



DEMAND CAPACITY BALANCING FOR URBAN AIR MOBILITY USING MULTIAGENT SIMULATION

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Abstract

Urban air mobility (UAM) is a new concept of air transportation, and discussions to make its operation safe and efficient are ongoing. Because UAM is primarily battery-powered, flight time is limited, and it is difficult to remain airborne when congestion occurs. Therefore, planning flights to avoid congestion is crucial in urban air traffic management (UATM). Demand capacity balancing (DCB) is a method that predicts future air traffic demand and coordinates flights such that the capacity is not exceeded. While DCB is centrally controlled for existing aircraft, UAM can be managed by regional UATM (RUATM) because UATM must be scalable to deal with a rapidly increasing number of UAMs. This study proposes a distributed DCB for UAM that functions in multiple RUATM environments. Two algorithms, cooperative DCB with information sharing among RUATMs and noncooperative DCB without information sharing, are prepared to investigate how information sharing affects DCB performance. Simulations showed that cooperative DCB performs better; however, excessive information exchange among RUATMs can negatively affect the scalability of the entire UATM system. The performance of the noncooperative DCB was improved using the expanded capacity; however, the DCB violations increased, revealing a trade-off relationship. The RUATM and distributed DCB concepts proposed in this paper can serve as benchmarks and fundamental technologies for future distributed DCB development.

Keywords: Urban Air Mobility, Demand Capacity Balancing, Urban Air Traffic Management, Air Traffic Flow Management

1. Introduction

Urban air mobility (UAM) is expected to become the new type of air transportation for passengers and cargo. Most recently, limited passenger transportation via UAM will be implemented for the 2024 Paris Olympics and the 2025 Osaka World Expo. In the early stages of UAM, methods and procedures of UAM operation are expected to follow the current air traffic management (ATM) operating environment requirements. However, as the UAM industry matures, the current ATM systems must be upgraded as the density of UAM operations increases, automation/autonomy increases and airspace users become more diverse. Thus, a new urban air traffic management (UATM) for UAM must be developed. As UAM traffic density increases, congestion is expected to occur, particularly around vertiports, which are take-off/landing places specialized for UAM. If congestion occurs around vertiports, arrival UAM may be held. Because UAM is an electric vertical take-off and landing (eVTOL) aircraft, the flight range and flight time are smaller than those of existing aircraft owing to battery capacity. The time available to hold UAM airborne is significantly limited. Furthermore, if the aircraft is operated without considering the vertiport capacity, UAM is forced to hold excessively, which may result in an emergency landing. Demand capacity balancing (DCB) is important for UAM operations to anticipate future congestion before each aircraft's departure and delay the departure time (hereinafter referred to as the ground delay).

In existing ATM, this role is performed by air traffic flow management (ATFM). ATFM is in charge of early-stage air traffic control (ATC) to protect the airspace from overloading and balance traffic

demand with airspace capacity. An illustration of DCB is presented in Figure 1. In Japan, ATFM is supported by a monolithic traffic management system throughout the Fukuoka Flight Information Region [1].

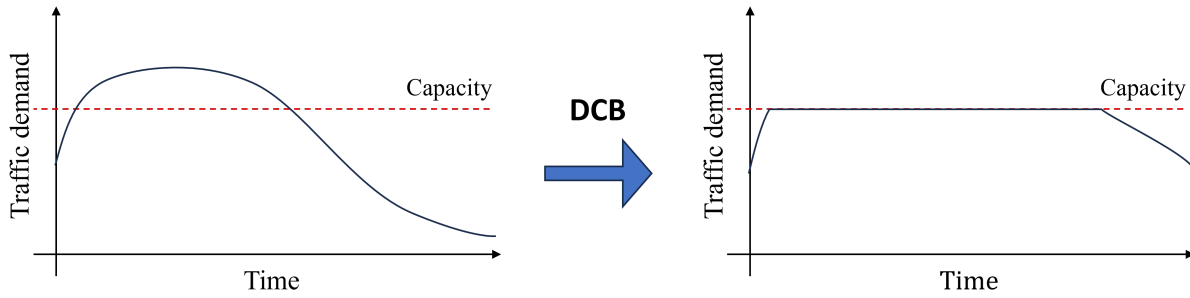


Figure 1 – Role of the DCB.

By contrast, UAM traffic can be managed in a distributed system. UAM flights are expected to increase in the future, and a scalable distributed system is preferred over a monolithic system with less flexibility. In addition, because UAM flights have a shorter range than existing aircraft, distant flights do not affect each other, and there is no requirement to manage using the same system. According to the Japanese concept of operations for UAM [2], the airspace served by the UATM services is defined as the UATM service area (UASA). In this study, it is assumed that each UASA has its own UATM. This UATM is defined as the regional UATM (RUATM). Each UASA can have several vertiports, and many flights can be considered to be completed within one UASA. However, areas that more than one UASA can access are possible. An example is a transfer between an airport and several neighboring cities, as shown in Figure 2. Such transport services between airports and cities are considered one of the most significant uses of UAM. In this situation, if each RUATM does not have information on the flights managed by other RUATMs, unexpected congestion in the vicinity of the vertiport located near the airport could occur. RUATMs must share information and manage traffic flows cooperatively while maintaining the scalability and flexibility of the UATM system.

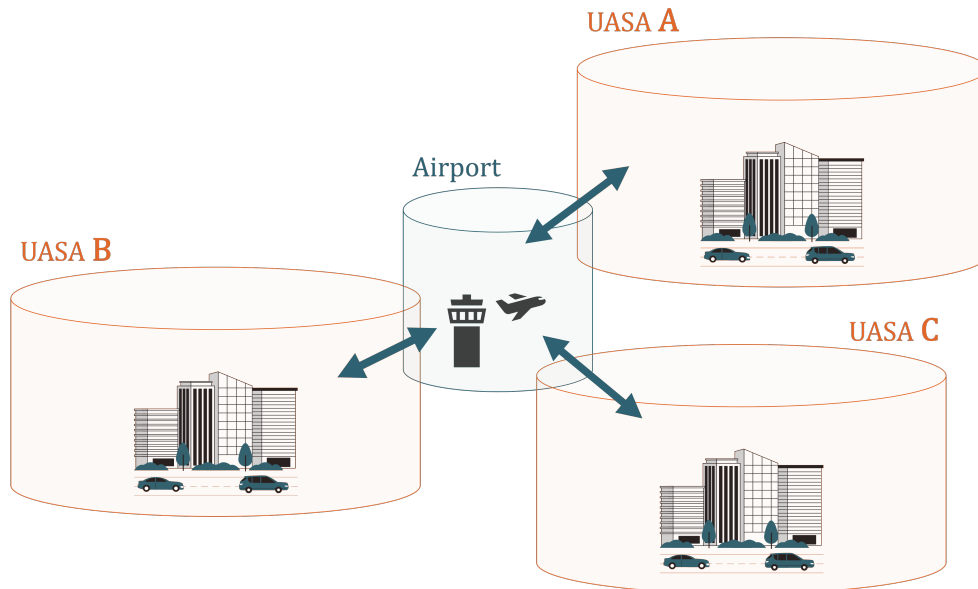


Figure 2 – Airport is accessible from several UASAs.

Researchers have studied the use of DCBs for UAM. Lee et al. ([3]) developed a flight scenario for the Dallas/Fort Worth urban area and an initial DCB algorithm to perform vertiport DCB. In addition, they investigated how several conditions that occur during UAM operations affect UAM flight schedules. Chen et al. ([4]) proposed a novel framework that applies DCB to strategic conflict management and

reinforcement learning for tactical separation. Souza et al. ([5]) proposed a simulation framework for evaluating DCBs considering uncertainties such as sudden meteorological changes, navigation errors, or unforeseen circumstances. All these studies assume a single UATM and do not define the specific concepts required for multiple RUATMs to cooperate in DCB. Therefore, this study proposes the first DCB framework in which multiple RUATMs share the resources of UAM operations and work in a distributed manner.

The type and amount of information that should be shared among RUATMs when each RUATM cooperates in a distributed DCB are important parameters. While more shared information is expected to make future congestion forecasts more accurate, it is not always better. When UAM becomes more popular, the number of UAM operations is expected to be greater than that of today's existing aircraft, and the information regarding UAM flights is expected to be vast. The information to be shared in RUATM should be kept as minimal as possible because the system may be unable to process a significant amount of information if extra information is shared.

In this study, as an initial investigation of information sharing among RUATMs, a distributed DCB algorithm is developed for UAM arriving at vertiports such as hubs that can be accessed from multiple UASAs, as shown in Figure 2. Cooperative DCB that shares all flight information and noncooperative DCB that does not share flight information between RUATMs are prepared. Flight plans are randomly generated, and numerical simulations reveal the differences in performance between cooperative DCB and noncooperative DCB. In addition, to improve the performance of noncooperative DCB, a method is proposed to allocate expanded capacity to RUATMs. Simulations are conducted, and the relationship between the performance of the noncooperative DCB and flight demand saturation is described.

The remainder of this paper is structured as follows. Section 2 presents the DCB algorithm for UAM operations. In addition, the section describes the flight plans, cooperative DCB, and noncooperative DCB used in this study. Section 3 describes the simulation setup and presents the simulation results for the cooperative and noncooperative DCBs. Furthermore, the methods for improving noncooperative DCB and their effectiveness are described. Finally, Section 4 presents conclusions and outlines future research directions.

2. Demand Capacity Balancing for Arrival Vertiport

Figure 3 shows an overview of the simulation setup used in this study. The hub-like vertiport, which acts as a hub, is located at the center of the three UASAs. The black circle and the letter 'V' represent the vertiport. Each UASA is managed by a different RUATM and has one or more vertiports within the UASA. The hub vertiport can be accessed using any RUATMs. This study focuses only on UAM flights from the vertiports of each UASA managed by the three RUATMs to the hub vertiport. In addition, the arrival throughput at the hub vertiport is subject to DCB. This is because the capacity of the vertiports is likely to be a bottleneck for overall UAM traffic.

Simulations are performed using two DCB algorithms: a cooperative DCB that functions similarly to a conventional centralized DCB and the noncooperative DCB proposed in this study. Figure 4 shows the simulation flow for cooperative DCB and noncooperative DCB. At the beginning of the simulation, several UAM operators, such as airlines, submit their flight plans for each flight to one RUATM. The RUATM to which the flight plan is submitted is the RUATM that manages the UASA over which the flight will fly. The flight plans are simplified and contain the following minimum information:

- Departure RUATM
- Estimated departure time
- Estimated flight time

After the RUATMs receive flight plans, each RUATM checks the demand-capacity balance. In a cooperative DCB, all RUATMs can share flight plans and perform DCB processing cooperatively, as shown on the left in Figure 4. As shown on the right-hand side of Figure 4, RUATMs do not share flight plans. Each RUATM checks the balance between demand and capacity based solely on the flight plans it receives by each RUATM.

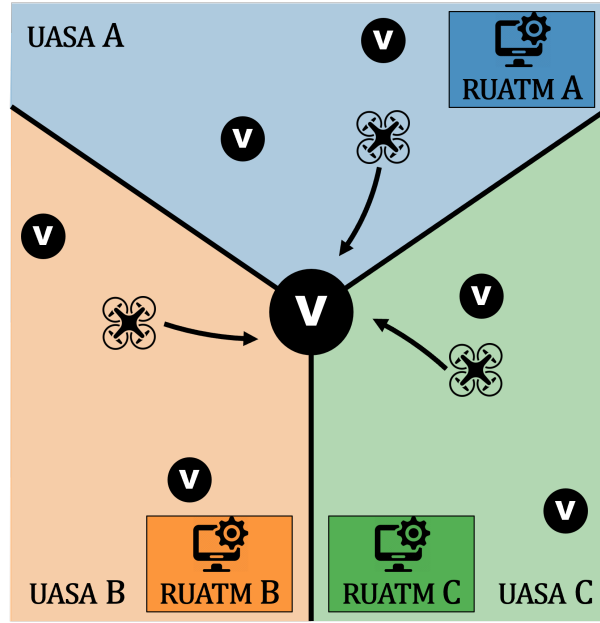


Figure 3 – Distributed RUATM.

A time bin is used to check the demand-capacity balance. The time bin is the time interval Δt as shown in Fig. 5, and each time bin has the flight capacity. Δt and capacity are determined by the processing ability of the vertiport and the flight characteristics of the vertiport and UAM, which may change depending on future operational practices. For each time bin, if there is a demand for flight operations above capacity, it is considered over capacity, and the flight is instructed to have a ground delay.

Because this study does not focus on the algorithm of the DCB itself, the ground delay is performed on a simple first-come/first-served basis, as shown in Figure 5. If the capacity of each time bin is two, bins 1, 4, and 5 are unbalanced in the original flight plan, as shown in Figure 5. In these time bins, the last flight is subjected to a ground delay and moved to the latest time in the next time bin. If two or more flights exceed capacity, the next most recent flight is subject to ground delay. If the next time bin is saturated, the flights move to the next time bin.

Figure 6 shows a method for RUATMs to check the demand-capacity balance without information exchange. In a noncooperative DCB, the original capacity is divided and allocated to RUATMs. Figure 6 shows the case where the original capacity is three flights, and one flight of capacity is assigned to each RUATM. Each RUATM checks the demand-capacity balance by comparing the capacity allocated to the RUATM with the flights to be managed. The subsequent ground delay process using the time bin is similar to that of cooperative DCB.

3. Numerical Simulation

3.1 Simulation Setup

This section describes the simulation environment setup. To simulate distributed DCB, a multiagent simulation is developed with each RUATM as agent. With reference to Ref. [3], each RUATM was modelled as an agent performing DCB in FCFS based on the flight plan submitted by the operator. In cooperative DCB, information about flights can be shared between agents; in noncooperative DCB, information about flights cannot be shared. The simulation time is 3 h, and the time bin size Δt is 9 min. The capacity per time bin is three flights. If a noncooperative DCB is used, this capacity is divided, and only one ration per time bin is allocated to each RUATM. The traffic scenario includes 36 flights. Therefore, the demand-capacity ratio is 60% for the entire simulation, which is based on a previous study [3]. The traffic scenarios consist of 36 flight plans. The flight plans are randomly generated under the following conditions: The flight time is set in the range of 1060 min, and all flights are completed within a simulation time of 3 h. In addition, the departure RUATM is randomly selected.

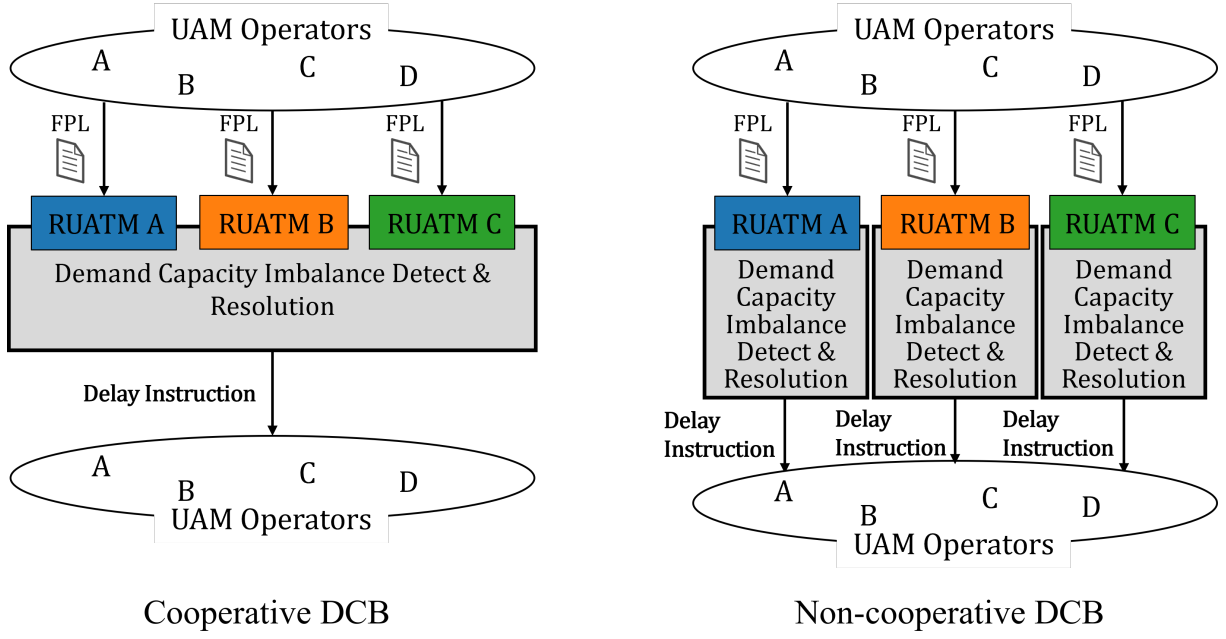


Figure 4 – Simulation flow for two DCBs.

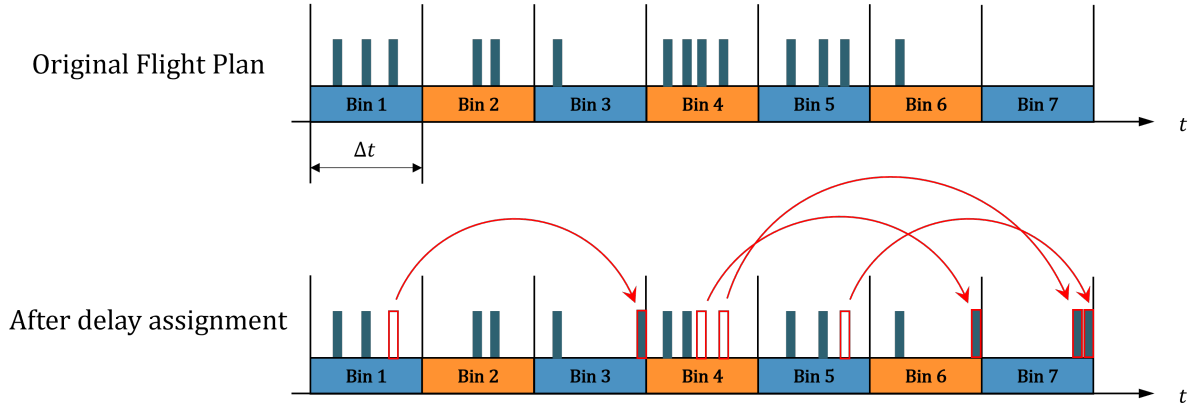


Figure 5 – First-come first-served DCB.

3.2 Comparison of Cooperative DCB and Noncooperative DCB

Figure 7 shows a visualization of the demand in each time bin using the RUATM based on the original flight plan submitted for a certain traffic scenario. The demand graph is stacked from the bottom in the order RUATM A, B, and C. This order does not indicate the arrival sequence in the first-come, first-served algorithm of DCB. The red horizontal line indicates the bin capacity. As mentioned in Section 3.1, the number of flights each RUATM manages may differ because traffic scenarios are randomly generated for each simulation. In this scenario, RUATM A manages 13 flights, RUATM B manages 10 flights, and RUATM C manages 13 flights. As shown in Figure 7, one flight exceeds the capacity in time bins 45-54 and 54-63, and two flights exceed the capacity in time bin 126-135. The key point is how the two DCB algorithms manage the four excess flights.

The results of the ground delay processing with cooperative and noncooperative DCB for the original flight plan are shown in Figure 8. Evidently, for both DCBs, the flights are adjusted to within capacity in all the time bins. The DCB algorithm developed in this study was effective for this flight scenario. However, different results were shown for cooperative and noncooperative DCB, which will be discussed in future distributed DCB development.

There may be more time bins with only one flight demand in a cooperative DCB than in a noncooperative DCB, resulting in a waste of slots. For example, the cooperative DCB has time bins of 117126 min with a flight demand of one. This does not indicate inefficient results because there is no

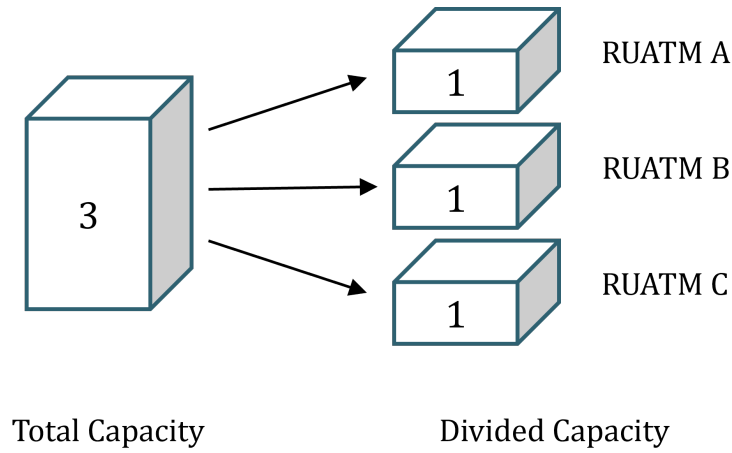


Figure 6 – Method of dividing capacity for RUATMs.

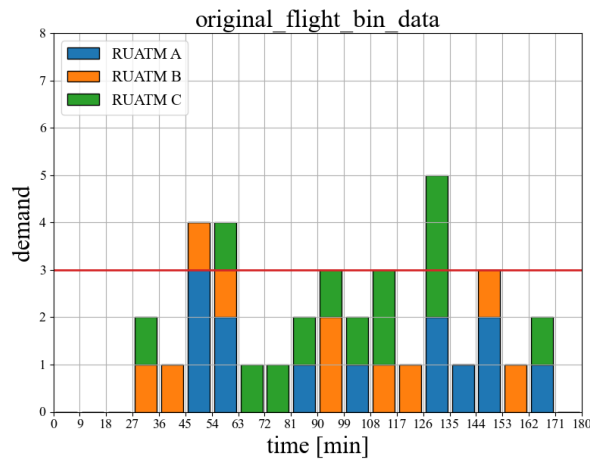


Figure 7 – Demand of flights based on original flight plan.

excess demand in the previous bin. The number of flights in this simulation was 60% of the maximum number that could be performed. This buffer resulted in more time bins with only one demand. If a more congested vertiport is targeted, the number of time bins whose demand is equal to the capacity increases. In addition, if UAM operations require the demand in each time bin to be as uniform as possible, further improvements to the DCB algorithm may be required.

Table 1 lists the total ground delay time, maximum ground delay time, mean ground delay time, and number of ground-delayed flights for the two DCBs with one scenario. The total and mean ground delay times were calculated from the ground delays of 36 flights included in the scenario. The mean ground delay time was calculated only for ground-delayed flights. For all four indicators, the results of the noncooperative DCB exhibited larger values, that is, less efficient results. In this scenario, there was a significant difference in the total ground delay, particularly for RUATM A. The reason for the considerable total ground delay time of RUATM A in the noncooperative DCB was the concentration of the original flight demand from RUATM A in the two time bins of 45-63 min in Figure 7. In the noncooperative DCB, the capacity for each RUATM was one per bin; therefore, if flights are concentrated at a specific period, it is likely that there will be no available capacity in the next bin for ground delay processing, resulting in a significant total ground delay time. An increase in the total ground delay indicates a deterioration in the overall efficiency of the DCB system. It can be observed that the overall efficiency was higher for the cooperative DCB. The difference in the total ground delay time between each RUATM was more significant for the nonoperative DCB, which means that the noncooperative DCB exhibited less fairness between the RUATMs. The fairness among RUATMs is an important factor in the efficiency of DCB. In this study, the flights located at the end of the time

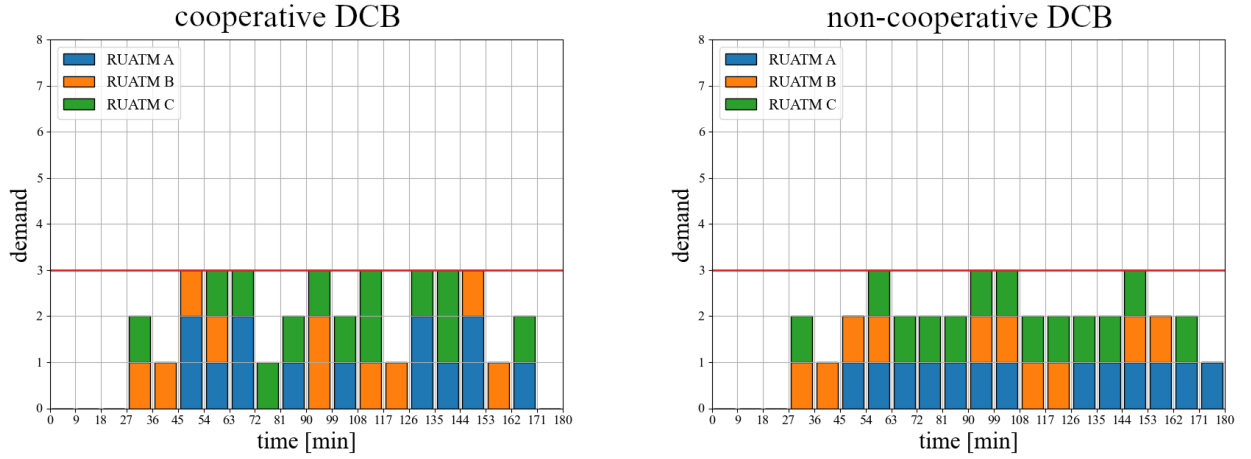


Figure 8 – Demand of flights ground delayed by cooperative DCB and non-cooperative DCB.

bin were subjected to ground delay. However, in actual operation, it may be preferable to process flight plans on a first-come, first-served basis of submission, as used in previous research [3]. The maximum ground delay time is likely to be large, owing to the characteristics of the DCB algorithm. In the DCB algorithm shown in Figure 5, if an imbalance between demand and capacity occurs in a time bin, the last flight in that time bin is moved to the end of the next time bin. If the demand again exceeds the capacity in the time bin after the move, the flight that moved from the previous time bin is moved to the next time bin. Thus, the ground delay for a particular flight may be extremely high. Changing the algorithm to move the flight subject to ground delay to the beginning of the next bin instead of the end would be expected to reduce the maximum ground delay time but instead increase the number of ground-delayed flights. This should be determined according to the requirements of the UAM operation.

Table 1 – Comparison of performance of two DCBs.

	cooperative DCB			non-cooperative DCB		
	RUATM A	RUATM B	RUATM C	RUATM A	RUATM B	RUATM C
Total ground delay [min]	31.4	0	26.6	154.0	9.2	48.3
Maximum ground delay [min]	21.8	0	13.7	36.6	9.2	22.7
Mean ground delay [min]	15.7	0	13.3	30.8	9.2	16.1
Number of ground delayed flights	2	0	2	5	1	3

The cooperative DCB consisted of eight time bins with a flight demand of three, whereas only four time bins were observed in the noncooperative DCB. Noncooperative DCB cannot fully utilize the three capacities owing to the lack of information on the other RUATMs. Therefore, in the next section, additional capacity is distributed to each RUATM compared to the actual capacity in anticipation of capacity vacancies.

3.3 Improvements of Noncooperative DCB

The noncooperative DCB in Section 3.2, which allocated each RUATM a capacity of one, was changed to allocate each RUATM a capacity of two. The results of the DCB simulations are shown in Figure 9 and Table 2. It is evident from Table 2 that the ground delay times and the number of flights subject to ground delay were significantly lower than those for the noncooperative DCB shown in Table 1. Furthermore, the values were even lower than those for the cooperative DCB; hence, the efficiency has improved. However, the demand exceeded the capacity in the 54-63 min and 126-135 min time bins, as shown in Figure 9. This is called a DCB violation. The occurrence of a DCB violation indicates that air traffic congestion is expected, and there is a potential risk of increasing the frequency of tactical separation provisions in the air, which is the second layer in conflict management[3]. To investigate the relationship between the expanded allocated capacity and DCB

performance in detail, several simulations were conducted by varying the ratio between the actual and allocated capacities.

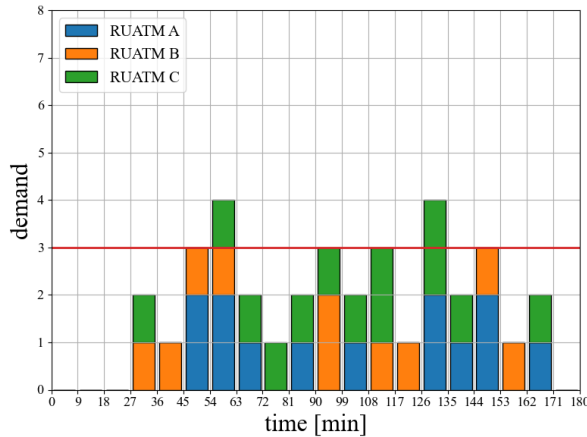


Figure 9 – Results for the noncooperative DCB where each RUATM is allocated two capacities.

Table 2 – Performance of the noncooperative DCB where each RUATM is allocated two capacities.

	noncooperative DCB		
	RUATM A	RUATM B	RUATM C
Total ground delay [min]	21.8	0	13.0
Maximum ground delay [min]	21.8	0	13.0
Mean ground delay [min]	21.8	0	13.0
Number of ground delayed flights	1	0	1

In the following simulations, the capacity allocated to each RUATM was fixed at two, and the actual capacity was varied to change the ratio between the actual and allocated capacities. The bin size was varied to increase the actual capacity without changing the vertiport throughput. The simulation up to this point was 3 ops / 9 min, the rate was maintained, and two settings of 4 ops / 12 min and 5 ops / 15 min were added. The original flight demand with 4 ops / 12 min and 5 ops / 15 min time bins and the results for a noncooperative DCB with two capacities for each RUATM are shown in Figures 10 and 11. The results were based on the same flight plan as the flight demand shown in Figure 7. Figures 10 and 11 show the bin size and the actual capacity change. The noncooperative DCB result of the time bin of 5 ops / 15 min in Figure 11 shows no demand exceeded the capacity. It can be assumed that the DCB violation rate improves if the difference between the actual capacity and the capacity allocated to RUATM is reduced. To investigate this, 10 flight scenarios were prepared, and 10 noncooperative DCB simulations were performed for each setting: 3 ops / 9 min, 4 ops / 12 min, and 5 ops / 15 min.

Figure 12 summarizes the ground delay results for a noncooperative DCB in three time-bin settings, where each RUATM is allocated two capacities. Each graph shows the mean of 10 trials for the total ground delay, maximum ground delay, mean ground delay, and number of flights subject to ground delay. The four graphs in Figure 12 show that the smaller the bin size, that is, the larger the difference between the actual capacity and the capacity allocated to the RUATM, the lower the ground delay time and number of ground-delayed flights. Previous studies [3] have shown that increasing the bin size reduces the mean ground delay time even if the vertiport throughput remains the same. Therefore, allocating a larger capacity than the actual capacity significantly impacts the ground delay compared to changing the bin size.

Figure 13 shows the mean number of DCB violations. It counts the number of flights exceeding capacity in the same time bin. DCB violations decreased with increasing bin size, and there were no more than two DCB violations when using 5 ops/15 min time bins. These results indicate that

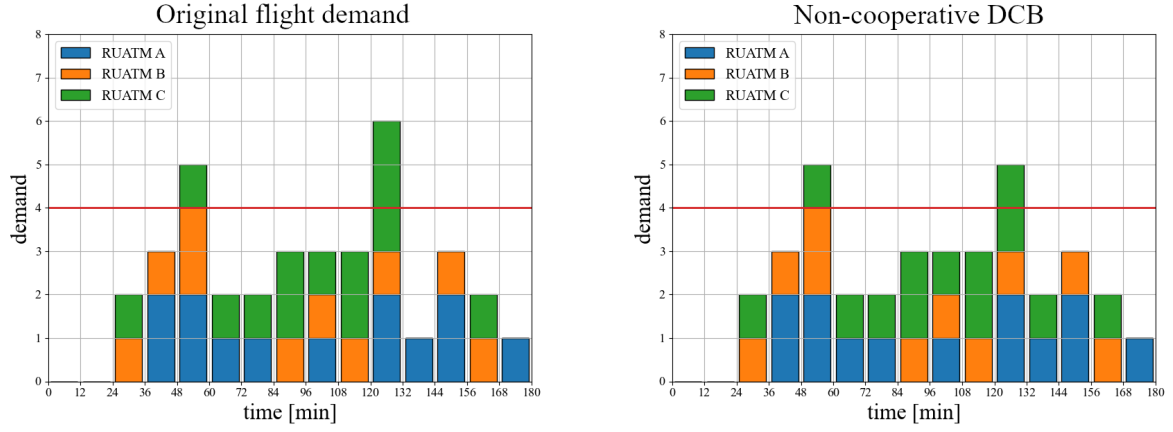


Figure 10 – Results for the noncooperative DCB in 4 ops / 12 min time bins where each RUATM is allocated two capacities.

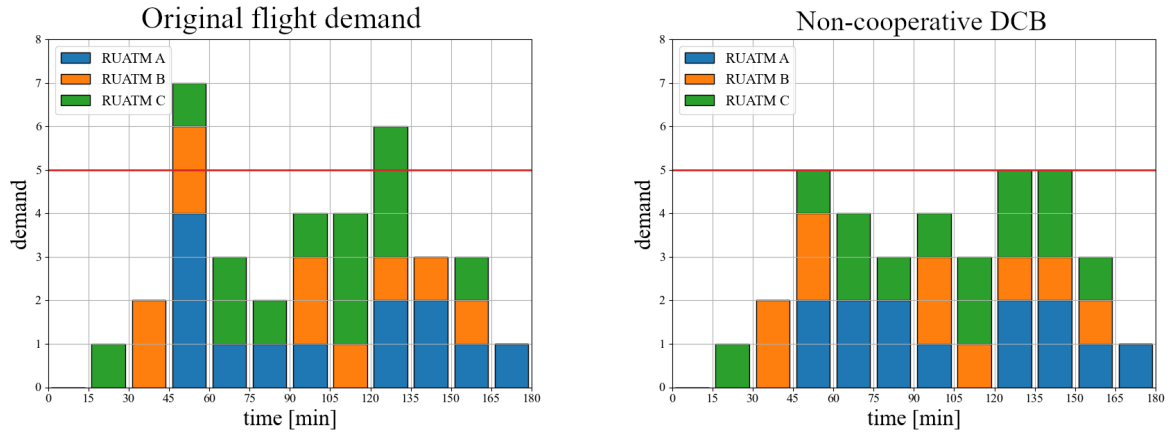


Figure 11 – Results for noncooperative DCB in 5 ops / 15 min time bins where each RUATM is allocated two capacities.

the performance of noncooperative DCB can be improved by allocating a more expanded capacity to RUATMs than the actual capacity. In addition, the results show a trade-off between the performance of a noncooperative DCB and the number of DCB violations. If the actual capacity is divided and allocated to RUATMs, DCB violations do not occur; however, capacity can be wasted. For traffic scenarios with higher demand, capacity wastage may be more pronounced, and operating all flights in the simulation time may not be possible. In traffic scenarios with higher demand, allocating more capacity than the actual capacity to reduce capacity wastage may increase DCB violations, resulting in tactical separation during UAM flights. The number of DCB violations that can be tolerated is beyond the scope of this study; however, the simulation results provide a basis for developing more sophisticated distributed DCB algorithms.

4. Conclusion

In this study, the RUATM concept and a distributed DCB algorithm were proposed to manage the regional operations of future UAM. Because multiple RUATMs may employ common resources, DCB simulations focused on a single-arrival vertiport that multiple RUATMs can access. Because the presence or absence of information exchange between RUATMs is a demand factor, simulations were performed for two configurations: cooperative DCB, in which RUATMs share flight information, and noncooperative DCB, in which RUATMs do not share flight information. The noncooperative DCB uses a method in which the overall capacity is divided and allocated to RUATMs. The simulation results showed that the developed distributed DCB maintained the given flight demand within its capacity. Sharing flight information between RUATMs increased the efficiency of the DCB, whereas

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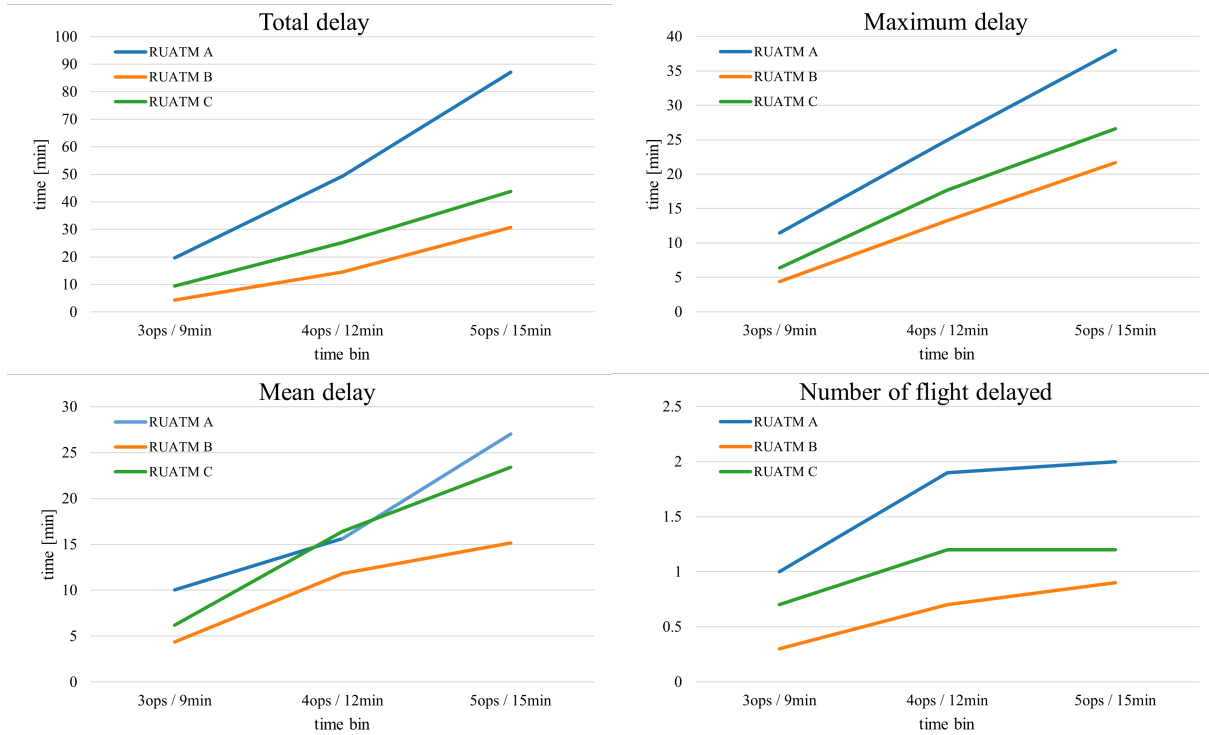


Figure 12 – Mean ground delay times and number of flights subject to ground delay from 10 trials in three time bin settings.

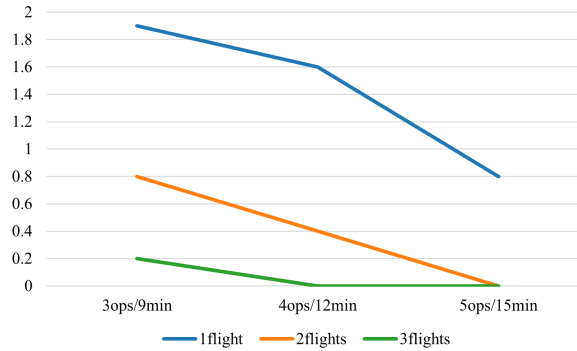


Figure 13 – Mean number of DCB violations from 10 trials in three time bin settings.

without information sharing, a large number of capacities were unused, reducing efficiency. To improve the efficiency of noncooperative DCB, a method was proposed to allocate more capacity to RUATMs than the actual capacity. Furthermore, additional simulations were performed. Ten simulations were performed, and the mean values of several indicators were compared. The results showed that distributing additional capacity significantly improved efficiency; however, it increased the incidence of DCB violations.

In future studies, the DCB algorithm will be improved. In this study, ground delays were processed on a first-come, first-served basis based on the departure time of flights to ensure fairness in determining which flights were ground delayed. Based on flight plan submission time, the DCB algorithm will be improved to a first-come, first-served basis. The simulations in this study were conducted under two extreme DCB simulation settings: one with all information sharing and one with no information sharing. Future research will develop a DCB algorithm that allows partial information sharing and clarify the impact of the amount of information sharing on the efficiency of DCB.

5. Acknowledgements

I thank Professor Takehiro Higuchi of Yokohama National University and Dr. Daichi Toratani of the Electronic Navigation Research Institute for their constructive suggestions and comments.

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