ANALYSIS OF FLIGHT-EFFICIENT ECOSYSTEM SOLUTIONS IN A MULTI- AIRCRAFT CONFLICT ENVIRONMENT

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Abstract

To accommodate future demands in air traffic management, this article qualitatively elaborates the multi-aircraft conflict resolution relying on the concept of an airborne ecosystem, as a set of autonomously operating aircraft whose trajectories are causally involved in a tactically detected conflict. The methodology provides two types of solutions: Air Traffic Control-based resolution that is considered as one from a set of compulsory avoidance maneuvers at a certain time instance, and the multi-agent simulated resolution as a product of the aircraft negotiation interactions and agreement on the avoidance maneuvers for the conflict state removal. The article further analyses a flight efficiency of the ecosystem resolution, in both distance and time, by comparing the compulsory against the negotiated solutions. From the total amount of tested trajectories and identified conflict patterns, three ecosystem scenarios have been randomly selected and efficiently quantified. Finally, the results have shown the significant savings in favor of the multi-agent solution approach.

1 INTRODUCTION

The aerial ecosystem framework relies on the analysis of spatiotemporal interdependencies between aircraft located in the proximate airspace volume of a pairwise conflict that must consequently lead to a trajectory amendment. By checking the manoeuvrability impact of any aircraft that could be affected by a pairwise conflict resolution, it is possible to predict an operationally emergent behaviour of the surrounding traffic, and identify a subset of the trajectory amendments that will not cause a negative domino effect with neighbouring aircraft. At a technological level, the proposed ecosystem concept [12] is based on multi-agent technology [13], [14], in which agents represent a set of aircraft inside a computed airspace volume, with a trajectory-amendment decision-making capability, whose trajectories are causally involved in the safety event.

Relying on this concept, this paper elaborates two conflict resolution methods, and further quantitatively analysis the efficency effects of such decisions. The principal objective aims to, first, illuminate the methodology behind the generation of the ecosystem resolution for both the air traffic controller (ATC) and the multi-agent system (MAS) in the event of a violation of the separation minima between aircraft in the ASEAN en-route traffic, before illustrating a comparative analysis of the differences between Air Traffic Control (ATC)-based and MAS-based approach relative to flight efficiency metrics such as time, distance and fuel savings. This comparison is performed in a direct-route operational environment within a single functional airspace block formed from the union of current sectorised ASEAN airspace.

In addition to this introductory section, the paper comprises additional six sections. Section 2 provides a background on the conflict resolution methodology as a subject to complexity of the conflict scenarios. Section 3 defines the ecosystem concept from a mathematical point of view, while Section 4 desribes the ecosystem resolution methods. Section 5 derives an analytical framework for the flight efficiency in applied resolution, and Section 6 discusses the simulation results. Concluding remarks and directions for the further research are given in Section 7.

2 BACKGROUND

The consequence of a continuous increase in air traffic density within ASEAN is a higher frequency of violation of the separation minima among any pair of aircraft. Yet, there exists continual downwards pressure on improvement of air traffic control technology to ensure satisfaction of key performance metric: safety, capacity, cost-efficiency (Gulding et al. 2010; Gluchshenko, Foerster 2013). Evidently, this call is led by The Single European Sky ATM Research (SESAR) and Next Generation Air Transportation System (NextGEN) joint initiatives (FAA 2016; Enea, Porretta 2012), calling for a complete replacement of the centralized tactical ATC interventions with a more efficient decentralized separation-management (SM) operations relying on the advanced decision-support tools (DSTs). An area of research is the study of logic deficiency of the traffic alert and collision avoidance system (TCAS) under the circumstance of induced collisions from surrounding traffic (ST) scenarios (Murugan, Oblah 2010). Furthering the logical deficiency of TCAS is the frequent inconsistency between standard ATC separation procedures (Bennett 2004), creating a lack of integration between the separation management (SM) on the tactical level, and, collision avoidance (CA) on the operational level. This outcome prompts new research in the direction of a collaborative and decentralised separation management (SM) layer with which better alignment between human performance and automation may be enabled.

From an ATC perspective, the compulsory directive exists as a function of ecosystem time, and is dependent only on the horizontal maneuverability with respect to parameters of different heading values and time delays. Ignoring Vertical maneuverability allows for coherence between ATC compulsory directives for a longer look-ahead time with TCAS advisory, that are triggered as vertical directives.

On the contrary, a multi-agent simulated solutions approach to conflict mitigation between aircrafts in an ecosystem is dependent on the trajectory preferences of airlines and the availability of conflict-free trajectories within some proximity in some forward time. The mathematical model and methodologies in the preceding section is approached deterministically but provides for a basic concept from which more complex exploration may entail for use in both tactical and operational level. As such, stochastic factors arising from navigation, positioning and weather are ignored. Following this, an analysis of flight efficiency in terms of time and distance is compared, in both ATC-based and MAS-based solutions in ASEAN en-route airspace, to determine savings in time and distance of maintained aircraft speed over resolution segments, in a direct-route operational environment.

The evidence of time and distance savings in this paper has been shown to be an economic impetus for the introduction of a decentralised, angent-based modelling approach for the design of a decision-support tool (DSTs) as a pivotal role in the mitigation of conflict between aircrafts in an ecosystem. In addition to this introductory section, the article comprises five other sections. Section 2 addresses the problem of emergent dynamics, and introduces the ecosystem concept as a response to this problem. Section 3 elaborates the ecosystem resolution methodology from ATC and MAS perspectives whereas Section 4 exposit flight efficiency performance and its software-based generation. The paper culminates with discussion of the simulation results (section 5), with concluding remarks and directions for the follow-up research given in Section 6.

2.1 Need for complexity analysis

The need for complexity analysis is driven by the need for a multi-agent frame capable of providing a conflict-free configuration of the system. The time-evolution of the conflict-free configuration of the system determines the number of acceptable solutions within the system. For complex configuration of conflicts, collaborations between agents involved in an ecosystem are required and within a shorter ecosystem time for a solution compared to a less complex conflict configuration which allows for a longer ecosystem time. The information regarding the complexity of the system is crucial (Lyons 2012; Prandini, Piroddi, Puechmorel, Brázdilová 2011).

3 DEFINITION AND CONCEPTS

3.1 Ecosystem Definition, Mathematical Formalism and Identification of Ecosystem Aircrafts

Definition 1. An ecosystem is defined as a set of at least two aircraft caught in a conflict.

Definition 2. Any two aircraft A/C1 and A/C2 are defined to be in conflict if a way point of A/C1 exists in the cylindrical volume of space due to the separation minima of A/C2 at some time $t \in \mathbb{Z}_0^+$

Definition 3. For any aircraft, if there exists at least one maneuver that, can be performed during an ecosystem time interval, by either this aircraft or at least one other aircraft resulting in a conflict, then at least two of these aircrafts are part of a surrounding traffic.

Note: A closed ball of radius r = 25 nautical miles centered on the location p of any aircraft represents the horizontal separation minima. The vertical separation minima is z = 0.5 nautical miles centered on the location p of any aircraft represents the vertical separation. This invites a construction of a cylinder space encasing any aircraft observing a separation minima.

Definition 4. $X = \prod_{i=1}^{n} X_\alpha$ of some space X_α indexed by some index α. The canonical projection correspond to some α is the function $p_\alpha : X \Rightarrow X_\alpha$ that maps every element of the product to α component. A cylinder set is a preimage of a canonical projection or finite intersection of such preimages.
Formally, it is a set of the form, $\cap_{i=1}^{n} p_{\alpha_i}^{-1}\left(A_{\alpha_i}\right)\left\{(x_\alpha) \in X : x_{\alpha_i} \in A_{\alpha_1} \in A_{\alpha_1}, \cdots, x_{\alpha_n} \in A_{\alpha_n}\right\}$ for any choice n and a finite set of index α_i and subset $A_{\alpha_i} \subseteq X_{\alpha_i} \forall i \in [1, n]$

Definition 5. A graph G is an ordered pair $G = (V(G), E(G))$ comprising of a set V of vertices such that $V \neq \varnothing$ and a set E of edges such that $E \neq \varnothing \wedge E = \varnothing$.

Definition 6. A vertex V of a graph G is a set $V(G) = \{p_i : p_i \in \mathbb{R}^n, n, i \in \mathbb{Z}^+\}$ of a graph.

Definition 7. An edge E of a graph G is a set $E(G) = \left\{e_{p_i, p_{i+1}}, i \in \mathbb{Z}_0^+\right\}$

Definition 8. Let p_i be a node on the major axis of an ellipse at which an ecosystem aircraft performs a control action in an attempt to mitigate a conflict. Let $p_{tactical} = p_{i+1}$ be a vertex on the boundary $\partial_{ellipse}$ defined by an ellipse to which this aircraft maneuver to and let $p_{return} = p_{(i+1)+1}$ be a vertex on the major axis (representing the original flight path) symmetrical about the y-axis. Then, $\exists i \in \mathbb{Z}_0^+, \exists n \in \mathbb{Z}^+$, a resolution candidate is a set $S = \left\{p_i \in V \subseteq \mathbb{R}^n : e_{p_i, p_{i+1}} \cup e_{p_{i+1}, p_{(i+1)+1}}\right\}$.

3.2 Model Assumptions and Restrictions

Three fundamental assumptions: Firstly, the airspace within which the aircrafts trajectories lives is discretised in both, three, spatial and one time euclidean coordinate so that the deviation in aircraft trajectory from the original trajectory is a function of discrete time. Maximum aircraft angle deviation is assumed to be 30°. Secondly, the variance in the aircraft's horizontal and vertical spatial displacement as a function of time is assumed to be zero. Lastly, any maneuver performed by any agents within any ecosystem should be synchronous.

4 GREEDY ALGORITHM FOR SOLUTION SEARCH IN DISCRETISED SPACE AND TIME

The search for a set of solutions to mitigation of conflict between any pairwise aircraft in a discretised space and time is underpinned by an algorithmically efficient mechanism that is, unfortunately, known as the greedy algorithm. In general, the greedy algorithm seeks to maximise or minimise an objective function $\mathscr{F}(x_1, \cdots, x_N)$

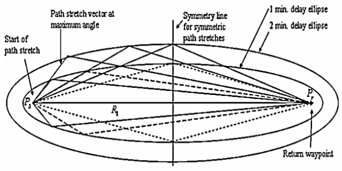

Figure 1:

Step 1:

The search for a set of solutions in a discretised space and time Euclidean coordinate system works in a manner like this: Suppose for a moment that there exists a conflict between a pairwise aircraft indexed A/C1 and A/C 2. By Definition 1, A/C1 and A/C2 exists within an ecosystem. Suppose further that the burden to maneuver rests on A/C1 to mitigate the conflict with A/C2. By the assumptions in section 3.2, there exists a maneuver angle $\phi \in [-30°, +30°]$, to which A/C1 may subscribe to. This is, otherwise, also known as a perturbation to its initial trajectory.

Step 2: Assuming an approximately constant cruise velocity then, a range of tactical nodes $p_{tactical}$ is generated, which forms a subset of nodes on the boundary $\partial_{ellipse}$ of an ellipse to which A/C1 travels to before traveling to the return node p_{return} on the original trajectory.

Step 2.1: If no further conflict is encountered in the time t between the time instant at which A/C1 performs a maneuver angle $\phi_{i_1} \in [-30°, +30°], \exists (i_1 < \infty) \in \mathbb{N}$, between $p_{tactical}$ and p_{return}, a solution is recorded. This process is iterated from time t using a maneuver angle $\phi_{i_j} : j \neq i_{j-1}, i_{j-2}, \cdots i_1$. For maneuverer that does not produce further conflict, the solution is count.

Step 2.2: If a conflict is encountered in the time t between the time instant at which A/C1 performs a maneuver angle, $\phi_{i_1} \in [-30°, +30°], \exists (i_1 < \infty) \in \mathbb{N}$, to $p_{tactical}$, before heading to p_{return}, a new maneuver is assign to the traffic aircraft involved in the new conflict. Any maneuver resulting in a conflict is rejected and does not count as a solution.

5 Types OF RESOLUTIONS IN ECOSYSTEM

5.1 Compulsory Resolutions

Compulsory resolutions describes the ATC-based approach as a solution to non-agreed negotiated interactions among aircrafts within an ecosystem. The generation of compulsory resolutions via control action δ to ensure safety key performance indicator by an algorithm shares an inverse relationship with trajectory efficiency ξ. Indeed, any algorithm that aims to generates a compulsory resolutions must satisfy:

- zero net change in the complexity within the ecosystem, among ecosystem aircrafts.
- ensuring a steady-state trajectory efficiency of the system; sum of the trajectory efficiency brought about by control actions within an ecosystem is approximately stable.

With complexity $\mathscr{C}$ and efficiency $\mathscr{E}$ being independent parameters of a cost function, $\mathscr{F}(\mathscr{C}, \mathscr{E})$, optimisation of this cost function (Section 4.2) with subjected boundary conditions generates the optimal parameter $(\mathscr{C}, \mathscr{E}) \in \mathbb{R}^2$ to produce the best compulsory resolution for at least two aircraft in a conflict. [1] illustrates the implications of this idea on the design of the algorithm. The time evolution of an ecosystem complexity is described by an exponentially decay rate in the number density of member resolution trajectories in an ecosystem. Qualitatively, a resolution candidate trajectory is a set of tactical waypoints (TWPs), $p_{tactical}$ and return waypoints (RWPs), p_{return} to the RBT. The TWPs $p_{tactical}$ are located on the boundary $\partial_{ellipse}$ of any ellipse to which any aircraft ,located at a node p_0 along a semi - major axis at some initial time t_0, must travel to before returning to any node located on the diametrical semi - major axis at some time t_{return}. The different length of the major and minor axis of the ellipse is dependent on different time delay introduced to the flight.

A pair of candidate trajectories is then evaluated against one another by computing the time evolution of the ecosystem complexity defined in [1]. If the trajectories of any two ecosystem candidates have a complexity values greater than the values analogous to the traffic advisories

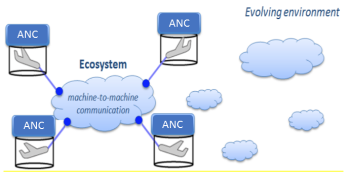

Figure 2:

of TCAS, the compulsory resolution is rejected. Further, the compulsory resolution is rejected if it results in a violation of the separation minima between any two member aircraft within an ecosystem.

5.1.1 Algorithmic Definition

Figure 2 provides the methodology for computing conflict - free resolution trajectories. The methodology composing the algorithm:

- priority sort: An input is fed into the algorithm to determines a list of aircrafts within the ecosystem that generate conflict - free trajectories from higher to lower priority, (complexity minimization).
- resolution trajectories generation: For each member aircraft in an ecosystem, a set of potential resolution trajectory is computed.
- complexity minimisation: The output from italicpriority sort is used to compute the complexity at different phase of the resolution trajectories via minimisation of a cost function. This includes the complexity and the delays introduced because of the resolution trajectory [1].

5.2 Negotiated Resolutions

The concept of multi - agent system (MAS) underpins the negotiated ecosystem resolution. A multi-agent system comprises of at least two intelligent agent interacting with each other within an ecosystem to mitigate the conflict - performing control actions within their degree of freedom without external intervention. [3], [4] illustrates some literatures demonstrating the use of MAS for problem solving of complex system in the field of ATM. The caveat in the application of MAS to conflict resolution (CR) lies in the criticality of spatiotemporal interdependencies present within any airspace configuration, resulting in different emergent dynamics, with each emergent dynamics requiring certain resolution trajectories to avoid new conflicts in forward time. Indeed, the consequence to modeling a conflict - resolution method is constraint by MAS verification. In more sophisticated models, success with a MAS air traffic conflict resolution framework necessitates the introduction of emergent dynamics together with uncertainties and perturbations on traffic behaviors. Figure 3 illustrates an ecosystem as being a self - governing, adaptive and aerial multi - agent system. In this illustration, the ecosystem involves 4 agents enhanced with advanced negotiation capability (ANC) involved in a conflict actively interacting amongst themselves for a conflict resolution.

5.2.1 Satisficing as a Solution Concept

The concept of game theory argues an impossibility to provide a definition for a unique optimum for an ecosystem where any agents that exists within this system practices pareto-optimality. Under these constraints, a hybrid solution concept - satisficing - requires each agent to provide their minimal requirements. The degree of acceptability of a hybrid solution is defined by the aggregation of these minimal requirements. The advantages to satisficing as a solution is multi-fold, of which, only two will be mentioned. First, a satisficing solution forces conflicted agents within an ecosystem to engage in the decision - making process among themselves to enable a distribution of decision - making. Second, the decision - making process resembles a branching search for a solution where the process of finding a solution is equivalent to a search strategy. The

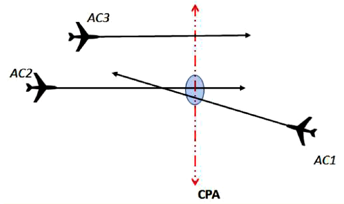

Figure 3:

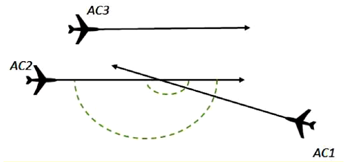

Figure 4:

search strategy branches into classification of exploratory and exploitative - the former branch principal on a broad search space and the latter, to find a solution in the shortest time possible[7]. An exploitative - based search strategy converges to a solution at an exponential rate. It is clear that the exponential convergence to a solution to resolve a multi - agent conflict within an ecosystem is the obvious solution.

5.2.2 MAS - Explored Solution Approach

The advantage to having a satisficing solution enables the quantisation of the decision - making process into positive integer steps and a italicdivide and conquer approach. The negotiation between A/C1 and A/C2 in Figure 3 illustrates a search for a specific conflict - free solution at time t_0, avoiding an induced conflict with A/C3. In contrast to Figure 3, Figure 4 illustrates a possible induced conflict between A/C2 and A/C3 at time t_1, propagated due to an earlier negotiated agreement between A/C1 and A/C2 at time t_0 - of which, a failure to arrive at a conflict - free solution between A/C2 and A/C3 meant that the negotiated solution between A/C1 and A/C2 at time t_0 is refuted.

5.2.3 Negotiated Interactions

The *divide and conquer* approach is described in greater detail in this section. At the start of a negotiation between a pairwise aircraft, solutions are explored such that one aircraft deviates from its initial trajectory. The deviation to mitigate a conflict, however, results in efficiency disincentives due to additional fuel consumptions. A pairwise aircraft can, however, adopt this strategy so that the efficiency disincentives are distributed among the pair of aircraft. In mitigating a conflict, pair aircraft arrive at a conflict - agreement through accessible degree of freedom or a range of control actions as parameters of a probabilistic function, to which a probability value is assigned to a control action. Table 1 illustrates the probability distribution function constructed by considering the number of interdependencies any aircraft would have for a given control action taken.

Table 1. Number of interdependencies of a pairwise aircraft in conflict per each possible performed maneuver

	left	right	up	down
A/C1	0	3	2	0
A/C2	5	2	3	1

6 FLIGHT EFFICIENCY IN APPLIED RESOLUTION

6.1 Airspace User's Preferences

The flight strategies in the planning phase for the creation of an RBTs is underpinned by the business model of the airspace users. The factors affecting the business model are flight schedules, airspace systems requirements, nature of flight (long - haul vs short - haul) and aircraft types have a considerable impact on the generation of the business model and its efficiency output. The flight strategies employed are based on the multi - cost index (CI) analysis relative to the fuel - time efficiency along the entirety of the flight envelop.

The advantage of the business model is two - fold:

- Generation of ecosystem scenario: A business strategy for generated traffic data (flight plans), operational constraints and selection of aircraft performance model can be implemented to define the reference business trajectories. This applies only to customised flight plans in accordances to user preferences.
- MAS objective function: With the OD design supporting the MAS approach, the business models are integral to MAS functionality. While the negotiation process does not foresee human intervention in the simulation, the MAS model can express the objective function. Since the AGENT scenarios are simulated in an en - route airspace, the objective function is valid only for the cruisig phase. The greatest percentage of trip time and fuel are typically incurred during this phase.

The two primary variable that affects cruising duration and fuel consumption is speed selection and altitude selection. The generation of the OD scenarios and speed selection can be analysed using three objective functions:

- Maximising the cruising distance for a fixed amount of fuel
- Minimising the consumption of fuel for a fixed give distance.
- Minimising the trip time While the speed variable in the resolution can regulated, the speed value must be selected based on the scenarios. The algorithm does not foresee a significant change in the horizontal speed during the ecosystem process, unless the compulsory resolution is triggered. In this case, vertical speed might be subject to changes. Therefore, for agents using this strategy the speed maintenance must be an objective function, that applies to both cruising and evolving aircraft. Further, from the selected BADA aircraft type the optimal speed value in cruise can be used as a reference. The altitude selection can also rely on the relevant aircraft performance model. From a designing perspective, each aircraft has one optimal flight level (FL). However, the optimal FL is subjected to changes on grounds of airspace system requirements and weather conditions. While the generated RBT should include this consideration, this means a possibility of an altitude change during the cruising phase. Once an aircraft becomes an ecosystem member, the agents in cruising will have to maintain their current altitude until agreed resolutions or unless the compulsory advisory is issued. Once changed, the objective function will be to resume to the selected FL.

6.2 Cost Efficiency Function

In light of section 5.1, a natural choice for qualitatively and quantitatively evaluating the additional economic cost to an agent would be the cost function with independent parameters Δ_{Fuel} and Δ_{Time}. Since the ability to enable agents the flexibility to adhere to different business models is of pertinent importance, the cost function should be as general as possible. In following standard models in literature and practice [8], the cost function is introduced as

$$f_{cost} = (1 - Index_{cost})\, Coefficiet_{cost}\Delta_{Fuel} + Index_{cost}Coefficient_{delay}\Delta_{Time} \tag{1}$$

where

[9] $Index_{cost}$ is for the cost index define to be $\frac{Time\,cost}{Fuel\,cost}$

$Coefficient_{cost}$ is the cost efficient

$Coefficient_{Time}$ is the delay coefficient

Δ_{Fuel} is the change in fuel

Δ_{Time} is the change in time
with the minimisation of the scalar cost function f_{cost}, requiring that

$$\nabla f_{cost} = \left\langle \frac{\partial}{\partial \Delta_{Fuel}}, \frac{\partial}{\partial \Delta_{Time}} \right\rangle f_{cost} = \langle (1 - Index_{cost}) \, Coefficient_{cost}, Index_{cost} Coefficient_{delay} \rangle = \langle 0, 0 \rangle \tag{2}$$

$$min \left(f_{cost} \left(\Delta_{Fuel}, \Delta_{Time} \right) \right), \exists \Delta_{Fuel}, \Delta_{Time} \tag{3}$$

In spite of the popularity of (1) as a model, it lacks the robustness to capture the time - dependency of an MAS procedure due to $Coefficient_{Fuel}$ and $Coefficient_{Time}$ being constant with time. To accommodate time - dependency of the MAS model, the paper introduces

$$f_{modified\,cost} = (1 - Index_{cost}) \, Coefficient_{Fuel} \, (t) \, \Delta_{Fuel} + Index_{cost} Coefficient_{Time} \, (t) \, \Delta_{Time} \tag{4}$$

where

$Coefficient_{Fuel} \, (t)$ is the coefficient of fuel as a function of time

$Coefficient_{Time} \, (t)$ is the coefficient of delay as a function of time

The time rate of change gives

$$\frac{\partial f_{cost}}{\partial t} = (1 - Index_{cost}) \left(\frac{\partial Coefficient_{cost} \, (t)}{\partial t} \Delta_{Fuel} \right) + Index_{cost} \Delta_{Time} \frac{\partial Coefficient_{delay} \, (t)}{\partial t} \tag{5}$$

In matrix form:

$$\frac{\partial f_{cost}}{\partial t} = \left[\begin{array}{cc} (1 - Index_{cost}) & Index_{cost} \end{array} \right] \left[\begin{array}{c} \frac{\partial Coefficient_{cost}(t)}{\partial t} \Delta_{Fuel} \\ \frac{\partial Coefficient_{delay}(t)}{\partial t} \Delta_{Time} \end{array} \right] \tag{6}$$

7 SIMULATION RESULTS

7.1 Comparative Analysis of 3 Distinct Ecosystems

Table 2. Comparison of Fuel and Distance difference between Baseline and Compulsory Approach in Ecosystem 12

Baseline Fuel	Compulsory Fuel	Δ_{Fuel}	Baseline Distance	Compulsory Distance	$\Delta_{Distance}$
6695.55	6722.68	-27.13	1216.2	1223.3	-7.1
5483.21	5510.26	-27.05	777.5	781.4	-3.9
2955.19	2955.96	-0.77	742.7	742.6	0.1
7822.12	7761.81	60.31	1448.1	1463.9	-15.8

Table 3. Comparison of Fuel and Distance difference between Baseline and Negotiated Approach in Ecosystem 12

Baseline Fuel	Negotiated Fuel	Δ_{Fuel}	Baseline Distance	Negotiated Distance	$\Delta_{Distance}$
6695.55	6695.68	-0.13	1216.2	1216.2	0
5483.21	5510.26	-27.05	777.5	777.5	0
2955.19	2955.96	-0.77	742.7	742.7	0
7822.12	7761.81	60.31	1448.1	1448.5	-0.4

Table 4. Comparison of Fuel and Distance difference between Baseline and Compulsory Approach in Ecosystem 363.

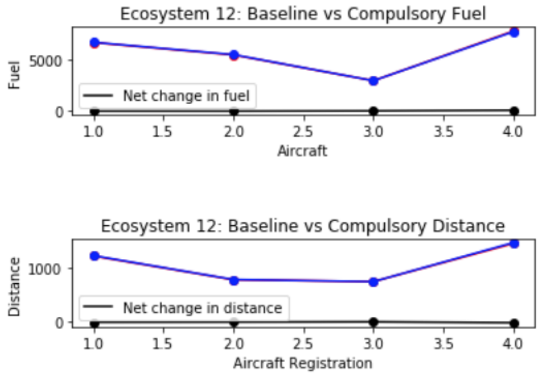

Figure 5: Baseline - Compulsory in Ecosystem 12.

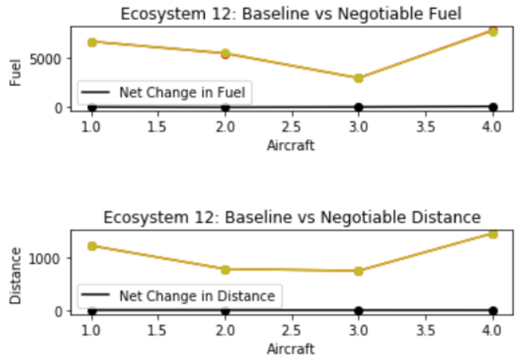

Figure 6: Baseline - Negotiable in Ecosystem 12.

Baseline Fuel	Compulsory Fuel	Δ_{Fuel}	Baseline Distance	Compulsory Distance	$\Delta_{Distance}$
5639.80	5673.62	-33.82	1655.6	1667.5	-11.9
5517.41	5613.58	-96.17	1080.5	1087.4	-6.9
3473.42	3506.05	-32.63	1082.1	1087.7	-5.6
4754.30	4768.82	-14.52	933.1	939.7	-6.6

Table 5. Comparison of Fuel and Distance difference between Baseline and Negotiated Approach in Ecosystem 363.

Baseline Fuel	Negotiated Fuel	Δ_{Fuel}	Baseline Distance	Negotiated Distance	$\Delta_{Distance}$
5639.80	5662.31	-22.51	1655.6	1655.6	0
5517.41	5559.66	-42.25	1080.5	1082.1	-1.6
3473.42	3473.05	0.37	1082.1	1082.2	-0.1
4754.30	4760.52	-6.22	933.1	948.2	-15.1

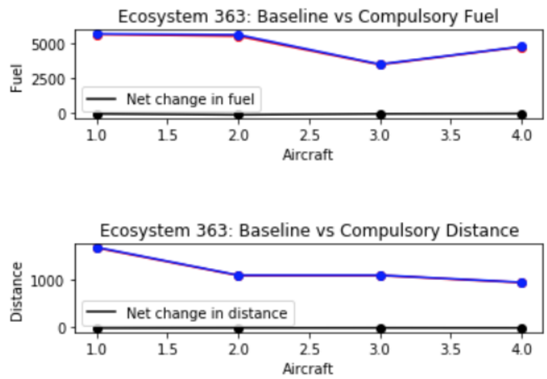

Figure 7: Baseline - Compulsory in Ecosystem 363.

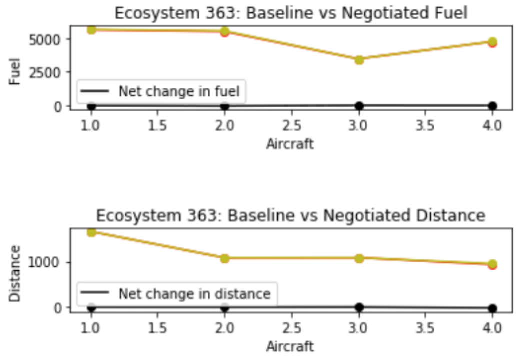

Figure 8: Baseline - Negotiable in Ecosystem 363.

Table 6. Comparison of Fuel and Distance difference between Baseline and Compulsory Approach in Ecosystem 452.

Baseline Fuel	Compulsory Fuel	Δ_{Fuel}	Baseline Distance	Compulsory Distance	$\Delta_{Distance}$
3312.0	3323.29	-11.29	886.8	894.3	-7.5
4026.14	4007.07	19.07	1265.6	1280.8	-15.2
7479.30	7535.60	-56.30	1473.0	1479.9	-6.9
3069.44	3096.24	-26.80	777.5	785.1	-7.6

Table 7. Comparison of Fuel and Distance difference between Baseline and Negotiated Approach in Ecosystem 452.

Baseline Fuel	Negotiated Fuel	Δ_{Fuel}	Baseline Distance	Negotiated Distance	$\Delta_{Distance}$
3312.0	3322.29	0	886.8	886.8	0
4026.14	4020.64	5.50	1256.6	1267.0	-1.4
7479.30	7489.71	-10.41	1473.0	1473.0	0
3069.44	3069.04	0.40	777.5	777.5	0

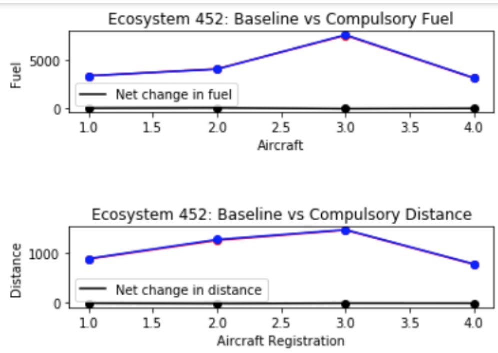

Figure 9: Baseline - Compulsory in Ecosystem 452.

Table 8. Comparison of Mean Net Change in Fuel and Distance between Compulsory and Negotiated Resolution.

Ecosystem Comparison	$\bar{\Delta}_{Net\,Change\,Fuel}$	$\bar{\Delta}_{Net\,Change\,Distance}$
Base - Compulsory Comparison	-61.775	-10.69
Base - Negotiated Comparison	-23.75	-0.55

Three ecosystems, indexed 12, 363 and 452, were drawn at random and simulated. The simulation showed demonstrates that the fuel and distance performance metric for each aircraft in ecosystem 12, 363 and 452 in the Baseline - Negotiated approach has a net change in fuel and

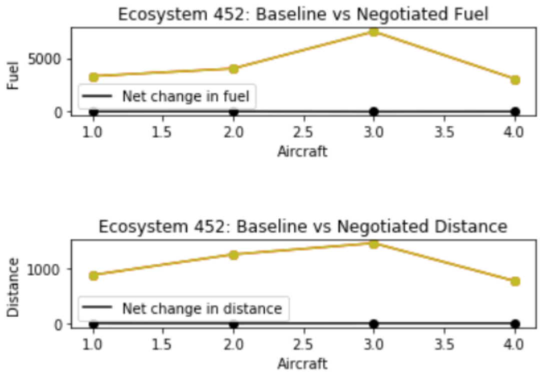

Figure 10: Baseline - Negotiable in Ecosystem 452.

distance that is least equal or less than the net change in fuel and distance in the Baseline - Compulsory approach. This is evident through taking any aircraft and making a comparison in the net change of the fuel and distance between Base - Compulsory and Base - Negotiated approach of ecosystem 12. Table 2. and Table 3. illustrates this. The improvement in fuel and distance comparison for a Negotiated approach is seen also in ecosystem 363 and 452, as evident from Table 4. and Table 5., and, Table 6. and Table 7. Using a sample size of n = 3, Table 8. illustrates the computation of the mean net change in fuel and distance $\bar{\Delta}_{NetChangeFuel}$ and $\bar{\Delta}_{NetChangeDistance}$ for both the Base - Compulsory and Base - Negotiated approach. As can be seen, the Negotiated approach to conflict mitigation provides a lower mean net change in both performance metric of fuel and distance, with $\bar{\Delta}_{Net\,Change\,in\,Fuel} = -61.775 < \bar{\Delta}_{Net\,Change\,in\,Fuel} = -10.69$ in the Baseline - Compulsory and Baseline - Negotiated approach, respectively. Compare also the distance performance metric, $\bar{\Delta}_{Net\,Change\,in\,Distance} = -23.75 < \bar{\Delta}_{Net\,Change\,in\,Distance} = -0.55$, between the Baseline - Compulsory and Baseline - Negotiated approach. From this, it may be inferred that the for a fixed fuel and distance value in the Baseline approach, the output value for the fuel and distance in the Negotiated approach differs only as much or greater in magnitude with the Compulsory resolution approach to conflict mitigation. With the Negotiated approach to conflict mitigation giving rise to an improved performance fuel and distance metric, the consequence is an improvement to the economic model of airlines.

8 CONCLUSION

This article has been studying a novel resolution approach in the multi-aircraft conflict scenarios using the multi-agent modeled behavior against against the conventional resulting directives coming from the air traffic control system. With this, it is deployed as a new airborne resolution model with an advantage over the conventional ground-based separation technique. The main driver in this successfully implemented multi-agent solution is an agreement on certain maneuver(s) in a timely manner that is acceptable from the airspace user's business preferences, conditioned on the available proximate airspace volumes and spatio-temporal interdependencies among the ecosystem actors. These interdependencies influence the resolution moment, the number of avoidance maneuvers and, consequently, the magnitudes of trajectory amendments. From the three simulated ecosystems, it is evident that the multi-agent concept provides more efficient solutions in terms of both the extra distance and fuel. Naturally, the efficiency metric cannot be significantly reflected in a short time intervals as the ecosystem time is tactically measured in several minutes of flight. On the other end, this evidence provides an excellent insight for measuring the ecosystems resolution impacts on the air traffic flow and capacity management, considering the whole ecosystem configuration over the full operational days. At the macro-level, those solutions can provide significant improvements, not only to the flight efficiency but also in terms of the capacity and controller's workload which is pertinent to the present and future state of the air traffic management system. Further research is two - directional: first, the integration of the aircraft performance model into the ecosystem resolution algorithms and automation in the flight efficiency analysis considering the whole aircraft trajectories in which a single aircraft might participate in more than one ecosystem. The first direction will consider the type of the aircraft and its performance characteristics in accepting the additional distance and fuel quantities. The second direction will consider the optimality in a decision -making process of any single aircraft, over the entire flight envelope, as well as the airspace capacity limited by the system requirements.

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