

Resolution of Potential Conflicts caused by Contingency Events in an AAM Traffic Network

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Abstract—This study presents an approach for pre-flight replanning process to be used in the future Advanced Air Mobility (AAM) system especially after contingency situations and relevant activities take place. The methodology for pre-flight replanning phase is analyzed and modeled in two steps as optimization based potential conflict resolution and demand capacity balancing, which respectively provides safety for the surrounding traffic and efficiency for the traffic network in case of a contingency. These two models can work iteratively to achieve pre-flight replanning for the Unmanned Aircraft System Traffic Management (UTM). The developed pre-flight replanning model can also be used at strategic planning phase. For the use cases, a very large UTM traffic network is considered to have a highly dense traffic environment since the expected complexity is high with the AAM system and to show the efficiency and scalability of the models. Two use cases are examined. First one is about initial flight planning where the conflicted flight plans are safely separated and balance in demand and capacity at vertiports is provided. Second scenario is related to potential conflict resolution for the flights at pre-tactical phase after contingency events observed within the network and demand-capacity balancing after safety related events are resolved. The main objective of this work is to develop a pre-flight replanning service to work compatible with contingency management activities to build the introduced system-wide contingency management concept for the AAM system.

Index Terms—AAM; UTM; pre-flight replanning; potential conflict resolution; demand capacity balancing; contingency management; optimization

I. INTRODUCTION

The current air transportation structure is anticipated to be transformed into a more accessible, flexible, resilient, and agile passenger and cargo carrying air transportation system where underserved and not served places such as rural, suburban, urban, local, and regional areas are served via cutting edge vehicles, under the envisioned future Advanced Air Mobility

(AAM) system. With the future AAM concept, the subjected operations might be various since it considers different area operations with wide range of new platforms such as manned or unmanned multicopter, fixed wing vertical take off and landing, and vectored thrust configurations at different sizes with different autonomy levels and capabilities. There are many challenges that will have to be overcome such that infrastructure, technology, safety, scalability, regulations, accessibility, social and environmental impact, and so forth.

One of the most important challenges to overcome for such system is safety. Managing disruptive events during operations and providing safety to the whole network in case of an adverse event are not trivial problems since the safety of the AAM system can be compromised with those disruptive events. Therefore, a proper system-wide contingency management concept which aims to provide not only safety but also efficiency by considering contingent operations and surrounding traffic, has to be developed to deal with expected or unexpected off-nominal and disruptive situations. The system-wide contingency management concept takes a very important role to enable the full potential of the future AAM system and make it a reality, since safety is one of the main concerns for such a complex system. Both the contingency situation itself and its effects to the network shall be considered with the proposed system-wide approach. System-wide contingency management concept becomes even more important especially considering the expected high density of operations and heterogeneous nature of the traffic which prevents easy procedural activities. Additionally, real-time interconnection and coordination between air and ground-based stakeholders form an interdependent system which must be considered as a whole, especially under disruptive events.

Concept of operations (ConOps) to date for AAM by

various industry leaders, discusses about contingency and emergency management processes for the envisioned system alongside the operational requirements and concepts, yet contingency management activities are given from vehicle perspective focusing on on-board contingencies [1]–[4]. Moreover, autonomous [5] and intelligent [6] contingency management concepts are introduced where the vehicles are aware of their capabilities and the environment while making decisions and taking actions on their own. On the other hand, contingency management activities are expected to be an autonomic system where autonomous selection of predefined actions are made without direct supervision but has a possibility to be intervened [4]. Additionally, development of a contingency management process on-board for various tactical contingency situations and testing with actual flights, are studied both in the Galician SkyWay project by Boeing Research Technology Europe [7] and AMU-LED project, by the authors [8]. The solutions provided by those studies mostly consider the vehicle-centric approaches where it is very useful for solving such cases in low traffic density environments, yet might not work well with the expected increase in the traffic. Thus, the AAM system requires a system-wide contingency management concept which is defined with base requirements in our previous work [9].

For developing the mentioned system-wide contingency management concept, all the AAM stakeholders and Unmanned Aircraft System Traffic Management (UTM) services shall be in a coordination with contingency management activities so that safety can be provided for the system while managing the traffic efficiently. Pre-flight planning shall be one of those services that can be coordinated with contingency management activities through replanning of the flights that have potential conflicts due to contingency events. The reason why that is considered as pre-flight planning is because separation for the flights affected by a contingency event, happens before their departure. Pre-flight planning can mainly consist of two elements which are potential conflict resolution and demand and capacity balancing.

There are several works focusing on different aspects of the strategic planning process of UTM which shows similarities with pre-flight planning process. Potential requirements for strategic deconfliction concept for UTM is presented in [10] which mainly covers strategic operational schemes such as prioritization, negotiation, and intersection. Based on those defined potential requirements about strategic conflict resolution problem in UTM, various methods are developed and analyzed considering different aspects. For example, the fairness parameter is quantified and first-come, first-served algorithm's performance is evaluated with respect to fairness for strategic conflict resolution in [11] and effects of operational uncertainties in UTM over strategic deconfliction problem is analyzed in [12]. Furthermore, analysis on the requirements for volume based deconfliction in UTM is conducted through comprehensive simulations including other UTM services in [13]. Also, performance improvement on first-come, first-served algorithm for strategic conflict resolution is studied in

[14]. With regards to the capacity allocation problem, first-come, first-served algorithm is tested on AAM system to assess its performance over vertiports in [15] and new on-demand dynamic capacity management algorithm is developed in [16] by considering flight planning, airspace configuration, and demand and capacity balancing phases. Demand-capacity balancing is also studied in air transportation domain through mathematical programming [17]–[19], which is also followed in this study for capacity allocation modeling. Yet, the developed models in mentioned studies, especially the conflict resolution approaches, are not suitable to use right after contingency management activities since it requires very quick response in a complex traffic.

This paper presents a pre-flight replanning service for the traffic that may be interrupted by contingency management activities of other flights. The developed service deals with resolving potential conflicts caused by contingency events, which require quick recovery for the rest of the traffic. The methodology for defined pre-flight planning phase is analyzed and modeled in two steps as optimization based potential conflict resolution and demand and capacity balancing, which respectively provides safety for the surrounding traffic and efficiency for the traffic network in case of a contingency by only giving ground delays. Those two models can work in an iterative manner to achieve pre-flight planning for the UTM. The reason behind for the iterative process is to provide advantage on solving complex cases since integrating those two problems into one decreases the computational efficiency. Therefore, pre-flight planning is constrained with potential conflicts and vertiport capacity limits, in an iterative manner. The developed pre-flight planning approach is also suitable to use for strategic planning purposes. Furthermore, a complex UTM network is created to be more realistic about what is expected with future AAM system and to see the boundaries of the modeled strategic planning module. Lastly, we demonstrated the results through couple of case studies. First one includes strategic deconfliction of the whole traffic at initial flight planning phase alongside demand capacity balancing through ground holding. Second one is a pre-tactical conflict resolution case where contingency events or proper contingency actions are observed and demands are allocated by taking vertiport capacities into account.

II. EFFECTS OF CONTINGENCY MANAGEMENT ACTIVITIES OVER TRAFFIC

Contingency management is one of the crucial parts of the UTM operations by providing safety, as well as efficiency for the traffic. Yet, contingencies and relevant activities to mitigate them may affect not only the flights suffering from contingencies but also the surrounding traffic since this situation may create new conflicts for the surrounding traffic both at tactical and pre-tactical phase. This paper considers the affected flights that are in pre-tactical phase. In this specific case, once conflicts due to a contingency event or mitigation action are observed, the affected vehicles are expected to update their flight plans. The considered situation requires

replanning of the surrounding traffic and that is provided through ground delays.

From the traffic network perspective, contingency management activities can be complemented with relevant AAM services as depicted in Fig. 1. The reason behind for such an approach is that the surrounding traffic in an AAM environment might be affected once a contingency or emergency event take place within the system. To provide safety and efficiency not only for the system parts that are suffering from contingency but also the surroundings, AAM services have to be in coordination with the management of safety-critic events. Considered AAM services can be named as risk assessment, tactical conflict resolution, strategic planning, and pre-flight replanning.

This work covers the development of the pre-flight replanning service by considering quick recovery due to an interruption by contingency events. This service plays an important role especially after contingency situations occurred within the traffic network. For instance, a contingent vehicle might interrupt the surrounding traffic by taking an action to resolve the contingency case or not conforming and deviating from its flight plan due to a contingency. The affected surrounding traffic may include flights that are about to take off. Therefore, pre-flight replanning service can be useful to resolve the potential conflicts of the flights at pre-tactical phase.

Fig. 2 represents an example where the pre-flight replanning is required. There are 4 flights as CRA01, CRA02, BDG01, BDG02 to take off at time t , $t + 2$, $t + 2$, $t + 2$ and lands at time $t + 7$, $t + 4$, $t + 4$, $t + 6$, respectively. At time t , CRA01 takes off and starts its operation. After one time step, at $t + 1$, CRA01 suffers from a contingency and has to do an emergency landing which means a change in its trajectory. Destination for CRA01 is updated and arrival time is changed to $t + 6$. Apart from that, CRA01's emergency landing action creates potential conflicts with the flights CRA02 and BDG02 which are at their pre-tactical phase. To resolve these conflicts, ground delay is given to CRA02 and BDG02 and new departure time has become $t + 3$ for both of the flights. Due to the departure time update for BDG02, a new potential conflict is observed between BDG02 and BDG01. Therefore, BDG01's departure time is also updated to $t + 3$ to prevent any conflicts. As a result from this case, the traffic network requires a quick replanning for the flights at pre-tactical stage in the moment of a contingency situation or relevant action taken.

III. UTM DATA PREPARATION

AAM traffic network data is generated by considering vertiport locations, demands, and capacities; vehicle types and their operational information; and possible origin-destination (O/D) pairs, their frequencies, and departure time windows. After those information are gathered, direct trajectories for each operation are generated from departure to arrival.

Vertiport network is built based on the studies in [20] which analyzes the historical transportation patterns to obtain the possible UTM demand trend for Dallas/Fort Worth area

and the vertiport capacities are used as detailed in [15]. The network model built consists of 102 vertiports.

As a vehicle model, a passenger carrying multicopter type vehicle is used for the whole traffic which has around 100 km/h cruise speed, 22 km/h vertical speed, 35 km range, and 21 minutes maximum flight time [21]. The range and endurance limits of the chosen vehicle are considered for obtaining the feasible O/D pairs.

Frequencies of the O/D pairs are evaluated through the current ATM network patterns where the node demands and flow between these nodes are considered. By combining the frequency information with the total vertiport demands, the number of flights between each origin and destination vertiport are obtained. Afterwards, departure times of the initial UTM scheduling is obtained by mapping the daily demand structure at main airports to vertiports. Demand at airports are split into 15-minute time windows and Gamma distribution $\Gamma(k, \theta)$ is fit to model the daily demand profile. Then, departure time windows are sampled for the corresponding vertiport which sets when the flight should take off from the vertiport in terms of time interval. Once the departure times are found, full trajectories are generated by considering vertical take off and climb to operating altitude which is 300 m, cruise, and vertical landing phases.

The UTM traffic that is generated for a day where the size of the dots refer to capacities of vertiports and the thickness of the lines refer to the number of flights between origin and destination vertiports, as depicted in Fig. 3. 48097 flights (blue lines) that take place between 102 vertiports (red dots) are generated for simulating a complex daily traffic case over Dallas/Fort Worth area. The purpose to use such a large traffic is to show the efficiency and scalability of the developed models. Also, since the traffic complexity is expected to be very high over urban areas with the future AAM system, a high density traffic network is considered.

IV. REPLANNING AFTER POTENTIAL CONFLICTS

Pre-flight replanning service is outlined in this section. A conflict is defined as at least two vehicles to exist in the same cell within the 3-dimensional grid map where each cell has 500 m length and 50 m height. For the flights on the ground, these conflicts can be observed either after contingency management activities of the flights at tactical phase or at the initial flight planning phase. Resolution of these conflicts are not trivial especially when a complex traffic is considered. Therefore, replanning of the flights that are at their pre-tactical phase, plays an important role to resolve the considered conflicts especially the ones observed after contingency events.

Pre-flight replanning can be divided into two processes as potential conflict resolution and demand capacity balancing as depicted in Fig. 4. Especially, when a contingency event takes place or is in the process to be resolved, strategic replanning might be required for the surrounding flights that are at their pre-tactical phase since a contingency situation is able to disrupt the whole UTM traffic in terms of safety and efficiency.

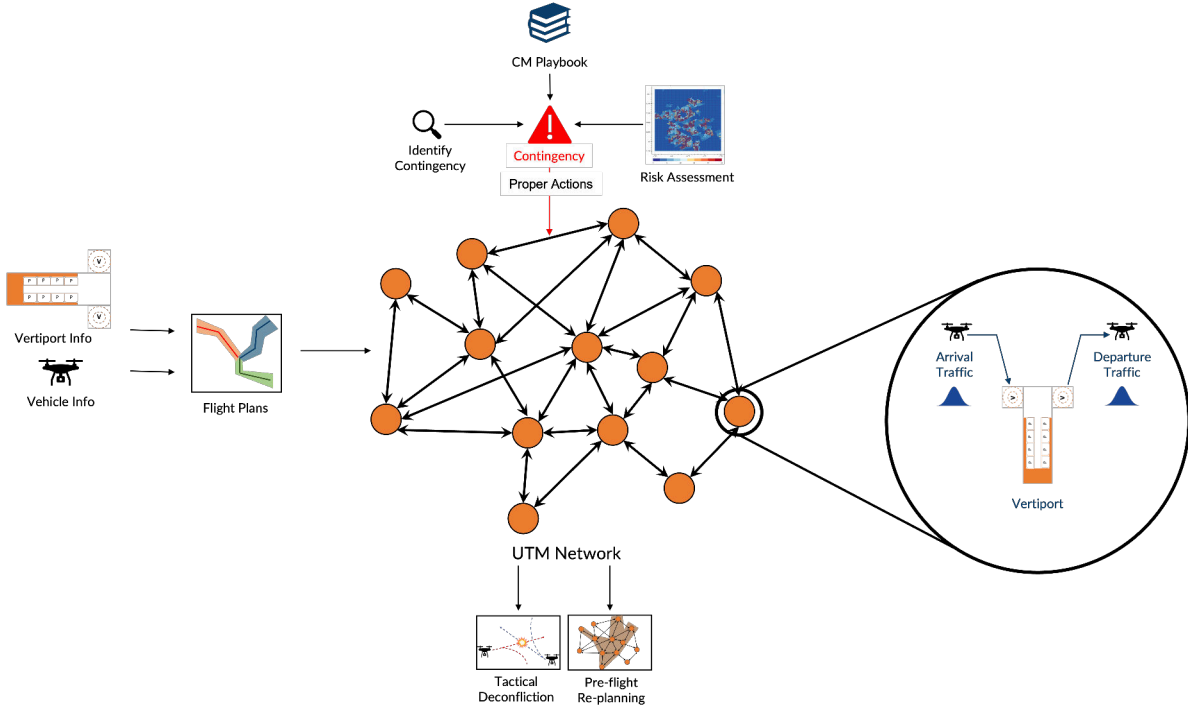


Figure 1. Projected contingency management process from the traffic network perspective.

Therefore, pre-flight/strategic replanning has to be in the loop to achieve the system-wide contingency management concept.

Ground delays are the considered actions for pre-flight replanning. To quickly mitigate potential conflicts and manage demands depending on vertiports' capacity usage, developed modules focus on delay-based actions.

A. Potential Conflict Resolution

First step of the pre-flight replanning model is the resolution of potential conflicts for providing safety. The main objective of the potential conflict resolution is to eliminate conflicts prior to operations. Pre-tactical conflict mitigation process becomes very handy for making the required adjustments and provide safe separation in a quicker way. To mitigate the effects of a contingency event to flights that are about to take off and provide safety for the whole traffic network, potential conflict resolution model is developed.

B. Demand-Capacity Balancing

Flight scheduling in AAM system by considering capacity limits of vertiports is not a trivial problem. After resolving the potential conflicts, demand and capacity balancing process steps in to refine the deconfliction solution by updating flight schedules considering the vertiport throughput. Therefore, the primary goal of the demand and capacity balancing model is to allocate flights efficiently depending on vertiport capacities. Vertipads and if applicable parking slots at vertiports, their condition and availability are the parameters that define the capacity constraint.

V. OPTIMIZATION SCHEME

The sequential pre-flight replanning process is implemented by transforming the aforementioned subproblems into optimization problems. The defined optimization scheme is structured in two steps. First part is the potential conflict resolution part which deals with solving conflicts that are observed in the grid map. Second part is the demand-capacity balancing process that provides rescheduling the flights at vertiports by considering vertiport capacities. Both potential conflict resolution and demand-capacity balancing is achieved by giving only ground delays and they can work iteratively for proper pre-flight replanning. The reason behind for the iterative process is to provide an advantage on solving complex cases since integrating those two problems into one decreases the computational efficiency. Also, that modularized approach allows to solve mentioned individual subproblems, separately. As a simulation environment setting, unit time step is taken as 1 second. Separation minima between vehicles are chosen as 500 meters for horizontal and 50 meters for vertical which also defines the cell sizes of the grid map. In this section mathematical formulation of both potential conflict resolution and demand-capacity balancing models are elaborated.

For potential conflict resolution step, objective is to minimize the variable z which refers to the flexibility that can be created by the system in terms of conflicting time. In other words, it is the buffer time for solving conflicts. $z = 0$ means that the whole traffic is separated properly and no additional buffer time needed. $z > 0$ refers to the time duration allowed that more than one flight can exist in the same cell. Parameters d and x are other decision variables. Ground delay

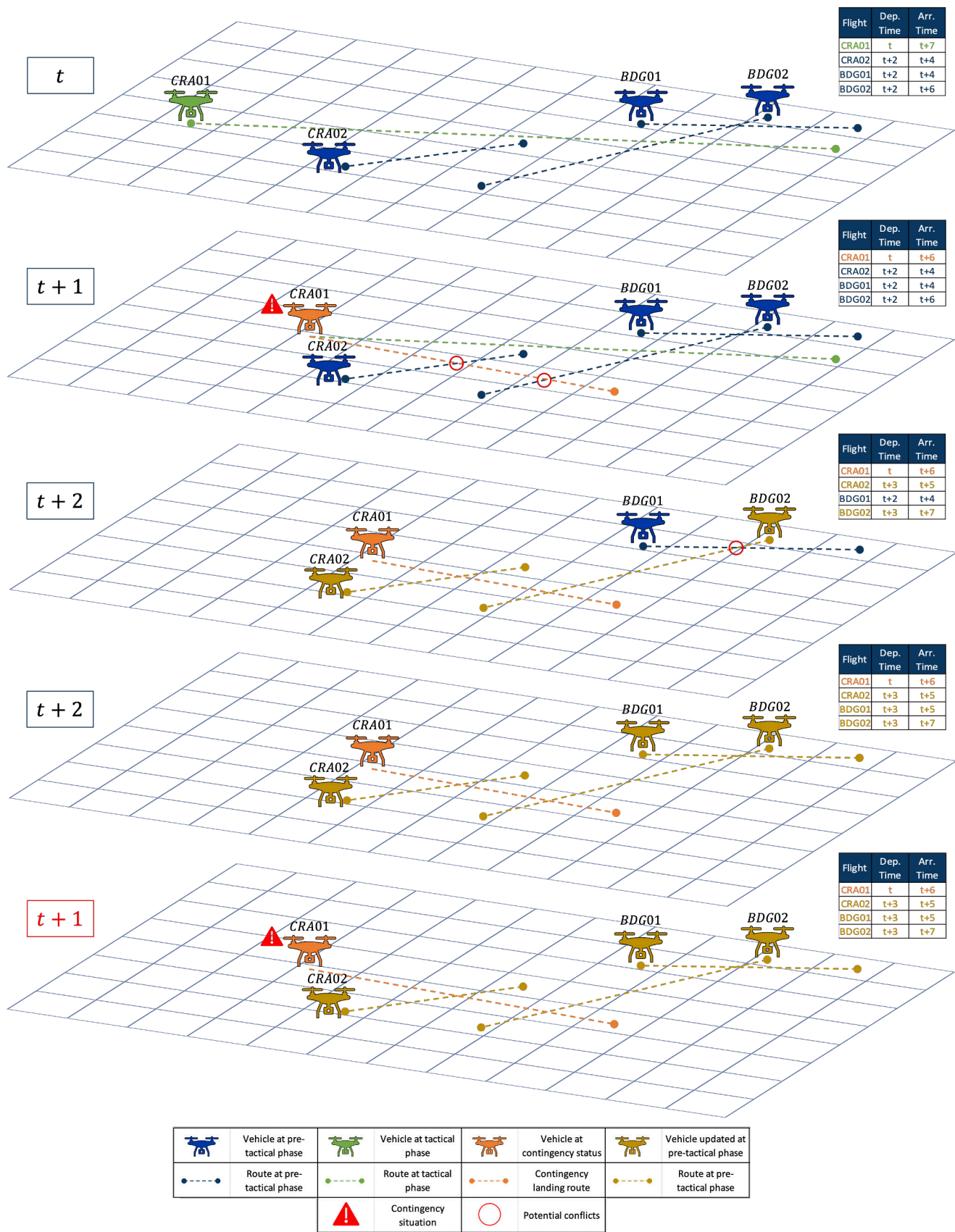


Figure 2. Representation of the pre-flight replanning.

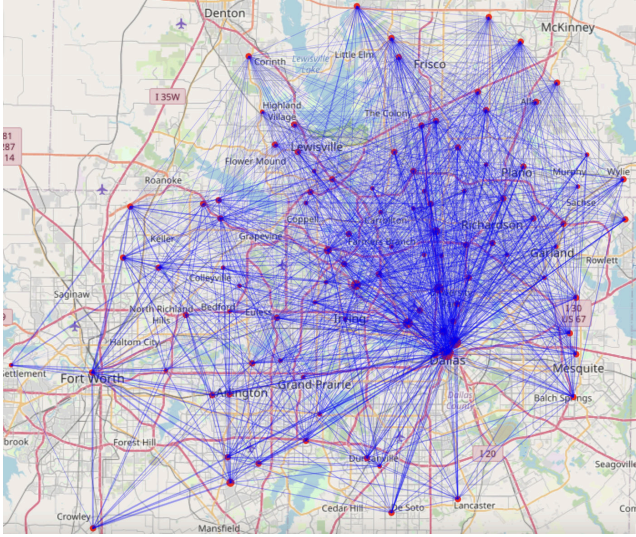


Figure 3. Generated UTM traffic.

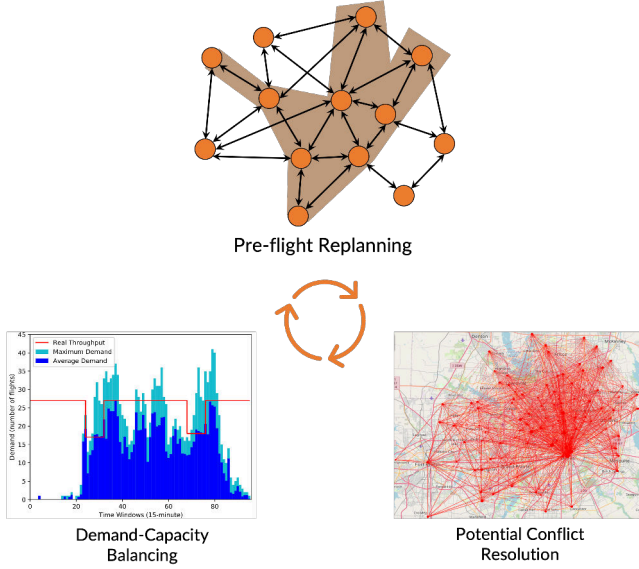


Figure 4. Pre-flight replanning structure.

that are assigned for the flights are represented as d . On the other hand, x is a binary decision variable to make sure one of the overlapping constraints is satisfied for separation and only that one is considered. The defined constraints are about ensuring a safe separation between the flight couples that have possible conflicts within the cells of the defined grid map. Those constraints check the flight pairs' entry and exit times by including related ground delays that are considered. These two constraints work together where one of them is satisfied the other one is cancelled with the dummy variable since one of them is enough for deconflicting the flight pairs. The optimization problem is presented as follows:

$$\begin{aligned}
 & \text{minimize} && z \\
 & \text{subject to} && (f_{j,ext}^c + d_j) - (f_{i,ent}^c + d_i), \\
 & && -M(x_{i,j}) \leq z, \\
 & && (f_{i,ext}^c + d_i) - (f_{j,ent}^c + d_j), \\
 & && -M(1 - x_{i,j}) \leq z, \\
 & && z \in \mathbb{R}, \forall f \in F, d \in [0, 180], \\
 & && \forall i, \forall j \in [1, \dots, N], i \neq j, \\
 & && \forall c \in [1, \dots, K], x_{i,j} \in \{0, 1\}
 \end{aligned} \tag{1}$$

where N is the total number of flights, K is the total number of cells, and M is a significantly large number. Parameters $f_{i,ent}^c$ and $f_{i,ext}^c$ depict the entry and exit times of the flight i to the cell c .

For demand-capacity balancing step, on the other hand, the objective function to minimize is set as the summation of all the delays required for demand and capacity balancing. Binary decision variable vector $t = [t^i, t^{i+1}, t^{i+2}, t^{i+3}]$ represents which one of the time windows is selected as departure delay to set the new departure time. Each element of that vector is a binary variable and the total sum of these elements must be one since only one delay option can be considered.

$$t^i = \begin{cases} 1 & \text{if flight } f \in F \text{ has a delay } d \in D_t \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The day is divided into 5-minute time windows and as the decision variable range, 4 slots are considered which corresponds to no delay, 5-minute delay, 10-minute delay, and 15-minute delay. First constraint is related to satisfy the capacity limits of the vertiports. Total departure and arrival counts at a specific vertiport within a specific time window is constrained with that specific vertiport's capacity limit for the considered time window. Second constraint is about to satisfy the flight duration time. Each flight has a fixed flight duration and given delays have to be in line with that flight duration as well. The reason for that constraint is to not consider the airborne delays since the optimization scheme is structured to consider only ground delays. Final constraints are related to assign only one delay option within the defined delay sets for departure and arrival times. The summation of the 4-slot binary variable vector t for all flights has to be equal to one. The corresponding optimization problem is presented as follows:

$$\begin{aligned}
& \underset{t}{\text{minimize}} && \sum_{f \in F} (t_{f,dep} D_t^T) \\
& \text{subject to} && f_{dep,v,tw} + f_{arr,v,tw} \leq C_{v,tw}, \\
& && (a_f + t_{f,arr} A_t^T), \\
& && -(d_f + t_{f,dep} D_t^T) = f_{dur}, \\
& && \sum_{i=0}^3 t_{f,dep}^i = 1, \sum_{j=0}^3 t_{f,arr}^j = 1, \\
& && \forall v \in V, \forall f \in F, \\
& && D_t, A_t = [0, 5, 10, 15], \\
& && t_{f,dep}, t_{f,arr} = [t^i, t^{i+1}, t^{i+2}, t^{i+3}], \\
& && \forall t \in \{0, 1\}, \forall tw \in [0, 288]
\end{aligned} \tag{3}$$

where F is the considered set of flights, f_{dur} is the duration for the flight f , and $f_{dep,v,tw}$ is the total number of departure flights departing from vertiport v at time window tw . V is the vertiports list and $C_{v,tw}$ is the capacity limit for the vertiport v at time window tw . D_t and A_t include the time window delay options where there are four options as possible delay actions. Lastly, $t_{f,dep}$ is a list of binary variables that helps to select the delay set for flight f from D_t .

The potential conflict resolution module runs first in the iterative approach. The first purpose is to solve all the potential conflicts observed for the flights at their pre-tactical phase. After the conflicts are resolved, demand-capacity balancing module starts and allocates demand by taking vertiport throughput into account. After the demand and capacity balancing step, new conflicts may be observed since two models work in an iterative manner. Therefore, convergence of that approach has to be tested to show if the system gets better in terms of resolving conflicts. Different traffic networks with different number of flights from 500 to 10000, are generated to test if the model converges in various case. Fig. 5 and Fig. 6 show an analysis on the convergence of iteratively using these two models. 100 Monte Carlo simulations were conducted. 67.62% of the conflicts are resolved in average after first iteration. The mean value for the percentage of conflict resolution after second iteration step is obtained as 86.80 %. In other words, in the second step, 86.80% of the observed conflicts at the beginning are resolved. Each conflict for each traffic is resolved after more than two iterations, depending on the size of the traffic and number of conflicts. Resolution time, conflict resolution percentage, or number of iterations can be used as a stopping criterion once the intended success rate is achieved.

VI. CASE STUDIES AND INTERPRETATION

This section covers the implementation of the pre-flight replanning model over the initial flight planning process of a whole day traffic and replanning of the traffic after safety critic scenarios are observed within the network. A high density traffic is considered since the expectation with the future

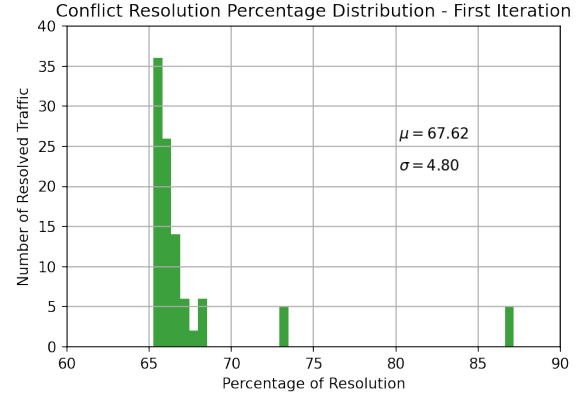


Figure 5. Percentage of conflicts resolved after first iteration.

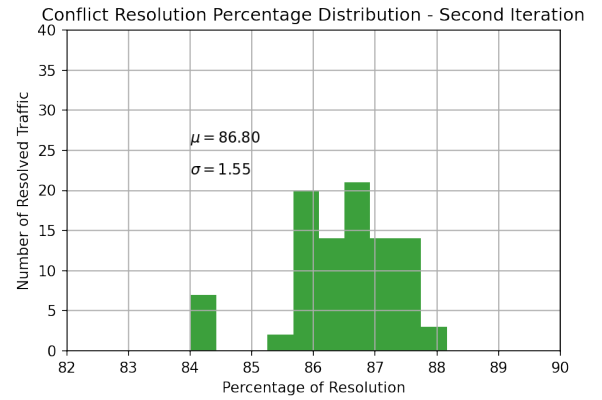


Figure 6. Percentage of conflicts resolved after second iteration.

AAM concept is a highly complex airspace and to show the algorithm efficiency and scalability even under that condition.

Python 3.8 is used for data preparation and to build optimization models and Gurobi Optimizer version 9.5.2 is used as a solver. The simulations have been run on AMD Ryzen Threadripper Pro 3995WX 64 Cores computer with 32 GB of RAM and Linux OS.

A. Strategic Planning of the Network Traffic

First scenario is about flight planning process of a daily UTM traffic. After flight plans are initially generated by not considering conflicts, first the potential conflict resolution model is used to eliminate the observed conflicts. Fig. 7 illustrates the conflicted cells of the initial flight plans throughout a whole day. 400738 conflicted flights (orange cells) are observed for the day with the initial flight planning.

All of the conflicts are resolved in 37.80 seconds. The maximum delay given by the model to an individual flight is observed as 3 minutes. Given delays by the deconfliction module and how many vehicles are affected can be seen in Fig. 8. Additionally, the average ground delay is observed as 87 seconds per flight.

After safety is provided by the potential conflict resolution model, demand and capacity balancing process takes place to

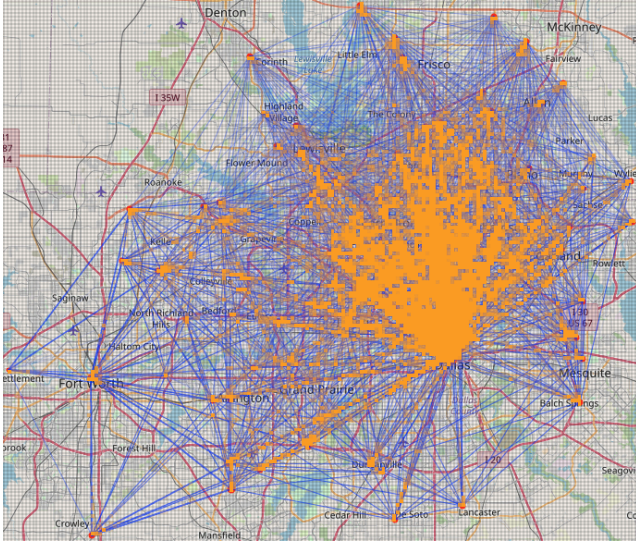


Figure 7. Initial flight plans before conflict resolution.

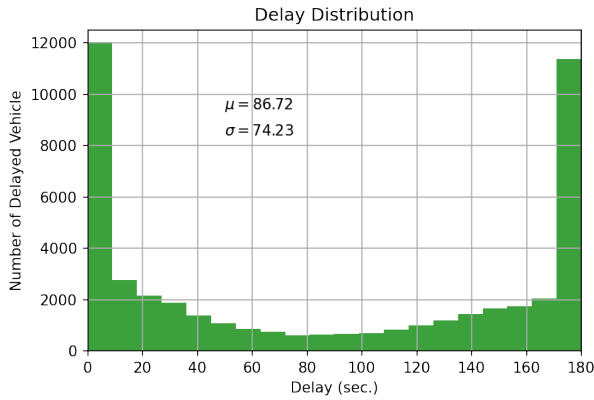
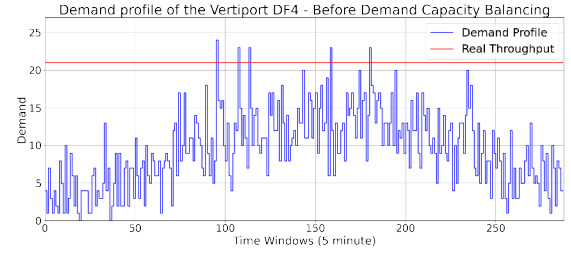


Figure 8. Given delay distribution after conflict resolution for "strategic planning of the network traffic" case.

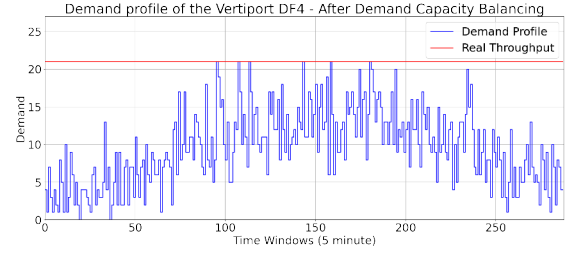
allocate flights efficiently within the vertiports. Fig. 9a depicts the demand profile at vertiport DF4. As it can be seen at several time windows, demand exceeds the real throughput. After demand-capacity balancing, all the demand values at each time window drops under the capacity limit as in Fig. 9b.

Similarly, DF21, another vertiport from the UTM network, has demand more than its capacity at some of the time windows as shown in Fig. 10a. Demand and capacity balancing model solves that capacity excess at DF21 as given in Fig. 10b. Demand and capacity problem is solved in 5.85 seconds for the initial flight scheduling case.

Solution for the strategic planning of the whole traffic case, is provided in three steps with the iterative pre-tactical replanning approach. The reason why for the three-step solution is that after demand-capacity balancing process new conflicts are expected to be observed. Therefore, complete solution including both conflict resolution and demand-capacity balancing problems, is completed in 97.84 seconds. First iteration

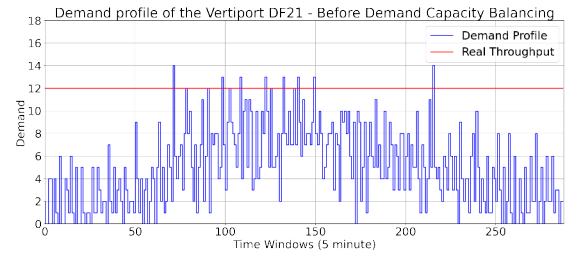


(a) Before demand and capacity balancing at DF4.

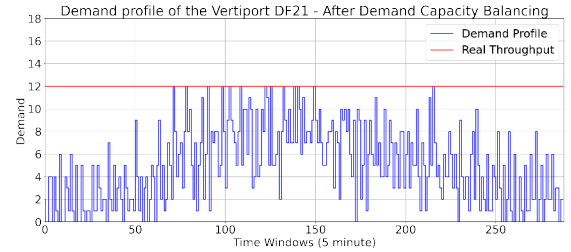


(b) After demand and capacity balancing at DF4.

Figure 9. Demand profile at vertiport DF4.



(a) Before demand and capacity balancing at DF21.



(b) After demand and capacity balancing at DF21.

Figure 10. Demand profile at vertiport DF21.

which resolved 67% of the conflicts with demand and capacity balancing takes 43.65 seconds. After second iteration, resolved conflicts are improved to 82% and in third iteration all of the conflicts are mitigated by also considering the capacity limits of vertiports. Fig. 11 elaborates the iteration process of the iterative pre-tactical replanning model in the strategic planning case.

B. Replanning after Contingency Events

In this scenario, resolution of the potential conflicts due to contingency management activities is considered in a conflict-free and demand-capacity balanced traffic. The scenario in-

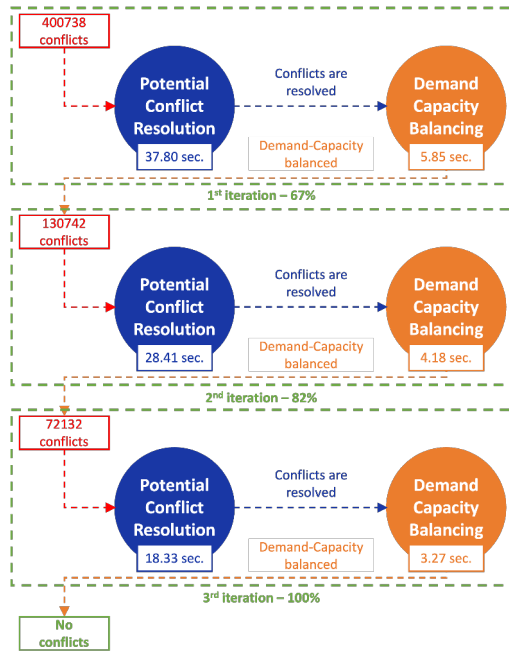


Figure 11. Iterative solution process for the strategic planning of the network traffic case.

involves several flights to suffer from a safety critical situation where the flights require and are able to both loiter and execute an emergency landing action. It is assumed that the contingent flights are either loitering and continuing their flights after the issue is resolved or taking emergency landing actions and changing their intended trajectories. Emergency landing action includes landing at an existing vertiport or an unprepared location. Changes in initial flight plans cause new potential conflicts with the flights that are in the pre-flight stage. This scenario, specifically focuses on these potential conflicts to resolve. After the flights are deconflicted and the environment becomes safe, demand and capacity balancing process takes place to properly allocate vertiport capacities. Fig. 12 shows the conflicted cells that are caused by contingency events, affecting the flights at their pre-tactical phase. There are 714 potential conflicts (yellow cells) observed on 255 flights throughout the day after contingency events or activities.

For the preparation of this case, it is assumed that there are 255 flights that are affected by new conflicts observed after contingency events and relevant actions within the traffic network. Thus, network requires these conflicts to be mitigated especially for the surrounding traffic at pre-flight stage where these flights are already deconflicted at the beginning based on their initial flight plans. Contingent flights are not able to change their departure delay since they are already at their tactical phase. After conflict resolution, demand and capacity balancing activities are conducted to allocate demand depending on the vertiport capacities.

Every conflict observed after contingency related activities, is resolved under 1 second. Delays observed for the flights that are affected by contingencies, can be seen in Fig. 13

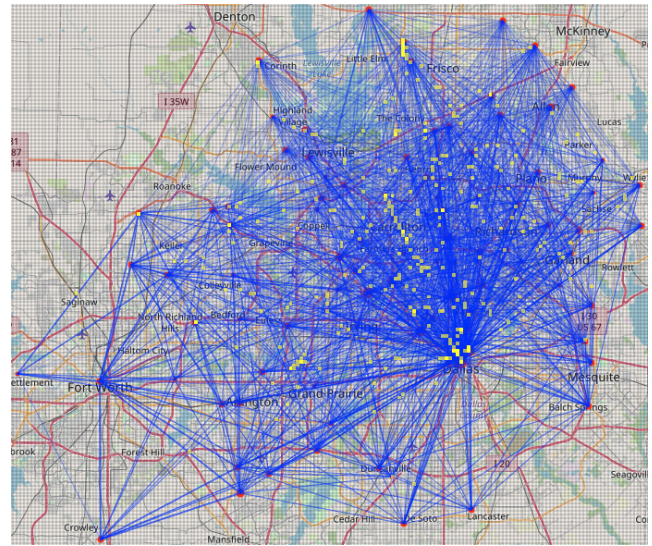


Figure 12. Potential conflicts due to contingency events.

which includes number of delayed flights and total delay given. According to that, the average ground delay given is around 20 seconds for each flight.

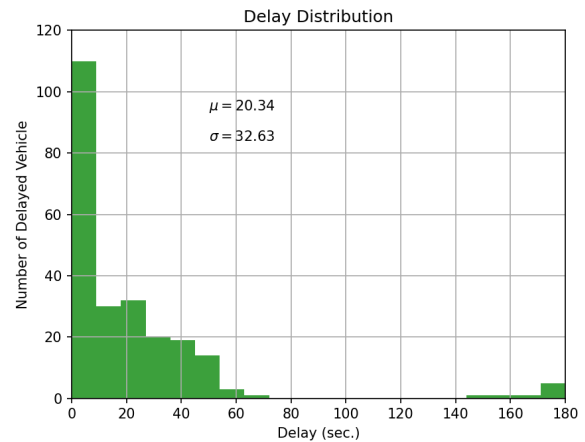
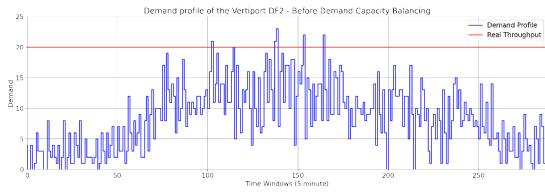


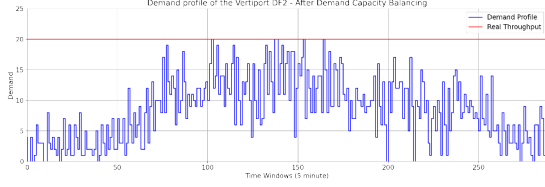
Figure 13. Given delay distribution after conflict resolution for "replanning after contingency events" case.

When the potential conflict resolution model ensures safety in the traffic after contingency situations, demand-capacity balancing process is involved to prevent excess capacity at vertiports. After resolving the conflicts observed due to contingency events within the network, Fig. 14a shows the demand profile before rescheduling flights considering demand and capacity balance at vertiport DF2. Upon demand and capacity balancing at the vertiport network, it can be observed in Fig. 14b that the demand values comply with the capacity limits.

Similarly at vertiport DF98, Fig. 15a and Fig. 15b represent the demand profile before and after optimizing the demand-capacity allocation, respectively. In a similar way to potential conflict resolution after contingency management, demand and



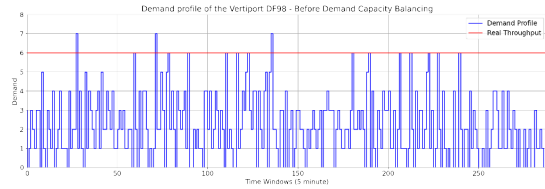
(a) Before demand and capacity balancing at DF2.



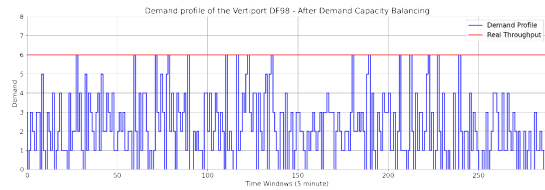
(b) After demand and capacity balancing at DF2.

Figure 14. Demand profile at vertiport DF2.

capacity balancing problem also took under 1 second to be solved.



(a) Before demand and capacity balancing at DF98.



(b) After demand and capacity balancing at DF98.

Figure 15. Demand profile at vertiport DF98.

The replanning after contingency events case is resolved with one-step iteration via the pre-tactical replanning solution. The problem is solved in one step which means demand-capacity balancing model did not create any new conflicts. The reason for that might be observing less amount of conflicts. Both the potential conflict resolution and demand capacity balancing modules took around one second to solve this scenario. The solution process is depicted as in Fig. 16.

VII. CONCLUSION AND FUTURE WORKS

In this study, we presented two optimization models for potential conflict resolution and demand-capacity balancing which can work iteratively for the pre-tactical replanning purpose. Pre-tactical replanning problem is significant for the flights that are still at their pre-tactical phase, yet, there are potential conflicts observed for them due to contingency management related activities for the flights that are in their tactical phase within the AAM system. Developed model is suitable

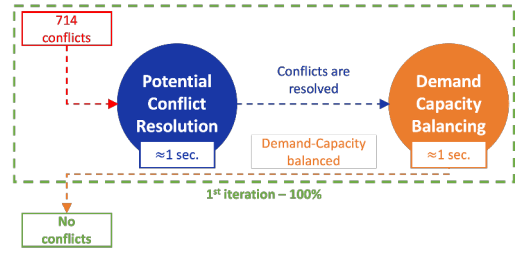


Figure 16. Iterative solution process for the replanning after contingency events case.

to be used in strategic planning problem as well. The model built is examined through a highly dense traffic and when the safety is compromised. Since the problem is safety related and it is important to provide quick potential conflict resolution, an efficient optimization scheme is introduced that resolves conflicts quickly. Quick resolution allows the model to be used after every safety related event in real time. On the other hand, demand and capacity balancing model considers the capacity limitation at vertiports for solving the pre-tactical replanning problem. Additionally, it enables an efficient allocation of the demand, constrained with vertiport capacities.

As a future work, instead of having an iterative process as potential conflict resolution and demand-capacity balancing, we plan to combine the optimization scheme for better performance. Likewise, we plan to solve the pre-tactical replanning problem with reinforcement learning based models and compare the pearls and pitfalls between optimization and reinforcement learning based solutions. The UTM ecosystem will be enhanced as well by including different type of vehicles such that various types of lift and cruise and vectored thrust vehicles. Also, fairness concept will be worked on to implement into our replanning process, to create a fair environment for every AAM system user. In addition, new action sets such as latitude, longitude, altitude change alongside departure time, will be considered to discover more options for increasing safety and efficiency within the traffic. Last but not least, risk assessment based pre-tactical replanning process will be examined to create a safer environment.

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