Simulation Platform Development

For an eVTOL on-demand service over a general UAM network, given eVTOL fleet size, infrastructure capacity, facility equipment and passenger demand, this study developed a platform to simulate the operational process of eVTOLs to fulfill the on-demand service requests from passengers while considering the operational constraints. Three primary objects (or agents) are included in the platform during simulation process – Vertiport, Vehicle and User. In other words, the whole simulation process can be regarded as using eVTOLs to transport passengers among vertiports based on certain rules as shown in Figure 2. These rules can be Level of Service (LoS) requirements, eVTOL operation energy requirement and eVTOL operation procedures and so on. In the following sections, we will firstly discuss about the assumptions and operation rules defined for the development of the simulation platform. Then we will provide a detailed description of each object. Finally, we will introduce the overall simulation framework and each module it contains.

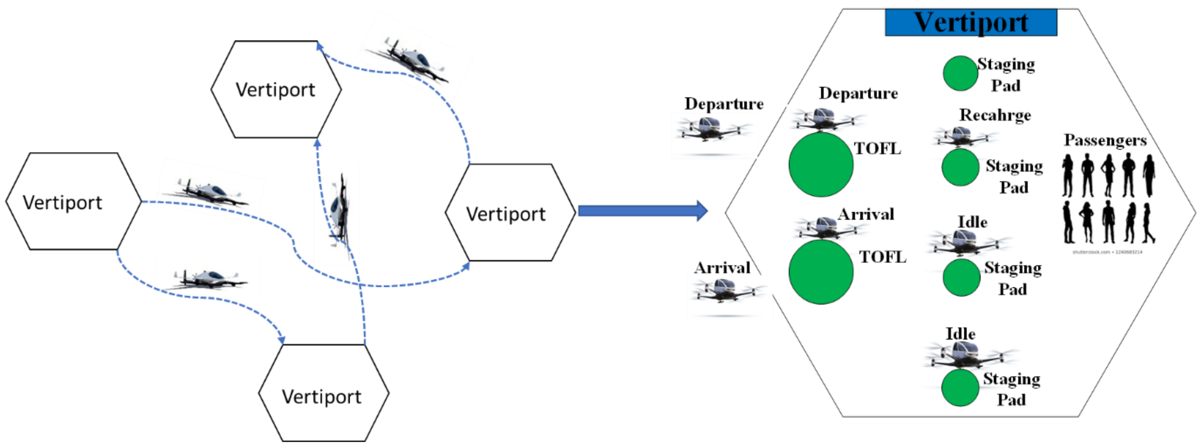


Figure 2. The operational process of eVTOL over UAM network

Assumptions and Operation Rules

The following assumptions were made for simulation platform development in this study:

1) There is no congestion in airspace and on taxiways within vertiport and eVTOL cruise at constant speed.
2) All eVTOLs in the network share the same property with respect to capacity, energy and time consumption at each state.
3) All vertiports have the same infrastructure design and all of them include taxiway, takeoff and landing pads (TOFLs) and staging pads.
4) There is no trans-shipment of passengers at vertiports – that is, one trip goes through only two vertiports.
5) Within certain time horizon, passenger arrivals at vertiports can be known and generated in advance.

For assumptions (1), consideration of uncertainties of travel time in airspace and operation time within vertiport requires integration of conflict detection and resolution of trajectories in airspace and taxiway design and operation management within vertiport respectively. Those assumptions can be relaxed in the further research to expand the function of the simulation platform. In assumption (2), without loss of generality, it assumes that there is only one operator, or all operators owns eVTOLs from the same manufacturer. In practice, operators can contract with different vehicle manufacturers to supply different types of eVTOLs. Assumption (3) can also be relaxed in practice for areas where there is such low demand that only one pad is enough to fulfill the function of both staging pads and TOFLs. The rationale behind assumption (4) is that trans-shipment will add more waiting time and inconvenience to traveler trips and will reduce the attractiveness of multimodal UAM service for urban travel [3]. The idea of generating arrival times of passengers at vertiport for UAM service follows that for TNCs in assumption (5). Passengers can request the service and estimate their arrival times before heading to their nearby vertiports through certain service platform so that operators can know their arrival times in advance.

We have also defined some operation rules for passenger transportation and eVTOL operations:

1) First arrive, first serve.
2) Passengers can take the same eVTOL as long as they share the same destination and the number of passengers assigned to the vehicle should not exceed its capacity.
3) Passenger service should not exceed the following three Level of Service (LoS) threshold:
    - LoS1 – the waiting time of the first arrival passenger for a specific eVTOL.
    - LoS2 – the waiting time of the last arrival passenger for a specific eVTOL.
    - LoS3 – the waiting time out-of-vehicle for an available eVTOL before switching to another transportation mode.
4) EVTOLs can start service only when current SoC satisfy the energy service requirements, which is the summation of the minimum reserve for safe operation and the energy required for the current service.
5) EVTOLs land at destination vertiport should satisfy the following two conditions:
    - There are at least two TOFLs available at the destination vertiport.
    - There are at least one parking pad and one TOFL available at the destination vertiport.
    - There is only one available TOFL but SoC of eVTOL is less than the minimum reserve.

Rules (1), (2) and (3) are defined for passenger transportation. For rule (1), it represents that passengers who arrive first will be firstly assigned to available eVTOLs. Rule (2) indicates that shared service is allowed in the simulation process. In rule (3), LoS1 and LoS2 are defined to ensure the service quality of arrival passengers and LoS3 reveals the natural mode choice behaviors of passengers. As for rule (4) and (5), they are defined to ensure the safe operation for eVTOLs (rule (4)) and to avoid possible bottle neck at vertiports during operation (rule (5)) for eVTOL operations.

Introduction of Objects in Simulation Platform

As mentioned above, there will be three objects to represent passengers, vehicles and vertiports in the simulation platform. The information contained by each object can be divided into two parts – fixed inputs and stochastic variables. Fixed inputs are information provided by the platform before the start of the simulation and will not change during the simulation process while the stochastic variables are those that vary during the simulation process as intermedium results.

a. Vertiport Object

Vertiport is the fundamental infrastructure to support a series of operation maneuvers for eVTOLs and the one where passengers' air trips start and end. As discussed above, vertiport objects all include the following critical elements – Takeoff and landing pads (TOFLs), staging pads (with charging facility equipped) and taxi ways. TOLFs are pads where eVTOLs take off and land while staging pads or parking pads are assumed to have the capability for eVTOLs to load and disembark passengers and get charged. Taxi ways are pre-designed routes within vertiports for eVTOLs to move among the aforementioned facilities and it was assumed that the there is always enough capacity of taxiways for eVTOL operations. The fixed inputs for the vertiport object are the number of TOFLs, staging pads and passenger arrival distribution for the whole simulation horizon and initial number of eVTOLs before simulation starts while the stochastic variables include the facility occupation conditions, passenger waiting queue at the vertiport and state of each eVTOL within vertiports.

b. User Object

User object is another critical element in the simulation platform. The fixed input for each user object includes passenger's origin and destination and arrival time at vertiport while the stochastic variables contain its in-vehicle waiting time, out-of-vehicle waiting time and the vehicle it is assigned to. In-vehicle waiting time represents the time passengers has experienced waiting for another passenger who sharing the same destinations after they have been assigned to an available eVTOL. Out-of-vehicle time indicates the time passengers experience waiting for an available eVTOL.

c. Vehicle Object

The vehicle object defines the properties of eVTOLs and several methods for moving eVTOLs through the simulation. The fixed input for vehicle objects include their initial locations before simulation, length of time and energy usage for each state while the stochastic variables contains their state of charge (SOC), seat occupation, destination, and their current states and locations.

To capture different operational states accordance with different mission segments, the vehicle object adopts a time-based state machine, similar as [22]. In one simulation, vehicles move from one state to another over time based on a state timer that controls how long an eVTOL remains in a mission segment. Several of these state timers may have an indefinite duration. The state variable has 9 possible values (0-8). In addition to the state variables, a hold flag can be used to keep an eVTOL in one state under certain circumstances. Table 1 below shows the possible states, the progression between states, states in which the hold flag is active, the timers for each of the states, and the energy depletion rates. The energy change rates are all referenced to the capacity of the eVTOL battery and energy level is tracked with a unit-less scale, in which 1.0 is full and 0.0 is empty.

An eVTOL in ready state indicates that it has been fully charged and ready to serve any incoming passengers. The vehicle will transition to load state from ready state when it has been assigned the first passenger and the vehicle can continue to take other arrival passengers as long as it satisfy the passenger service rules. We also noticed that there is a hold flag for the load state, representing that the eVTOL has stopped taking more passengers but will hold at the state as there is no available TOFL at the instant. Once TOFL is available, eVTOL will move to the next state and taxi-out to TOFL for takeoff. The state following the takeoff state is the cruise state and the duration of it is determined by the distance between start and end vertiport. The hold flag can also be set for this state and force eVTOL to hover over the destination vertiport after finishing cruising if certain landing criteria are not satisfied as mentioned.

After landing at the destination vertiport, we need to see if there are available staging pads for the vehicle to taxi in. Otherwise, the vehicle will hold at the state. Once the vehicle taxi in and unload passengers, eVTOL will move into recharge state until there is another request, or it is fully charged. When there is a new request and the vehicle has enough energy for the new trip, it can move to the load state and stop recharging. After fully charged, eVTOL will transfer to the ready state until the next request.

Table 1. Vehicle state definitions and properties

State	Description	Hold Flag	Time (minutes)	Energy Consumption (SoC/min)
0	Ready		Indefinite	0
1	Load	Yes	Indefinite	0
2	Taxi out		2	0
3	Take-off		1	0.05
4	Cruise	Yes	Dispatch Set	0.01
5	Land	Yes	1	0.05
6	Taxi in		2	0
7	Unload		2	0
8	Recharge		Indefinite	-0.04

Description of the Simulation Platform

a. Input Data

The first step of developing the simulation platform is to define the UAM network, which can be represented by a distance matrix that defines the distances between all vertiport pairs. Then, we should prepare for the all fixed input for each object as discussed above. It should be mentioned that we assume passenger arrives follow a Poisson Process. Therefore, we are able to generate exact passenger times given the time horizon and average arrival rate.

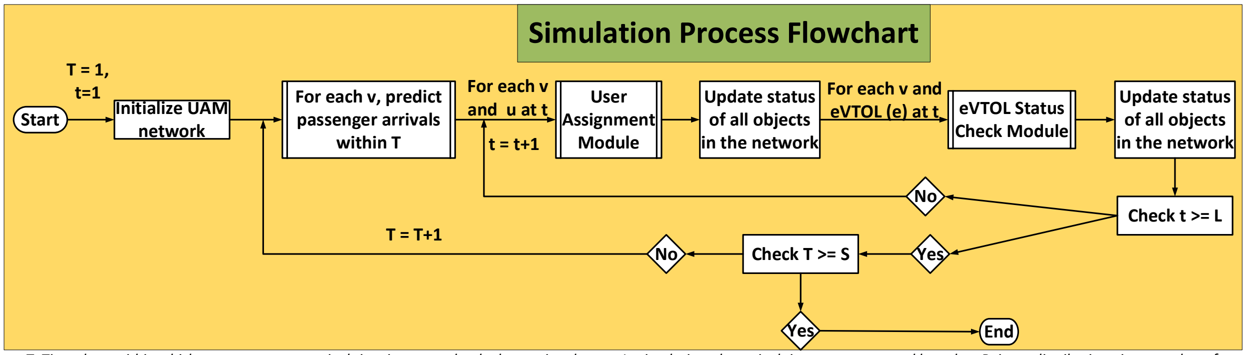
b. Simulation Process

Before the simulation starts, we need to firstly define the basic time unit (t) for each simulation step. In this platform, we also define another time unit (T), with which we assume that we are able to stochastically predict the exact arrival time of passengers at vertiport and obtain the information of their destination. For example, for a simulation horizon from 6:00am to 9:00pm, T and t can be set as 15 minutes and one minute respectively. Then, the simulation horizon can be divided into 60 time slot (T=60) and the simulation will run for 900 iterations. The simulation platform runs and updates information of objects each one minute and exact passenger arrival times are generated each 15 minutes. We assume passengers arrives following a Poisson process during each time slot T, where number of passengers and average arrival rate can be obtained from the predicted route demand as described above.

The overall simulation process is illustrated in Figure 3. There are mainly three modules during the simulation process, the module to generate passenger arrivals for each time slot T, the module to assign passengers to available eVTOLs and the module to update state of eVTOLs. Once the simulation starts, the timer starts to record both t and T and the UAM network will be initiated, including setting up the vertiport network, infrastructure capacity at each vertiport and initial distribution of eVTOLs. Since it is also the start of the first time slot T, the platform will conduct the first module to predict passenger arrivals at each vertiport following a Poisson process as mentioned above.

With the initial information from each object in the network, the platform will conduct the User Assignment Module and the detailed operation steps for the module is described in Figure 4. The main task for the module is to check available eVTOLs for passengers at each vertiport. eVTOLs in three states will be checked in the order, which are loading state, ready state, and recharge state. It should be mentioned that passengers that can be assigned to loading state should share the same destination with passengers already in the eVTOL. If there is no available eVTOL for one passenger, it will continue wait until the out-of-vehicle waiting time exceeds LoS3.

After the User Assignment Module, the status of each object will be updated and taken as the input for the eVTOL Status Check Module. As illustrated in the Figure 5, the module will check each eVTOL at each vertiport and update its state based on the state machine defined in the Table 1 and operation rules. With updated information for each object after this module, the timer will be checked if it has exceeded duration of time slot T. If not, time unit will update and continue another round of User Assignment Module and eVTOL Status Check Module process. Otherwise, the value of T should be checked to see if it exceeds the simulation horizon and the simulation should stop. If the value of T is less than S (number of time slots for the simulation horizon), update value of T and generate passenger arrivals at each vertiport for the new time slot.



T: Time slots, within which exact passenger arrival time is assumed to be known in advance. In simulation, the arrival times are generated based on Poisson distribution given number of arrivals and average arrival rate.
t: Time for each simulation step.
L: Length of time slots T
S: Number of time slots for the simulation horizon.
v: vertiport
u: passenger

Figure 1. Simulation platform flowchart

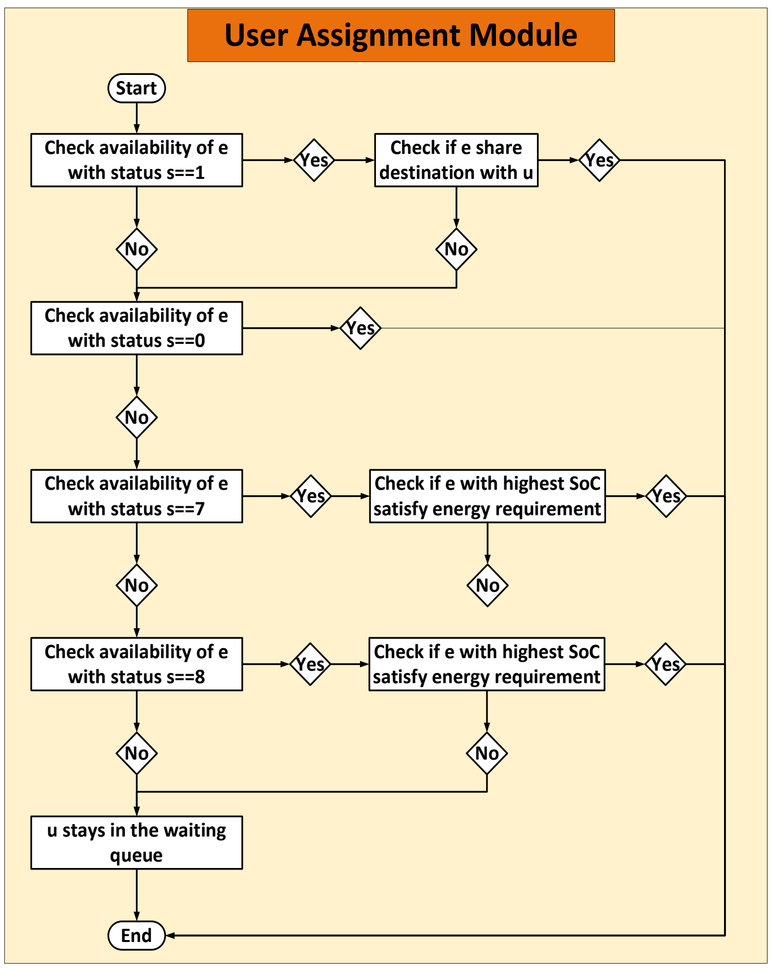


Figure 2. User Assignment Module working process flowchart

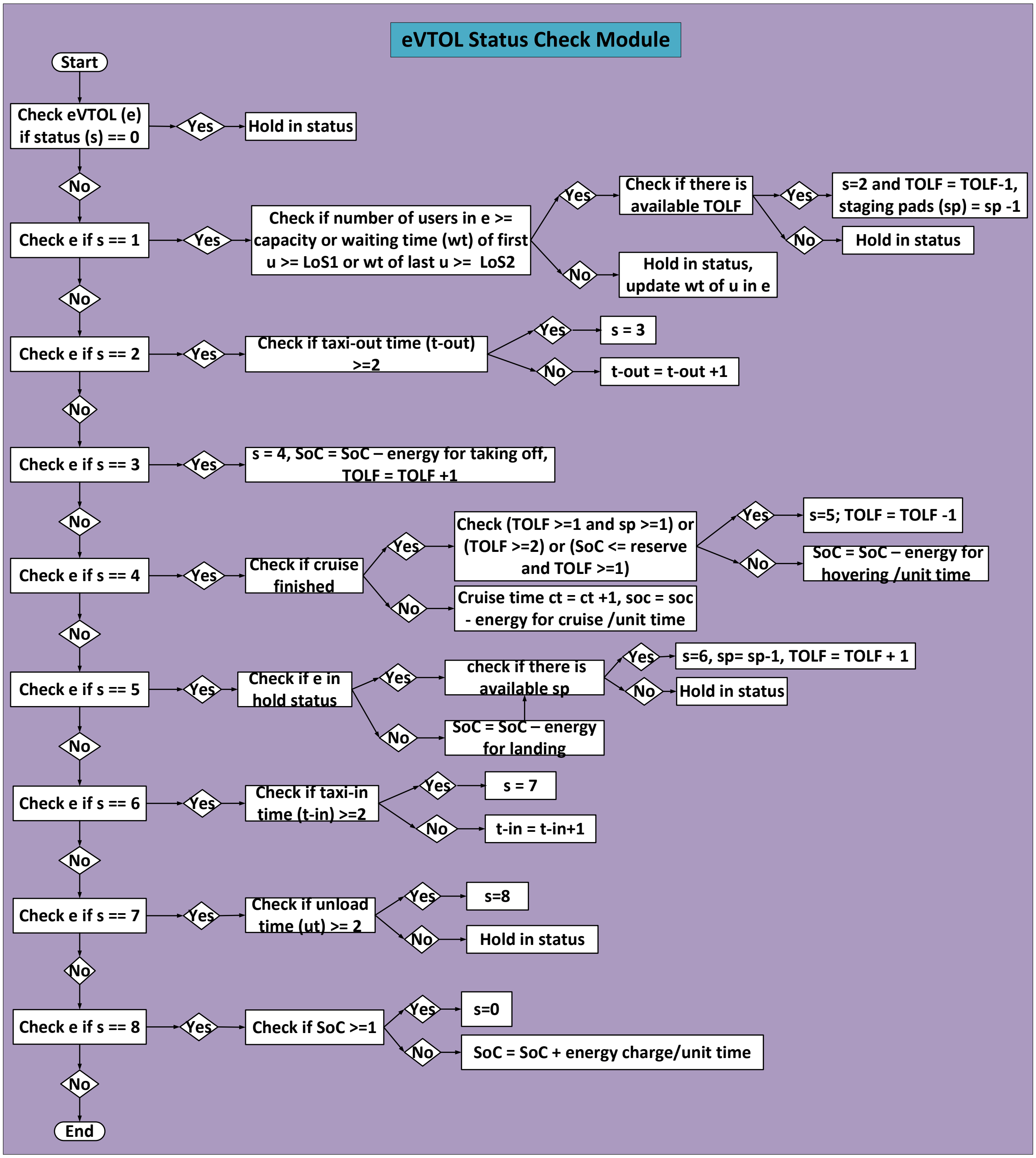


Figure 3. EVTOL Status Check Module working process flowchart