每个模型的时延分布差异不大；然而，对于所有三个模型，使用基于遗传算法 (GA) 的调度方法相比先来先服务 (FCFS) 方法 (不使用调度策略) 的时延分布更接近 0。这意味着在所有三个模型中都实施了最小化 STA 和 ATA 偏差的调度策略。

Similar results are shown in the OTP plot of Fig. 14. The OTP of the SBA model is 80.2% for FCFS and 85.9% for GA-based scheduling, which is the best of the three models; however, the difference is negligible. Nevertheless, the OTP for the scheduling strategy is better in all three models compared to FCFS.

图 14 的 OTP 曲线显示了类似的结果。SBA 模型的 OTP 在 FCFS 时为 80.2% ，在基于 GA 的调度时为 85.9% ，这是三个模型中最好的；然而，差异可以忽略不计。尽管如此，与 FCFS 相比，所有三个模型的调度策略的 OTP 都更好。

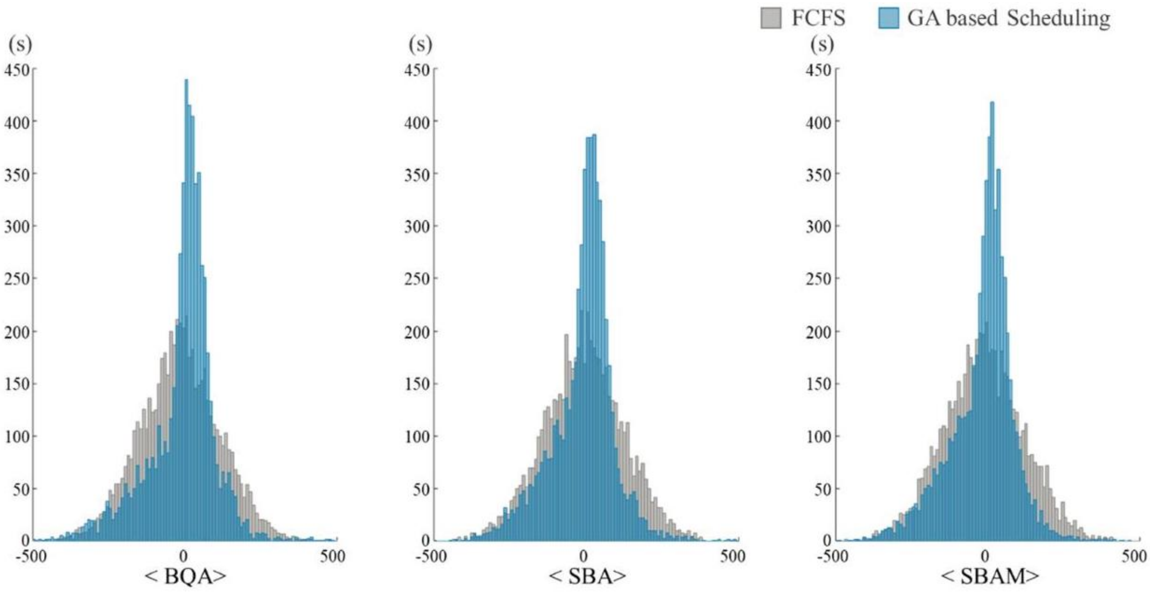


Fig. 13. Empirical results: Delay time.

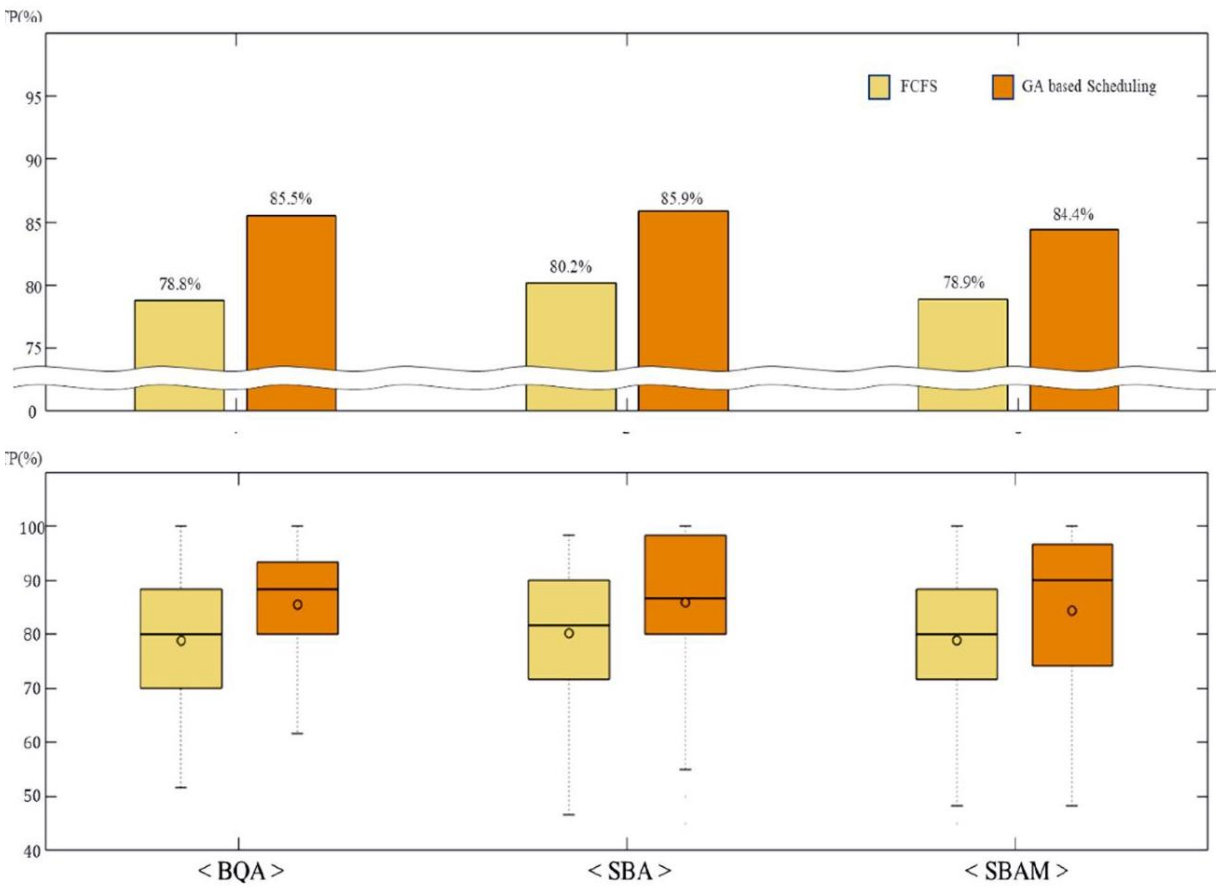


Fig. 14. Empirical results : OTP.

4.2. Loss of separation (LOS)

4.2. 分离损失 (LOS)

LOS concept is used to compare the airspace safety of the three models. LOS indicates that the distance between two aircraft is not secured by the minimum safety distance (Anthony and Cesar, 2020). The FAA's air traffic organization (ATO) refers to an operational error (OE) when LOS occurs because of an air traffic control error. As shown in Fig. 15, it is classified into four risk levels as per the ratio of the distance between the two aircraft to the minimum safety distance (Bailey, 2012). Table 2 shows the status and rate of occurrence

LOS 概念用于比较三种模型的空域安全性。LOS 表示两架飞机之间的距离未由最小安全距离保证 (Anthony 和 Cesar，2020 年)。当由于空中交通管制错误导致 LOS 发生时，美国联邦航空管理局 (FAA) 的空中交通组织 (ATO) 将之称作操作错误 (OE)。如图 15 所示，根据两架飞机之间的距离与最小安全距离的比例，将其分为四个风险等级 (Bailey，2012 年)。表 2 显示了状态和发生率。

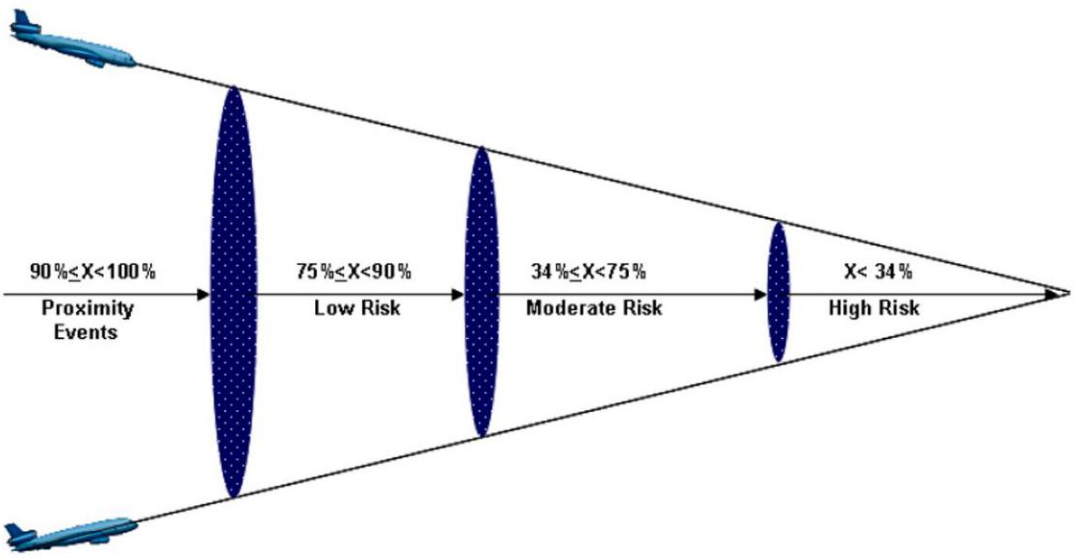


Fig. 15. Operational error severity defined by separation conformance remaining. (Bailey, 2012).
图 15. 通过剩余分离符合度定义的操作错误严重性 (Bailey，2012 年)。

Table 2
表 2
Number of OE occurrences for each model.
每个模型中 OE 发生次数。

OE Severity	BQA FCFS	GA	SBA FCFS	GA	SBAM FCFS	GA
Proximity Events (PE)	-	-	3,139 (1.77%)	3,152 (1.78%)	69 (0.04%)	64 (0.04%)
Low Risk (LR)	-	-	2,234 (1.26%)	2,093 (1.18%)	8 (0.21%)	369 (0.21%)
Moderate Risk (MR)	-	-	-	-	1,151 (0.65%)	1,142 (0.65%)
High Risk (HR)	-	-	-	-	983 (0.56%)	835 (0.47%)
OE Total	-	-	5,373 (3.04%)	5,245 (2.96%)	2,581	2,410
					(1.46%)	(1.36%)

OE 严重性	BQA 先来先服务 (FCFS)	遗传算法 (GA)	SBA 先来先服务 (FCFS)	遗传算法 (GA)	SBAM 先来先服务 (FCFS)	遗传算法 (GA)
接近事件 (PE)	-	-	3,139 (1.77%)	3,152 (1.78%)	69 (0.04%)	64 (0.04%)
低风险 (LR)	-	-	2,234 (1.26%)	2,093 (1.18%)	8 (0.21%)	369 (0.21%)
中风险 (MR)	-	-	-	-	1,151 (0.65%)	1,142 (0.65%)
高风险 (HR)	-	-	-	-	983 (0.56%)	835 (0.47%)
OE 总计	-	-	5,373 (3.04%)	5,245 (2.96%)	2,581	2,410
					(1.46%)	(1.36%)

of each OE risk stage by model. BQA is found to be the safest model. OE does not occur in both FCFS and GA methods because BQA moves only via a predetermined route with a minimum safety distance through the concept of a branch from the airspace design. Moderate risk (MR) and high risk (HR) does not occur in SBA, but proximity events (PE) and low risk (LR) occur at approximately 1.8%

and 1.2%, respectively, during the entire flight in both FCFS and GA. For SBA, a significant number of OEs occurs in the process of diagonally descending in search of an empty holding point. However, SBAM has fewer PE and LR, but more MR and HR. Unlike SBA, SBAM descends vertically rather than diagonally; therefore, it is clearly separated during descent. The same PE and LR that occur in SBA are small; however, both MR and HR are confirmed to occur in the process of turning the moving circle.

每个 OE 风险阶段的模型数量。BQA 模型被认为是安全性最高的模型。在 FCFS 和 GA 方法中不会发生 OE，因为 BQA 仅通过预定的路线移动，通过从空域设计中分支的概念保持最小安全距离。在 SBA 中不会发生中等风险 (MR) 和高风险 (HR)，但在整个飞行过程中，FCFS 和 GA 的接近事件 (PE) 和低风险 (LR) 分别大约发生 1.8% 和 1.2%。对于 SBA，在寻找空余等待点的对角下降过程中发生了大量的 OE。然而，SBAM 的 PE 和 LR 较少，但 MR 和 HR 更多。与 SBA 不同，SBAM 是垂直下降而不是对角下降；因此在下降过程中明显分离。在 SBA 中发生的相同 PE 和 LR 较小；然而，在移动圆的转弯过程中确认发生了 MR 和 HR。

5. Discussion

5. 讨论

This study presents three different strategies to identify the optimal UAM approach control model and analyze the OTP and LOS risk of each model through simulation. In terms of the OTP, the SBA model using the GA based scheduling strategy is the best with 85.9%. However, this model’s OE incidence rate is highest at 2.96%, as shown in Table 2. Considering severity, the SBAM model can be said to be the model with the greatest risk with many MR and HR even if the total occurrence of OE is small.

本研究提出了三种不同的策略来识别最优的 UAM 方法控制模型，并通过仿真分析了每种模型的 OTP 和 LOS 风险。在 OTP 方面，采用基于遗传算法调度策略的 SBA 模型表现最佳，达到 85.9%。然而，如表 2 所示，该模型的 OE 发生率最高，为 2.96%。考虑到严重性，尽管 OE 的总发生次数较少，SBAM 模型由于存在许多 MR 和 HR，可以认为是最高风险的模型。

Therefore, when the mobility of airspace vehicle is not limited such as in SBA and SBAM, additional supplementary measures such as the airborne collision avoidance system (ACAS) are required for individual vehicles to perform collision avoidance. However, if ATC with collision avoidance is implemented, the OTP will be worse than the current simulation result. Nevertheless, BQA, in which OE does not occur, is the best model in terms of airspace safety. In the aspect that UAM primarily targets urban areas, stringent safety standards need to be applied, and BQA can improve its safety by minimizing unnecessary movement in vertiport airspace by applying the feature that the hovering of VTOL aircraft to be used for UAM is possible. Despite having such an excellent safety feature, the OTP of the BQA model is 85.5% , which is superior to SBAM. The results are outstanding in terms of the OTP; therefore, it is difficult to say that it is significantly worse than 85.9% of SBA. BQA is a strategy to maximize the airspace’s safety, although there are certain restrictions in terms of sequence control; however, sequence control is well performed without significant difference in the OTP from SBA and SBAM, both of which are focused on sequence control. Therefore, the BQA model that shows an appropriate level of the OTP performance without any LOS risk is the most suitable approach control model for UAM. In terms of passenger comport, the BQA model, which minimizes route change, is more appropriate than the SBAM model that generates unnecessary vertical and horizontal movement.

因此，当空域车辆的移动性不受限制，如 SBA 和 SBAM 中时，需要为单个车辆执行避障的额外补充措施，例如机载避撞系统 (ACAS)。然而，如果实施了具有避撞功能的空中交通管制 (ATC)，OTP 将会比当前的模拟结果更差。尽管如此，在空域安全性方面，不发生操作错误的 BQA 模型是最好的。在 UAM 主要针对城市区域这一方面，需要应用严格的安全标准，BQA 可以通过应用 VTOL 飞机悬停的特点，最小化机场空域中不必要的移动来提高安全性。尽管具有这样的优秀安全特性，BQA 模型的 OTP 为 85.5% ，这优于 SBAM。在 OTP 方面，结果非常出色；因此，很难说它比 SBA 的 85.9% 差得多。BQA 是一种最大化空域安全性的策略，虽然在序列控制方面有一定的限制；然而，序列控制执行得很好，OTP 与 SBA 和 SBAM 相比没有显著差异，这两种模型都侧重于序列控制。因此，显示适当水平的 OTP 性能且没有任何 LOS 风险的 BQA 模型是最适合 UAM 的进近控制模型。在乘客舒适度方面，最小化航线变更的 BQA 模型比产生不必要垂直和水平移动的 SBAM 模型更合适。

Furthermore, additional studies are required to supplement the limitations of this study. In this study, the separation interval and aircraft’s speed are equally applied by assuming a small VTOL suitable for air taxi operation; however, in an actual vertiport operation, air taxi and air metro are mixed; therefore, it is necessary to consider the heterogeneous fleet situation. Moreover, this study assumes a congested vertiport airspace, but various situations shall be further considered such as low traffic volume. In the future, we plan to conduct a follow-up study on how to control the sequence more flexibly in the BQA model.

此外，需要额外的研究来补充本研究的局限性。在本研究中，分离间隔和飞机速度假设适用于空中出租车运营的小型垂直起降 (VTOL) 飞机，均匀应用；然而，在实际的垂直起降机场运营中，空中出租车和空中地铁是混合使用的；因此，需要考虑异质机队的情况。此外，本研究假设了拥堵的垂直起降机场空域，但还应进一步考虑其他情况，如低交通量。未来，我们计划进行后续研究，探讨如何在 BQA 模型中更灵活地控制序列。

6. Conclusion

6. 结论

In this study, an approach control model in terms of ATC, which is essential for successful UAM operation, is presented. In the approach control, the primary issue is to select the sequence of the arriving aircraft and to present the trajectory of the selected aircraft. Optimal scheduling suitable for UAM improves the OTP by reducing the STA and ATA deviation, and the strategy is selected to minimize the GT of the vehicle staying in the vertiport. Unlike airports, the vertiport utilizes limited space, which inevitably limits the space in which vehicles can stand as UAM is a concept applied in the center of the city. Therefore, in UAM, even if the HT increases, the scheduling strategy of landing close to the STA while waiting in the air seems to be a more suitable method. In this study, three different approach control models are presented, and the contents of the framework and trajectory generation for each model are described. Simulation experiments are conducted on the presented model, and OTP and LOS risk are compared. It is found that SBA shows the best results in terms of OTP; however, its difference from BQA is minimal. Furthermore, the SBAM model showed the worst OTP results, and LOS risk demonstrated the most inefficient result because of the occurrence of many MR and HR. However, BQA showed excellent results in both the OTP and LOS risk areas, thus confirming that it is the most suitable approach control model for

在本研究中，提出了一个关于空中交通管制 (ATC) 的进近控制模型，这对于城市空中交通 (UAM) 的成功运行至关重要。在进近控制中，主要问题是选择到达飞机的顺序，并确定选定飞机的轨迹。适用于 UAM 的最优调度可以减少预计起飞时间 (STA) 和实际起飞时间 (ATA) 的偏差，从而提高航班正点率 (OTP)，并选择策略以最小化车辆在垂直机场的停留时间 (GT)。与机场不同，垂直机场使用有限的空间，这不可避免地限制了车辆可以停放的空间，因为 UAM 是应用于城市中心的概念。因此，在 UAM 中，即使等待时间 (HT) 增加，看起来在空中等待接近 STA 的着陆调度策略似乎更为合适。在本研究中，提出了三种不同的进近控制模型，并描述了每种模型的框架和轨迹生成内容。对提出的模型进行了仿真实验，并比较了 OTP 和低空飞行风险 (LOS 风险)。发现 SBA 在 OTP 方面表现最佳；然而，其与 BQA 的差异很小。此外，SBAM 模型显示出最差的 OTP 结果，而 LOS 风险由于许多中等风险 (MR) 和高度风险 (HR) 事件的发生，显示出最无效的结果。但是，BQA 在 OTP 和 LOS 风险方面都表现出色，从而证实它是最适合的进近控制模型。UAM.

Declaration of Competing Interest

竞争利益声明

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.

作者声明，他们没有已知的可能影响本文报告工作的财务利益或个人关系。

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