Strategies to Mitigate Tight Spatial Bounds Between Conflicts in Dense Traffic Situations

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***Abstract*—The constant and rapid increment of air traffic demand is pushing current air traffic control systems to their limits. One of the factors that can contribute to extend current air space capacity, is the development of automatic decision support systems to assist tactical aircraft conflict detection and resolution. However, the combinatorial nature of the problem poses several challenges for such a task. We define an aerial ecosystem as the set of en route aircraft that can be affected by a conflict resolution. In dense traffic there can be situations were conflicts coexist in time with tight spatial bounds. Such conflicts form what we call compound aerial ecosystems. We investigate several strategies to decompose such ecosystems, in order to treat each conflict separately and reduce complexity. These strategies prove to be successful in the majority of the encountered cases.**

***Keywords*—Spatio-temporal regions, conflict resolution, resolution capacity, resolution complexity, ecosystems, compound ecosystems**

I. Introduction

Air traffic management's (ATM) mission is to make air transportation possible. This is attained by the means of efficient, environmentally friendly, and socially valuable systems, which have safety as their principal goal [1], [2]. In en-route traffic, at tactical level, safety is quantified through a minimum horizontal separation distance and a minimum vertical separation distance, that needs to be maintained between aircraft. A simultaneous violation of both horizontal and vertical separation is called a conflict. Current ATM provides minimum pairwise separation through a system with human air traffic controllers (ATCo) at the core of its decision making. In order to make the task feasible, in each sector navigation points are fixed and all aircraft's routes have to pass through them [3]. This result in few, repetitive conflict geometries which ATCos are trained to resolve.

As the air traffic demand is increasing in a rapid manner, economical and ecological costs caused by delays and extra fuel consumption are escalating [4]. Therefore, research focusing on alternative solutions is being performed. The most supported among them comes under the name Trajectory-Based Operations (TBO) Concept [5]. The realization of TBO requires four main technological enablers [6], specifically improvement of the aircraft computing systems, i.e. the Flight Management Systems (FMS), change of the communication technologies from voice communication to data communication, modernization of the surveillance systems (use ADS-B instead of RADAR technologies), and implementation of Air Traffic Control Decision Support Tools (DST).

Such a DST, often called Conflict Detector & Resolver (CD&R), should be able to identify, beyond the aircraft that involved in the potential conflict, the surrounding traffic aircraft that can be directly affected by such a solution. Koca et al. [7] identify the aircraft that might be affected by a resolution, after a potential conflict is detected. The conflict aircraft together with the aircraft that might be affected by a potential resolution are called an ecoystem. To make this possible, spatio-temporal regions are used. Each of these regions, constructed around each aircraft's original trajectory, contains all the trajectories that can result if the aircraft performs a feasible maneuver.

Koca et al. [7], define an ecosystem based on a single pairwise conflict and assume that detected conflicts are far enough from each other, to be treated independently. However, in futuristic, denser traffic this assumption will not necessarily hold true.

In this work, we treat simple aerial ecosystems, that affect each other by being close enough in time and space. We call such groups of simple aerial ecosystems, compound aerial ecosystems (henceforth referred as simple ecosystems, and compound ecosystems). We propose various strategies how these compound ecosystems can be decomposed and solved independently. This should result in a lower combinatorial complexity of the resolution procedure. To evaluate these strategies, we use historical, planned traffic data from Demand Data Repository II (DDR II) of EUROCONTROL. Furthermore, denser, synthetic traffic is obtained by constricting the altitude of the flights in the original traffic. This results in a higher number of compound ecosystems. However, we observe that the simple ecosystems themselves do not increase significantly in depth. We report the success rate of each strategy.

The rest of this paper is organizes as follows: in section, II we explain how we modelled the aircraft dynamics. We present in section III the idea of continuous space-temporal regions. In section IV, we summarize how we use the space-time regions to identify relevant aircraft in a conflict. We present and discuss the results of our work in section V. In section VI, we draw conclusions and suggest steps for further research.

II. Trajectory Dynamics Model

We employ in this work a widely used manner to model the aircraft dynamics [8], [9], [10], [11], [12], [13]. The trajectory of the flight is modeled as a series of 4D (space-time) waypoints. The aircraft is treated as a point mass in a 3D Euclidean space, evolving over time. We obtain its x and y coordinates by applying the stereographic projection [14] on the its latitude and longitude. The z coordinate represents the aircraft's altitude. During the flight, the involved aircraft are assumed to have piece-wise constant velocity between two consecutive waypoints.

Given the above, the flight state variables of the aircraft is specified as $(x, y, z,\ v_x, v_y, v_z)$, where (x, y, z) are its coordinates and (v_x, v_y, v_z) its velocity components.

III. Continuous Space-Temporal Regions

The core idea of the spatio-temporal regions lies in the observation that instead of trying to assign a single trajectory to each aircraft that must maneuver in the proposed solution, a region can be given to each one of them. Based on these conflict-free regions, aircraft are enhanced with the ability to modify the part of their trajectories inside the assigned regions while maintaining separation minima between aircraft.

Mathematically, classical approaches assign to each aircraft a function describing their motion:

$$\begin{cases} x = x(t) \\ y = y(t) \\ z = z(t) \end{cases} \tag{1}$$

Assigning a region instead could be expressed as:

$$[x(t), y(t), z(t)] \in S(t) \tag{2}$$

where $S(t)$ is a dynamic volume, evolving over time.

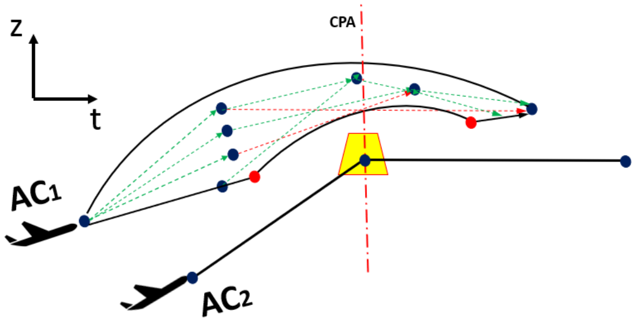

Figure 1. Assigned safe region for AC_1 and examples of various legs it can construct (green segments), or not (red segments)

In figure 1 we consider a single spatial dimension and time to illustrate safe spatio-temporal regions[1]. The black continuous line is the part of the original flight segment that can be preserved if AC_1 wants to. The black continuous curves are the border of AC_1 safe region (i.e. a conflict-free area). The green dashed lines represent feasible legs that AC_1 can fly, while the red dashed lines represent legs which will cause a loss of separation, i.e. a conflict. The trajectory of AC_2 is represented as well. The yellow trapezoid represents the region in space-time where the original conflict would occur, and the red dashed line shows the moment when the Closest Point of Approach (CPA) [15] is reached. The black dots represent feasible, conflict-free waypoints for each aircraft.

We can see that after a safe region is constructed, AC_1 has the ability to choose when it is going to perform a maneuver without the necessity to agree with AC_2 on the exact time instance[2] and this is essentially the system's ability to provide resilient solutions.

The regions we use in this work, are the regions based on horizontal maneuvers, proposed in [7]. In this type of regions, the aircraft can alter their horizontal velocity direction, while they maintain the velocity module.

IV. Identification of Aircraft Relevant to a Conflict Resolution using Spatio-Temporal Regions

We summarize, in this section, the two-step procedure, proposed by Koca et al. [7], to detect aircraft that are relevant to a conflict resolution procedure.

Both the cluster and the ecosystem are sets of aircraft based on pairwise spatio-temporal interdependencies. The concept of spatio-temporal interdependencies was the object of investigation in several European projects, such as PHARE [16], 4DCoGC [17], PARTAKE [18], and AGENT [19]. Even though the time horizons and purpose of use vary between them, in all of these projects two aircraft were declared interdependent if their assigned space-time regions (which can consist of a single trajectory, an assemble of trajectories, or some continuous space-time region) were closer than they should be (different distance metrics were used in each project).

More concisely, let AC_i and AC_j be two aircraft which can be en route, or have a planned flight. Let R_i and R_j be the space-time regions assigned to AC_i and AC_j respectively. Then:

$$AC_i \perp\!\!\!\perp AC_j \iff R_i \cap R_j \neq \emptyset \tag{3}$$

where $\perp\!\!\!\perp$ stands for "interdependent".

Based on the concept of the interdependency, we will construct a hierarchical structure over aircraft. Let there be a potential conflict between at least two en route aircraft. We will denote the set of aircraft involved in this conflict by C and define a hierarchy over the traffic, based on C, and denoted by H_C. The members of the first order of H_C are the members of C. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are not members of a lower order, but have an interdependency with a member of the $(i-1)^{th}$ order. Formally, given that H_C

[1] Cases when several aircraft form regions simultaneously are supported as well

[2] As long as it is inside the assigned safe time interval

is the defined hierarchy, and $H_C(i)$ is the set of members of the i^{th} order of this hierarchy, we define:

$$\begin{cases} H_C(1) := & C \\ H_C(i) := & \{\text{AC} \in F | \text{AC} \in H_C^-(i) \wedge (\exists \text{AC}' \in \\ & H_C(i-1) : \text{AC} \perp\!\!\!\perp \text{AC}')\} \end{cases} \quad (4)$$

where F is the set of all aircraft we can consider, and $H_C^-(i) := F \setminus \cup_{j=1}^{i-1} H_C(j))$.

In other words, H_C contains at its first order the pre-selected set of aircraft C. At its second order it contains aircraft which are not members of the first order, but have at least an interdependency with a member of the first order. In the third order we find aircraft that are not members of the first, or second order, but have at least one interdependency with a member of the second order. The logic goes on recursively.

A. Cluster Identification

Concrete implementations of the hierarchical traffic idea, defined above, depend on concrete implementation of the spatio-temporal regions we use to define the interdependencies. Let F denote the set of aircraft we will consider and AC_i and AC_j be two aircraft in it. Let further B_i and B_j be two spatio-temporal boxes constructed respectively around the trajectories of AC_i and AC_j, big enough to contain all the possible locations of the aircraft after feasible maneuvers are possibly performed. Then:

$$AC_i \perp\!\!\!\perp_{cl} AC_j \iff B_i \cap B_j \neq \emptyset \quad (5)$$

where $\perp\!\!\!\perp_{cl}$ stands for "dependent on clustering level".

In Fig. 2 an example is given, by representing the horizontal

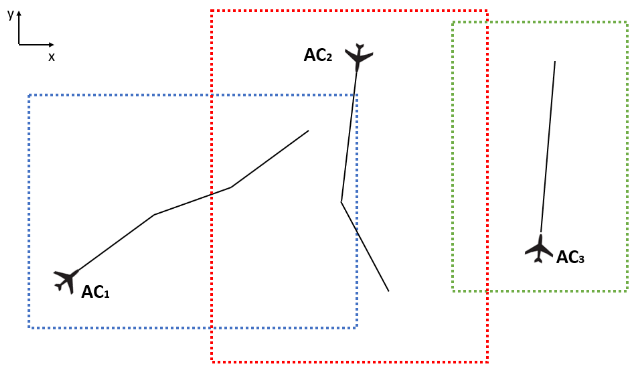

Figure 2. Example to illustrate cluster pairwise interdependencies.

components (x and y) of the spatio-temporal boxes. In this example, the blue box is the box of AC_1, the red one of AC_2 and the green one of AC_3. There is a cluster-level interdependency between AC_1 and AC_2, another one between AC_2 and AC_3, but no cluster-level interdependency exists between AC_1 and AC_3.

Based on the given interdependency definition (5), and the hierarchy definition (4), we will construct the hierarchical structure over aircraft, called cluster. Let there be a potential conflict between at least two en route aircraft. We will denote the set of aircraft involved in this conflict by C. Members of C then, are members of the first order of the cluster. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are not members of a lower order, but have an interdependency with a member of the $(i-1)^{th}$ order. Formally, given that Cl is the set of cluster members and $Cl(i)$ is the set of cluster members of the i^{th} order, we define:

$$\begin{cases} Cl(1) := & C \\ Cl(i) := & \{\text{AC} \in F | \text{AC} \in Cl^-(i) \wedge (\exists \text{AC}' \in \\ & Cl(i-1) : \text{AC} \perp\!\!\!\perp_{cl} \text{AC}')\} \end{cases} \quad (6)$$

where $Cl^-(i) := F \setminus \cup_{j=1}^{i-1} Cl(j))$.

In the example of Fig. 2, if we assume that AC_1 is a conflict aircraft[3], but AC_2 and AC_3 are not, then AC_1 will be a member of the first order, AC_2 a member of the second order and AC_3 a member of the third one.

B. Ecosystem Identification

The cluster structure, from the way its interdependencies are constructed, is too conservative. The use of spatio-temporal boxes, even though it is computationally efficient, results in an overestimation of the complexity of a given scenario. In order to provide a better estimation of the scenario complexity and the interdependencies between the aircraft, we introduce here the "ecosystem" structure. The difference between a cluster and its corresponding ecosystem lies on the nature of their interdependencies. While to construct a cluster, spatio-temporal boxes were used, as a mean of approximating the results of performing some maneuvers, to construct an ecosystem we will check the actual possible maneuvers.

Let F be the set of all aircraft we will consider. Let $tr(AC_k)$ denote the original trajectory of an aircraft AC_k in F, and M_k the set of possible maneuvers for AC_k. Furthermore, let $tr(AC_k, m)$ be the modified trajectory of AC_k after performing a maneuver $m \in M_k$. Then, given two aircraft AC_i and AC_j from F and their corresponding set of possible maneuvers M_i and M_j,

$$AC_i \perp\!\!\!\perp_{ec} AC_j \iff \exists m_k \in M_i, m_l \in M_j : \text{conf}(AC_i, AC_i, m_k, m_l) \quad (7)$$

where $\perp\!\!\!\perp_{ec}$ denotes an "interdependency in ecosystem level" and $\text{conf}(AC_i, AC_j, m_k, m_l)$ denotes that aircraft AC_i and AC_j will be in conflict if they perform maneuvers m_k and m_l respectively.

Spatio-temporal regions become relevant in the calculation of interdependecies at the ecosystem level. Instead of considering all possible pairs of trajectories, it is enough to check for an inter-regional conflict, between regions that include all possible maneuvers for each aircraft. This will suffice to consider all physically feasible simple heading maneuvers that a CD&R system can issue. Note that, while both the spatio-temporal regions proposed in the clustering procedure (i.e. the

[3]We assume AC_1 is in conflict with aircraft AC_0. AC_0 is not depicted in Fig. 2

spatio-temporal boxes) and the ones proposed here contain all feasible heading maneuvers, the spatio-temporal boxes claim a lot of extra space which the aircraft cannot actually utilize. These claims are eliminated in the spatio-temporal regions used in the ecosystem, the construction of which is briefly described in the previous section and is described in details in [7].

Given the ecosystem interdependency definition, the ecosystem can be also defined. Let Cl be a given cluster. The aircraft which are first order members of the cluster are also first order members of the ecosystem. Members of the i^{th} order, where $i \neq 1$, are the aircraft that are members of $Cl(i)$ and that exists an ecosystem member of $(i-1)^{th}$ order with which they have an interdependency at the ecosystem level. Formally, if Ec is the set of ecosystem members and $Ec(i)$ the set of ecosystem members of i^{th} order, then:

$$\begin{cases} Ec(1) := Cl(1) \\ Ec(i) := \{\mathrm{AC} \in Cl(i) | (\exists \mathrm{AC}' \in Ec(i-1) : \mathrm{AC} \perp\!\!\!\perp_{ec} \mathrm{AC}')\} \end{cases} \tag{8}$$

An ecosystem can be clearly defined directly in a given traffic, without the need of a corresponding, predefined cluster. In this work, we use a brute force approach to and check all the pairs. Therefore, the use of a cluster comes with high computational costs. However, using more sophisticated techniques, like hextree subdivisions [20], the computational efficiency can increase even further. In such a scenario, the ecosystem structure can be constructed directly from the traffic, without the cluster structure being a mediator.

Note that, because of the more complex structure of the ecosystem windows, which are changing shape in time, a schematic representation, similar to the one provided in Fig. 2 for the cluster case, could be misleading. Therefore, we decide to not provide one.

C. Compound Ecosystem Formation

The given ecosystem definition is based on a single pairwise conflict. We will refer such ecosystems, as simple ecosystems. In dense traffic situations, there can be conflicts that are found nearby and their corresponding, simple ecosystems might coexist in time with tight spatial bounds. A methodology therefore, to identify such cases is mandatory.

Let ec_1 and ec_2 be two simple ecosystems, $[t_{s1}, t_{e1}]$, $[t_{s2}, t_{e2}]$ their respective time intervals, and S_1, S_2 be their corresponding set of members-aircraft. Then ec_1 and ec_2 are dependent in case their time intervals overlap and they contain some common members.

We will define a compound ecosystem based on pairs of merged simple ecosystems. More specifically, let G be a defined graph, where each node represents a simple ecosystem and each edge represents a dependency between two simple ecosystems. We define a compound ecosystem to be a connected component in the created graph G, that contains at least two ecosystems.

Figure 3 illustrates the definition. We see that there are 6 initialized ecosystems. Moreover, there are some dependencies

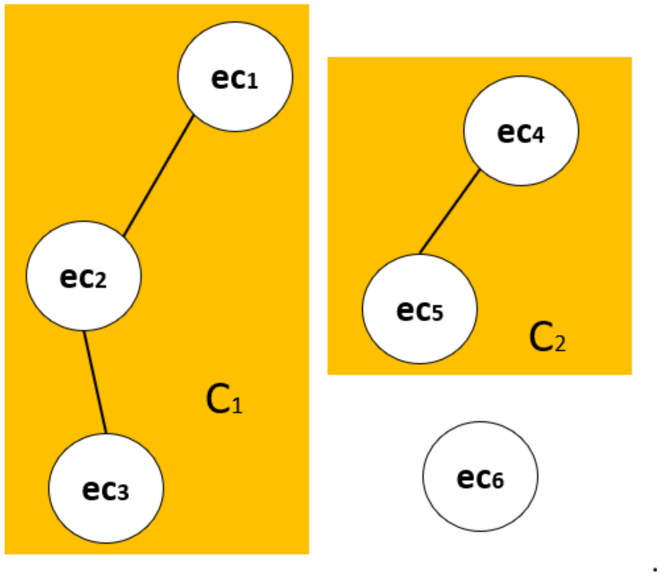

Figure 3. Illustration of two detected compound ecosystems, and an isolated simple ecosystem.

detected. Specifically, there is a dependency between ec_1 and ec_2, another between ec_2 and ec_3, and a last one between ec_4 and ec_5. Based on these dependencies two compound ecosystems are formed. the first one, C_1 contains the members of ec_1, ec_2, and ec_3, while the second, C_2 contains the members of ec_4 and ec_5. Note that ec_6 is an isolated, simple ecosystem.

D. Decomposition Strategies

Given the definition and the hierarchical nature of the compound ecosystems, there are different ways a decomposition can be constructed. We propose four simple strategies, which we will elaborate in the following paragraphs. The purpose of attempting to perform such decompositions is to decrease the combinatorial complexity that conflict resolvers will face.

We first consider the amount of time overlap. If it is less than 10% for either of the ecosystems, we cut the overlapping time interval from the duration of the ecosystem that starts later. This choice is based on the way we construct the ecosystems, i.e. we gather data from 5 minutes before the conflict and 2 minutes after the conflict. Illustration of how the time overlap is calculated is shown in Fig. 4a.

Through the second strategy, we will constrain the considered depth of the ecosystems in the sought solutions. This strategy can tackle two types of scenarios. Firstly, cases when none of the common members are conflict aircraft. Secondly, cases when there is a common member that is a conflict aircraft, however its order on the remaining ecosystems is higher than 2. Fig. 4b illustrates a scenario where such a strategy can be applied. The conflict pairs are $AC_1 - AC_2$ and $AC_4 - AC_5$. The only common member between the two simple ecosystems is AC_3. Fig. 4c shows a scenario when the common member is a conflict member in one of the simple ecosystems. AC_5 is in conflict with AC_6 and thus a first order member of that simple ecosystem, but it's a member of order 4 for the other ecosystem. In this case, constraining the depth of that simple ecosystem, will allow us to consider each ecosystem separately.

When this is not the case, we attempt to use the third strategy. Here, we attempt to solve the ecosystems by not moving the common, conflict member. In doing so, we restrict the solution in such a way that each ecosystem is solved by moving the non-common members, thus minimizing how the solution of one ecosystem affects the other. A toy example, where this strategy can be applied is presented in Fig. 4d. There, we constrain AC_2 and by maneuvering AC_1 and AC_3, both conflicts can be solved independently.

Finally, if no solution has been found by considering any

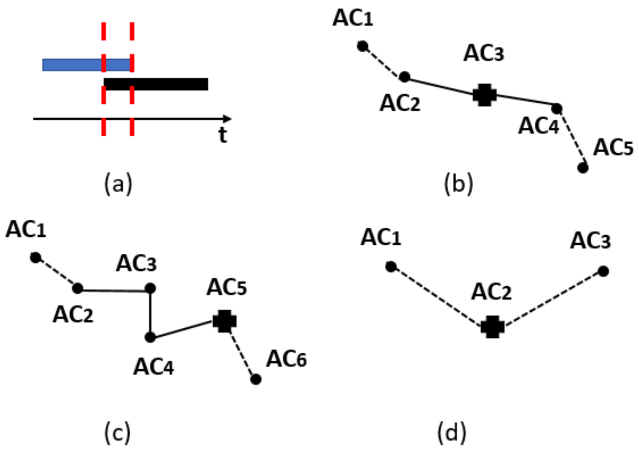

Figure 4. One illustrating scenario for each strategy.

of the above strategies, the compound ecosystem will have to be considered as a whole. This means that we will have to treat situations with more than one conflict present.

V. Simulation Results

A. Data and the parameters used

We evaluate our work using traffic data from Eurocontrol's (DDR II). The real historical traffic is from 12.02.2019. Furthermore, we simulate more congested traffic by compressing the flight level once by 25%, and then by 50%. Since we are interested in en route traffic conflicts, We compress the flight level (FL) of waypoints only if it is above 250 (i.e. 25000 feet), otherwise we keep the flight level as is.

Conflicts were detected using the methodology proposed in [21] with added filters to discard false positives, conflicts that last more than one minute, and conflicts that are found bellow FL250. As soon as a conflict is detected, the planned trajectory of each involved aircraft is filtered from five minutes before entering the conflict interval until two minutes after exiting it. Thus, the duration of the ecosystem is seven minutes plus the duration of the conflict.

B. Ecosystem depth

In this section, we illustrate how the depth of ecosystems changes with more congested traffic. Fig. 6 shows a histogram of the depth for each of the initialized ecosystems for the original traffic, the traffic compressed by 25% and the traffic compressed by 50%. For the original traffic, we see that the maximal depth is four, while most ecosystems have a maximal depth of one. This behaviour is preserved also in both compressed traffic scenarios, where most ecosystems have a maximal depth of one.

The maximal depth increases, however, this increment is

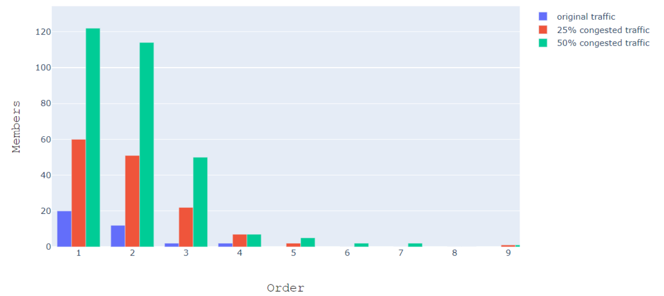

Figure 5. Histogram of the maximum depth of all ecosystems for all traffic.

smaller than expected. As we can see, the majority of the ecosystems have a depth of three, while there is one ecosystem for each compressed traffic scenario, which has a depth of nine. This shows that aircraft are spread in such a way that the depth of ecosystems doesn't blow up. It also serves as evidence that the constructed spatio-temporal regions use space-time in an efficient manner.

C. Compound Ecosystems

In this section, we present and discuss results regarding compound ecosystems. Table I shows an overview of ecosystems present in all traffic scenarios, as well as the effectiveness of each strategy to decompose the compound ecosystems.

In the original traffic, there 36 ecosystems present, where 6 are not isolated and form 3 compound ecosystems. All cases could be tackled using the third strategy. These attempts proved to be successful, thus there was no need to consider joining the involved ecosystems.

When compressing the flight level by 25%, we notice an increase in the number of total **ecosystems**, **not isolated ecosystems** and **compound ecosystems**. We solve 5% of the compound ecosystems by following the first strategy, and 20% by following the second. The majority, 60%, of the compound ecosystems could be solved by utilising the third strategy, while 40% need further consideration.

A similar qualitative behaviour is noticed also when compressing flight level by 50%. In this case, less compound ecosystems can be decomposed following the proposed strategies. This comes as a result of more complex geometries and stronger interdependencies that arise from compressing the traffic at such scale. However, it must be noted that the majority of compound ecosystems can still be decomposed by using one of the strategies proposed in our work.

TABLE I
ECOSYSTEM STATISTICS AND STRATEGY PERFORMANCE FOR EACH TRAFFIC.

Traffic	Simple Ecosystems	Not isolated Ecosystems	Compound Ecosystems	Strategies: Cut in time (%)	Cut in level (%)	Move one (%)	Join ecosystems (%)
Original	36	6	3	0	0	100	0
25% congested	143	49	20	5	20	60	40
50% congested	303	120	49	10.2	8.16	51.02	48.08

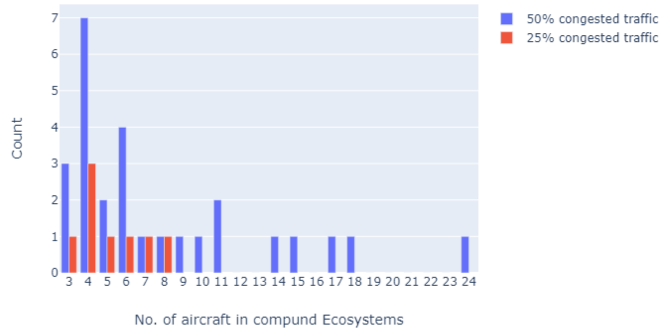

Figure 6. Histogram showing the number of aircraft in compound ecosystems for the simulated congested traffic..

In Fig. 6, we show a histogram of the number of aircraft in the compound ecosystems that we were not able to solve using one of the proposed strategies. As the original traffic did not contain such ecosystems, we show the results only for the simulated traffic. As can be seen, for both situations, the majority of compound ecosystems that could not be solved have 4 aircraft. This can be related to the fact that most ecosystems have a depth of one (i.e., 2 aircraft). As expected, the denser traffic shows more variety in the number of aircraft present in compound ecosystems. As stated earlier, such behaviour is the result of aircraft being closer to each other, which leads to bigger ecosystems.

D. Analyzing a Complex Compound Ecosystem

There is a wide range of geometries among the detected compound ecosystems on which our strategies of decomposition did not work. In this section, we present two examples, one that can be managed partially with our strategies, and another that cannot. Both situations were found in the denser simulated traffic.

Fig. 7 shows the graph of the first example. There are 4 present conflicts in this compound ecosystem. The case cannot be fully decomposed. However, if we look closely, we can see that conflict aircraft BAW955L, on the upper left corner, has no other interdependency than the conflict one. This means that this aircraft can find maneuvers to solve its conflict, while the other conflict aircraft keeps its original trajectory. Also conflict aircraft RYR7ME, also on the upper left corner, apart from the conflict interdependency, has only a single other interdependency with aircraft EVA067, which has no other interdependencies. So using these 2 aircraft we can achieve another conflict resolution.

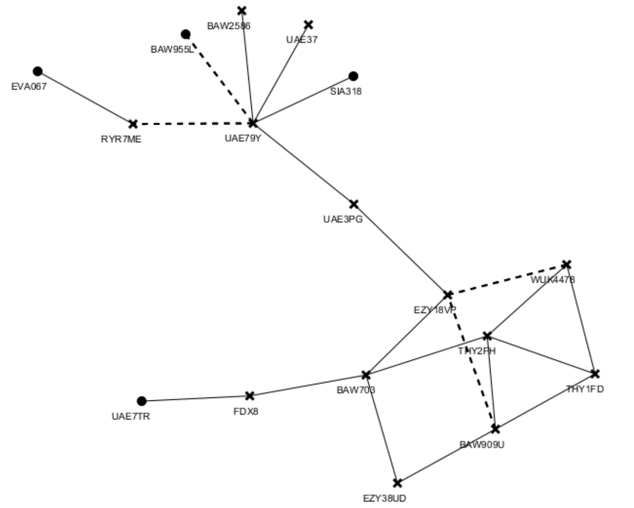

Figure 7. Example of a partially decomposable compound ecosystem. Conflicts are shown with dashed lines and common members are denoted with a cross.

Moreover, cutting the rest of the graph at aircraft UAE3PG (center of the figure), can make the other 2 conflicts independent of the 2 treated ones. In such a case, we will be left with 2 conflicts to solve, instead of 4, and 8 aircraft to consider, instead of 16.

Fig. 8 illustrates the graph of the worst detected compound ecosystem. We find 11 conflicts in it and 24 aircraft in total. In this scenario none of our strategies can help reducing complexity and the compound ecosystem needs to be treated as a whole. Realistically, such situation is not expected to occur in any projected, future scenario. Nevertheless, alternative decomposing strategies, or solutions by considering it as a whole need to be sought.

VI. Conclusion and Future Work

In this work, we propose an extension of the hierarchical structure of ecosystems introduced in [7] to identify relevant aircraft in conflict situations. We do so by considering compound ecosystems, which are ecosystems that have more than one conflict present.

As a second step, we investigate several strategies in decomposing such ecosystems, thus decreasing the complexity. From the results of our work, we can see that the majority of compound ecosystems present in our simulated traffic, can be decomposed using at least one of our strategies. The strategy that needed to be used most, was the third strategy, where common conflict members were constrained to follow their

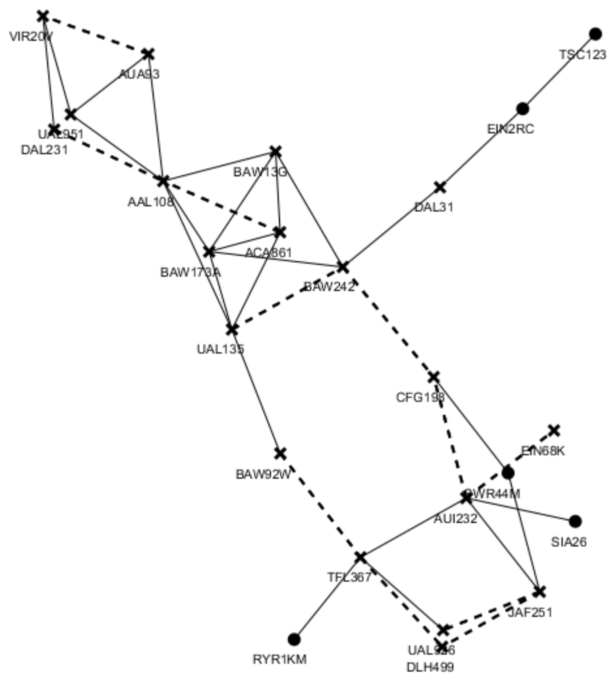

Figure 8. Example of a non decomposable compound ecosystem. Conflicts are shown with dashed lines and common members are denoted with a cross.

original trajectories.

However, there are still compound ecosystems that cannot be decomposed by following one of our strategies. Nevertheless, as presented, there are still steps we can take to lower somewhat the complexity of the situations.

The current definition of interdependencies is conditioned by an overlap in time between ecosystems. Future research steps include a more nuanced treatment, where we consider effects that solutions of present ecosystems can have on future ecosystems. This could be a first step towards defining a complexity metric that considers spatio-temporal structure of traffic at the tactical level.

Acknowledgment

This research is partially supported by the H2020 Research and Innovation Programme, Project: Evolution of cockpit operations levering on cognitive computing services. The second author has received funding from the SESAR Joint Undertaking under the European Unions Horizon 2020 Research and Innovation Programme under grant agreement No 783287. The opinions expressed herein reflect the authors view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

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