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

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ABSTRACT

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.

1. Introduction

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,

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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 aircraft$i$
GT_i	ground time of VTOL aircraft$i$
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 aircraft$i$
S_v	vertical speed of approach
STA_i	scheduled time of arrival of VTOL aircraft$i$
STD_i	scheduled time of departure of VTOL aircraft$i$
t	current time
W_i	early operation weight

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.

1.1. Related work and research motivation

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.

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).

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.

1.2. Contributions and outline of the paper

This study contributes to the research literature as follows:

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.
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.
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.

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.

2. Optimal sequence of arrival flights

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

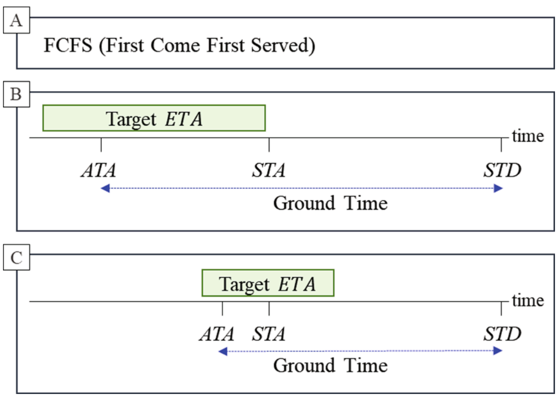

Fig. 1. Scheduling strategy.

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.

2.1. Scheduling strategy and problem statement

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.

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:

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

where ΔL is the minimum landing separation time, 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:

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

where W_i is early operation weight.

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

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

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.

$$W_i = \begin{cases} \alpha, ifVTOLaircraftarriveearlierthantheschedule(AETA_i \le STA_i) \\ 1-\alpha, otherwise(AETA_i > STA_i) \end{cases}, \tag{4}$$

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.

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:

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

2.2. Methodology

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.

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.

2.3. Comparison of scheduling strategies

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.

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:

$$GT_i = ETD_i - ATA_i$$

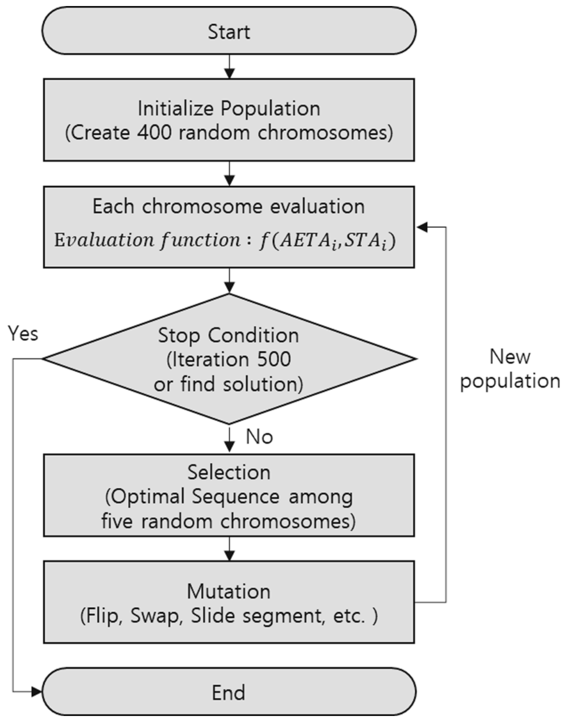

Fig. 2. Flow chart of the GA for arrival sequence.

Table 1
Data generation criteria.

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

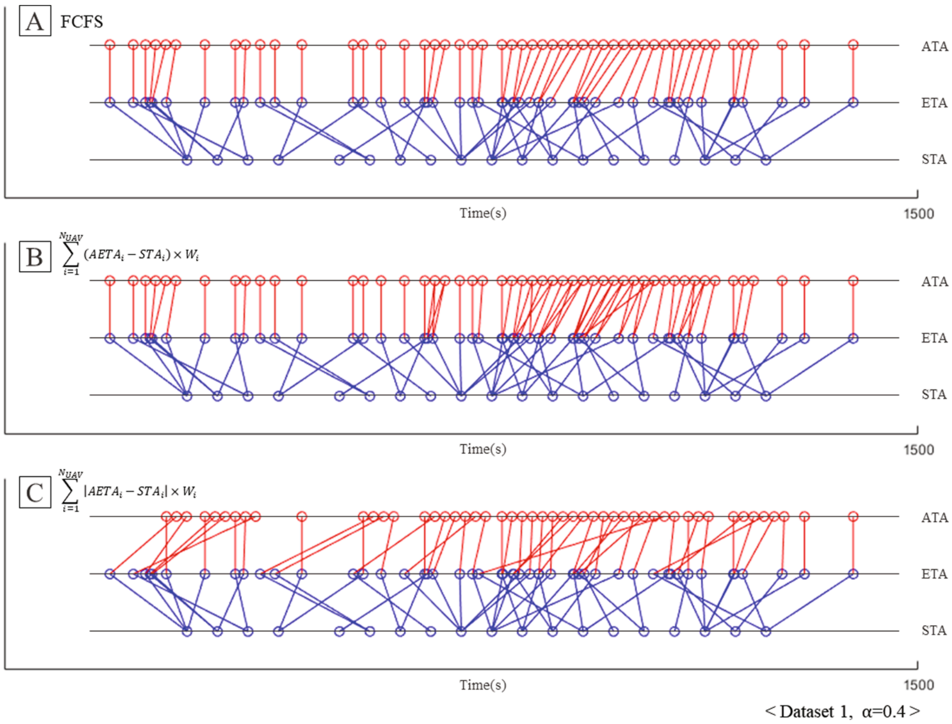

Fig. 3. Scheduling results of three strategies for Dataset 1.

where,

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

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

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.

2.4. Impact of changing early operation weight (W_i)

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

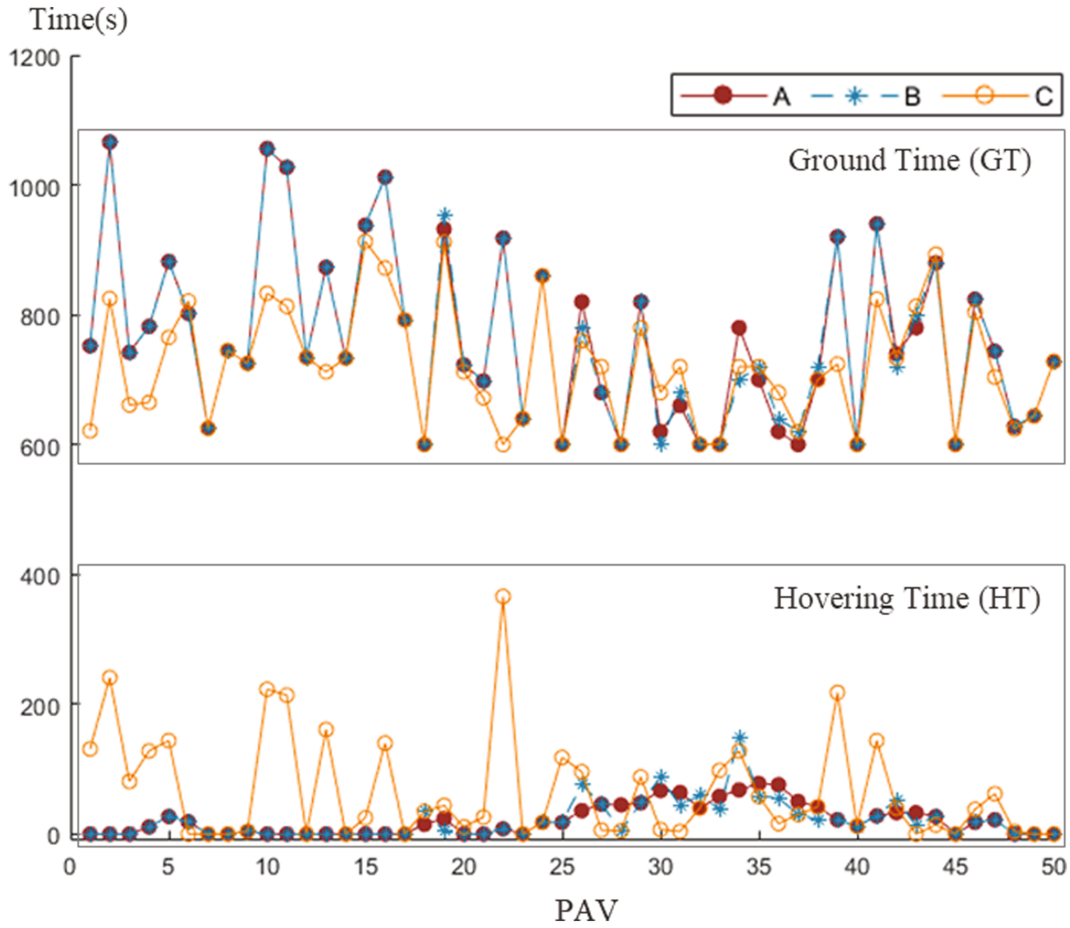

Fig. 4. Ground time (GT), hovering time (HT) for Dataset 1.

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:

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

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

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

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.

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.

3. Vertiport approach control model

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

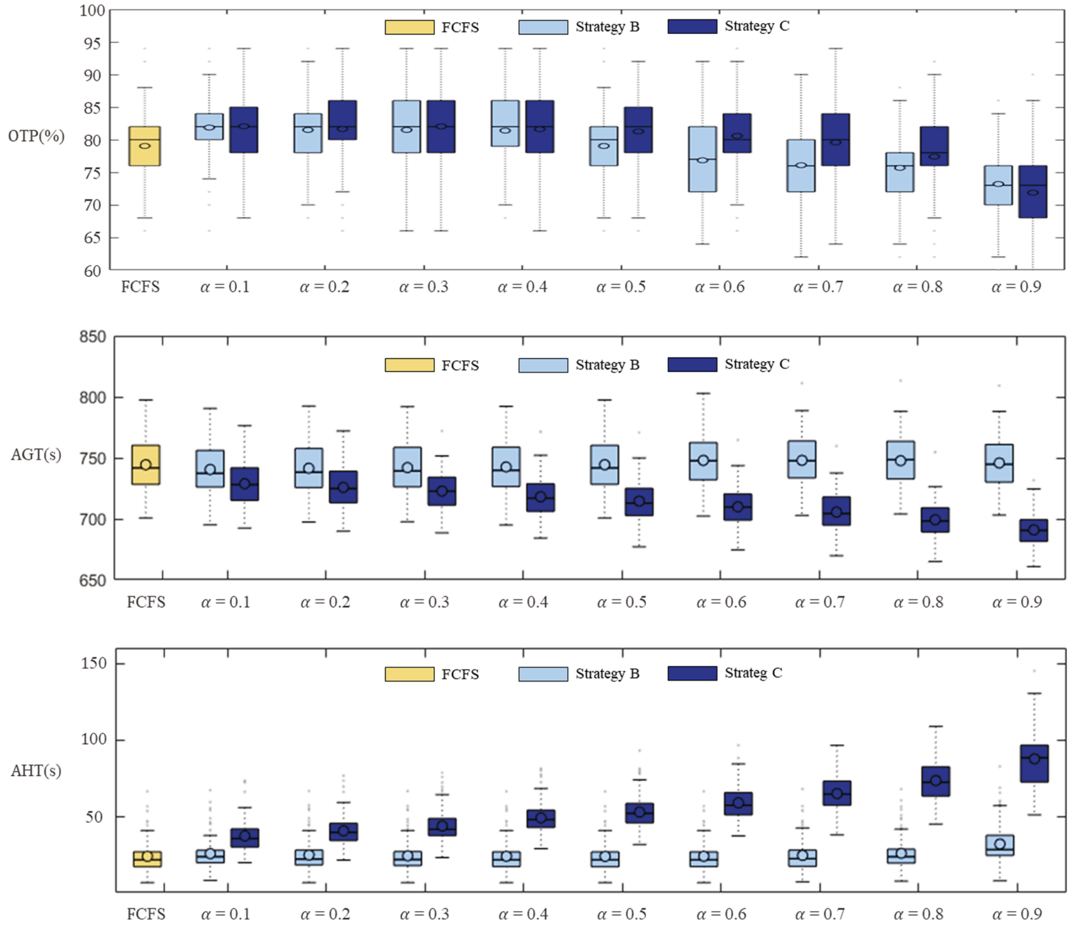

Fig. 5. OTP, AGT and AHT comparison by scheduling strategies.

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

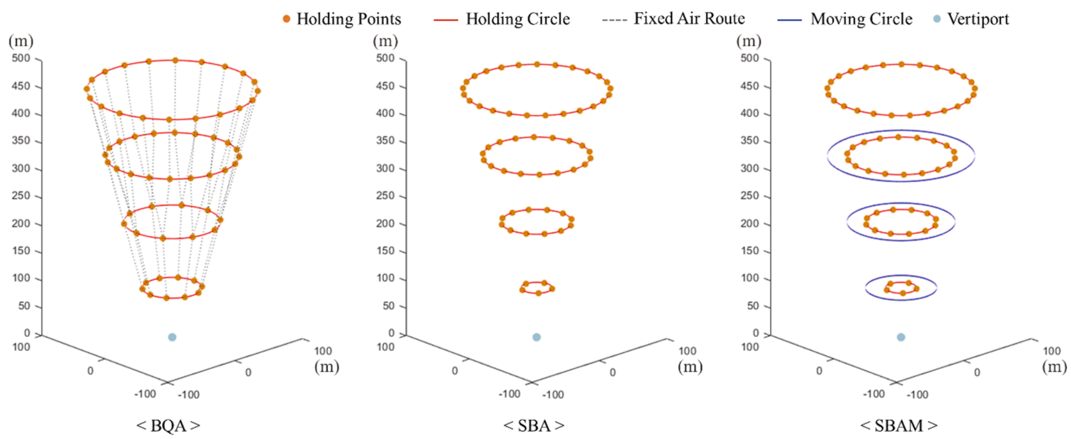

Fig. 6. Three proposed vertiport approach control concepts.

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.

3.1. Branch queuing approach (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.

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 ~ 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.

3.2. Sequence-Based approach (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.

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

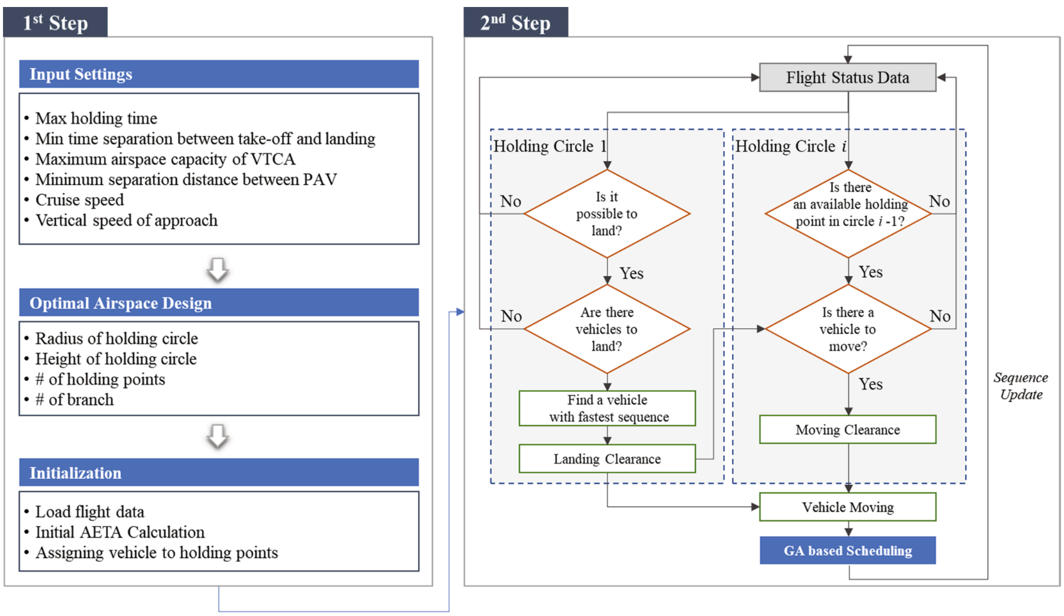

Fig. 7. The framework of BQA model.

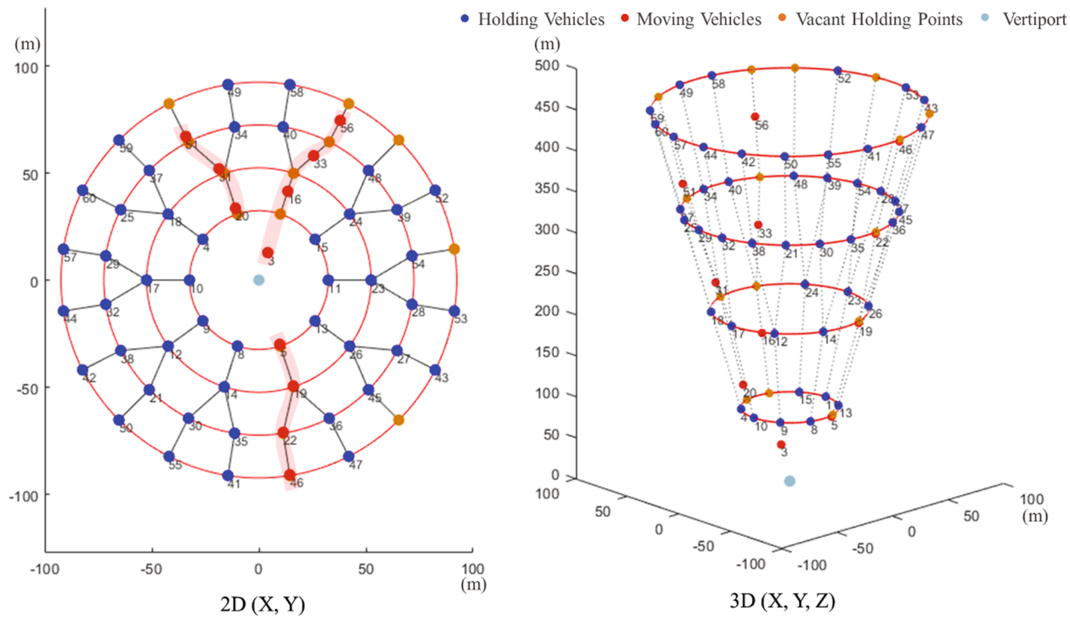

Fig. 8. A sample of BQA model application.

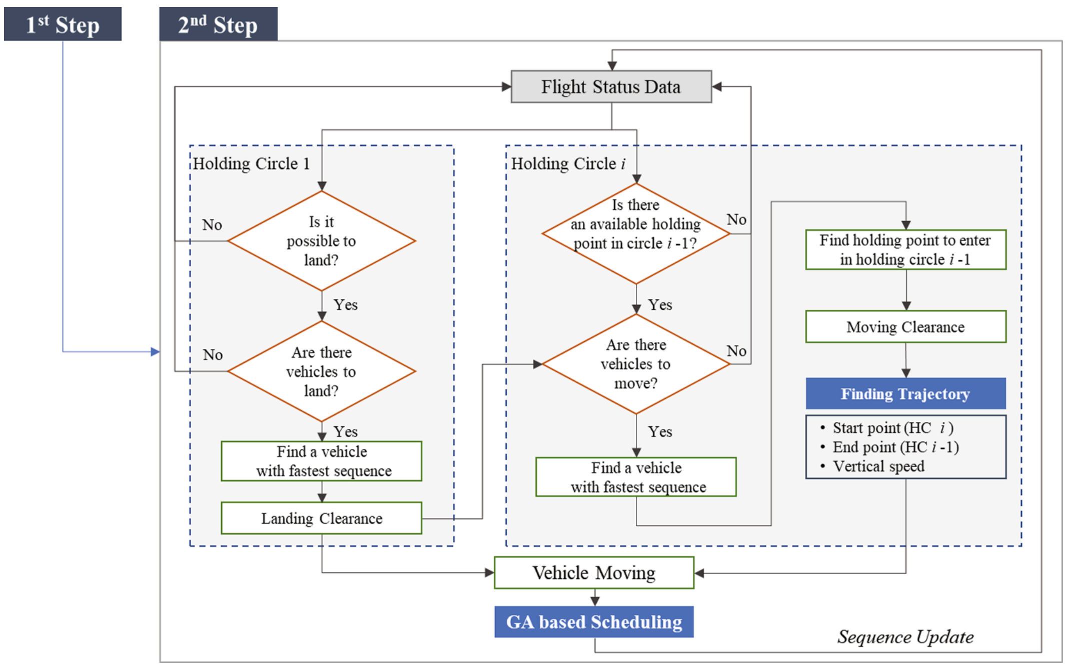

Fig. 9. The framework of SBA model.

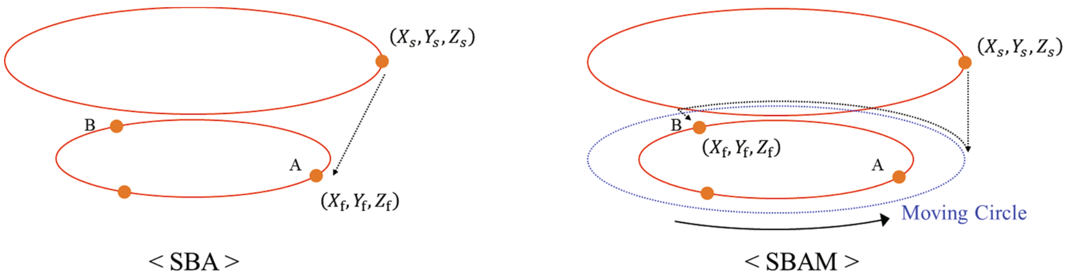

Fig. 10. Trajectory difference between SBA and SBAM.

point.

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:

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

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.

3.3. Sequence-based approach with moving circles (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.

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

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).

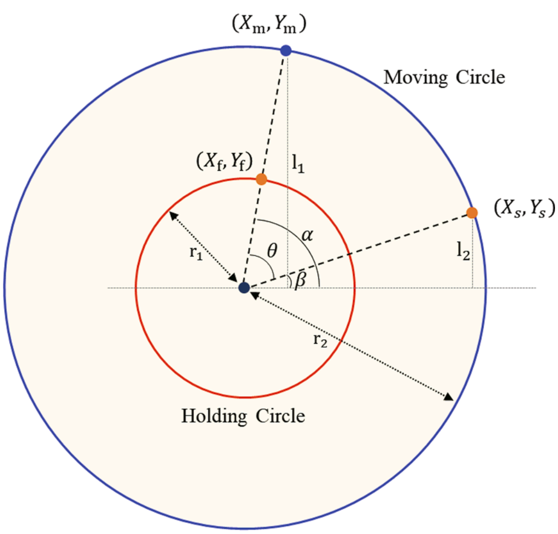

Fig. 11. SBAM trajectory calculation.

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

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.

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

$$\begin{aligned}\sin\theta &= \sin(\alpha - \beta)\\ &= \sin\alpha\cos\beta - \cos\alpha\sin\beta\\ &= \frac{Y_m}{l_1}\bullet\frac{X_s}{l_2} - \frac{X_m}{l_1}\bullet\frac{Y_s}{l_2}\\ &= \frac{1}{l_1 \bullet l_2}(Y_m \bullet X_s - X_m \bullet Y_s)\end{aligned} \tag{15}$$

$$\begin{aligned}\cos\theta &= \cos(\alpha - \beta)\\ &= \cos\alpha\cos\beta - \sin\alpha\sin\beta\\ &= \frac{X_m}{l_1}\bullet\frac{X_s}{l_2} - \frac{Y_m}{l_1}\bullet\frac{Y_s}{l_2}\\ &= \frac{1}{l_1 \bullet l_2}(X_m \bullet X_s - Y_m \bullet Y_s)\end{aligned} \tag{16}$$

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.

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

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

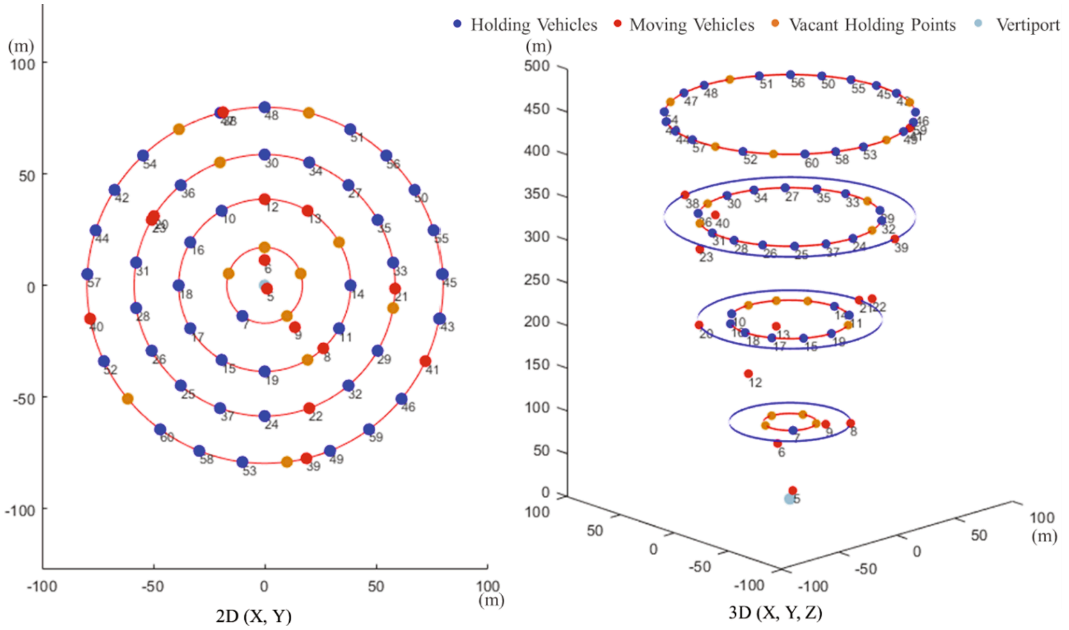

Fig. 12. A sample of SBAM model application.

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.

$$MovingcircleTravelTime(MTT) = \frac{r_2\theta}{S_c} \tag{19}$$

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

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

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

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

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.

$$T_{i,t}\begin{cases} (X_s, Y_s, Z_s - S_v \times t), if t \leq \frac{Z_s - Z_f}{S_v} \\ (cos\frac{\theta}{\frac{r_2\theta}{S_c}} \times \left(t - \frac{Z_s - Z_f}{S_v}\right) \bullet X_s - sin\frac{\theta}{\frac{r_2\theta}{S_c}} \times \left(t - \frac{Z_s - Z_f}{S_v}\right) \bullet Y_s, \\ sin\frac{\theta}{\frac{r_2\theta}{S_c}} \times (t - \frac{Z_s - Z_f}{S_v}) \bullet X_s + cos\frac{\theta}{\frac{r_2\theta}{S_c}} \times (t - \frac{Z_s - Z_f}{S_v}) \bullet Y_s,\ Z_f) \\ if \frac{Z_s - Z_f}{S_v} \leq t \leq \frac{Z_s - Z_f}{S_v} + \frac{r_2\theta}{S_c} \\ (X_m + \frac{X_f - X_m}{\left(\frac{r_2 - r_1}{S_c}\right)} \times (t - \frac{Z_s - Z_f}{S_v} - \frac{r_2\theta}{S_c}), Y_m + \frac{Y_f - Y_m}{\left(\frac{r_2 - r_1}{S_c}\right)} \times (t - \frac{Z_s - Z_f}{S_v} - \frac{r_2\theta}{S_c}), Z_f \\ if \frac{Z_s - Z_f}{S_v} + \frac{r_2\theta}{S_c} \leq \end{cases} \tag{24}$$

4. Empirical results

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.

4.1. On-Time performance (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.

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.

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.

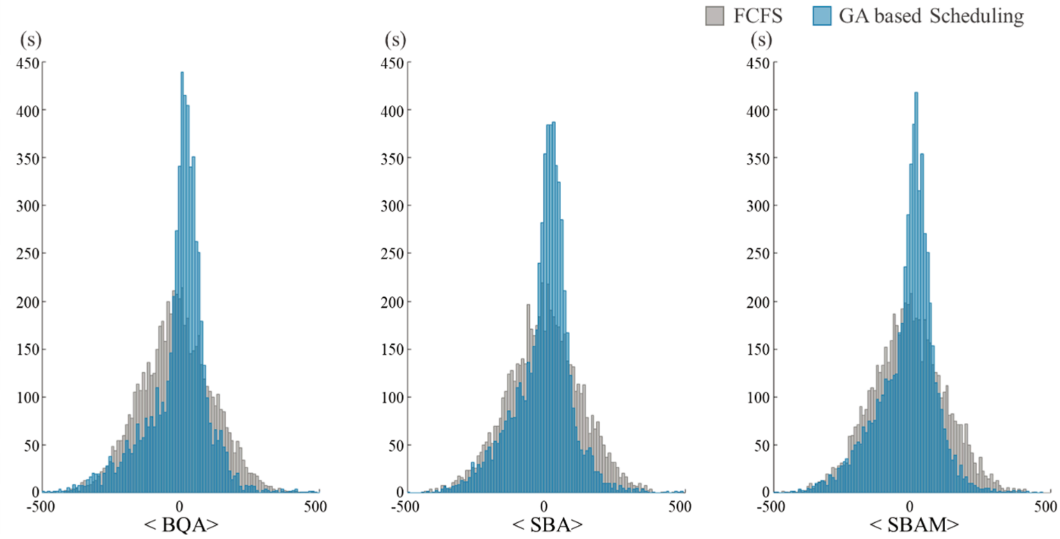

Fig. 13. Empirical results: Delay time.

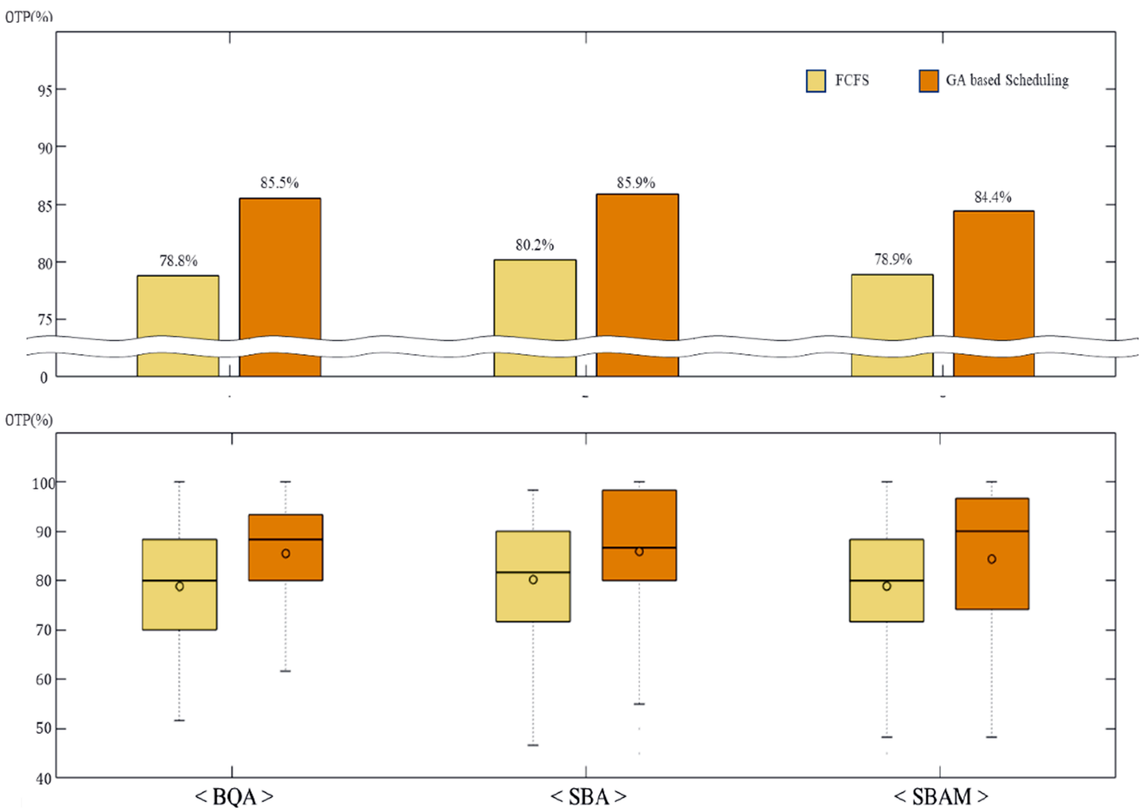

Fig. 14. Empirical results : OTP.

4.2. *Loss of separation (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

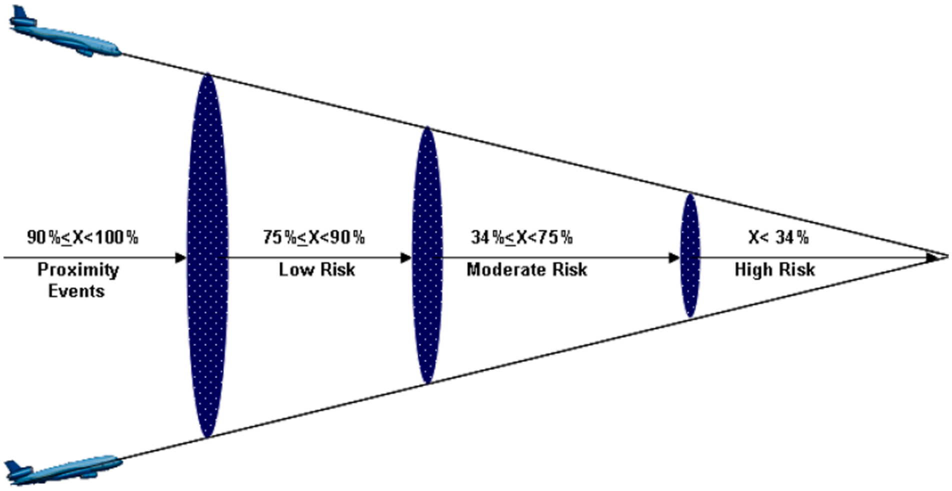

Fig. 15. Operational error severity defined by separation conformance remaining. (Bailey, 2012).

Table 2
Number of OE occurrences for each model.

OE Severity	BQA		SBA		SBAM	
	FCFS	GA	FCFS	GA	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 (1.46%)	2,410 (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.

5. Discussion

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.

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.

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.

6. Conclusion

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 UAM.

Declaration of Competing Interest

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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