INTELLIGENT OPTIMIZATION ON SLOTS NEGOTIATION IN COLLABORATIVE TRAJECTORY OPTIONS PROGRAM

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ABSTRACT

Collaborative Trajectory Options Program (CTOP) is a new way to improve the Air Traffic Management (ATM) by considering National Airspace System (NAS). To achieve the business goals of the NAS' users, their flight and airspace restrictions are considered for more flexible and financially stable in the operation. During a CTOP, airlines can share their route preferences with the control units of Federal Aviation Administration (FAA), combining delay and reroute. The consideration of the trajectory preferences will impact the final sort to be assigned in each available slot to fly though a restricted flow area, how airlines could achieve better results in slots negotiation process by the time. A Game Theory approach was developed to model this environment, and a case study was conducted using real data from two airlines with 100 different CTOP demands. The model achieved satisfactory results, which represented a delay reduction of 537 hours for an airline.

Keywords: Collaborative Trajectory Options Program, Air Traffic Management, Game Theory, Multiagent Systems.

1. INTRODUCTION

The Collaborative Trajectory Options Program (CTOP) is part of the NextGen initiative and is an evolution of programs such as Ground Delay Program (GDP) and Airspace Flow Program (AFP). The primary goal of CTOP is to improve operations during periods of constrained airspace capacity by considering National Airspace System (NAS) users and their business goals, the particularities faced by each flight and the airspace restrictions. This initiative was under test until 2014, when it was made available for use in US airspace (NOVAK et al., 2010; FAA,2012a; FAA,2012b; NBAA,2012).

When the FAA decides to create a CTOP, information such as start and end program time; affected flights; geographically affected areas and its capacities are shared with the involved NAS users. Considering that information, airlines need to inform to FAA their routes preferences for each affected flight by using Trajectory Option Set (TOS) messages. Each airline will need to decide its preferences considering only the known information about its own flights. However, the FAA will assign the available capacity to fly by each Flow Constrained Area (FCA) considering the Initial Arrival Time (IAT) in the FCA of each informed route, i.e., the flights are sorted by their earliest IAT, and so the flights are assigned for each available flight slot (FAA, 2014).

In this paper, a model and case study are presented for the flights of two airlines (A and B) from airports in Miami, Dallas, Chicago, San Francisco, Los Angeles and Las Vegas to the New York metropolitan area. Considering that a CTOP demand is created with two FCAs and all aircraft flying by these areas will have restrictions based on available capacity and excluding exempt flights. This paper examines how Airline A can improve the TOS messages planning for each flight, thereby reducing the global delay in its CTOP captured flights.

A Game Theory approach was developed to model the problem as a game between both carriers, which both are playing to get the best available slots for their flights. So, using different cases and strategies, this paper examines how this approach behaves, when there is a high level of uncertainty in the process.

This paper is organized as follows. Section 2 briefly reviews relevant research and concepts of CTOP and Game Theory. Section 3 proposes the optimization model in CTOP. Section 4 presents the case study and results. Section 5 concludes the paper and presents the direction of future study.

2. RELATED CONCEPTS

2.1. Collaborative Trajectory Options Program

During CTOP each airline provides its preferences to the FAA, including the preference to fly around the FCAs (FAA, 2012; NBAA, 2012). An important aspect of CTOP is that delay and reroute decisions are based on the TOS messages in a combined way to improve the management of the capacity and demand to fly by a FCA.

A CTOP example is presented in Figure 1. The example is a scenario with two FCAs, FCA001 and FCA002, and a flight coming from Dallas/Fort Worth International Airport (DFW) to LaGuardia Airport (LGA). In this example, there are three possible routes: the aircraft could flight through FCA001 or FCA002 or fly around the FCAs without CTOP restrictions.

In some cases, the carrier may want to fly around the FCAs to achieve better business results, e.g., the delay that would be incurred by a specific flight crew will impact another flight schedule; or fly through one specific FCA. In Figure 1, there is only one trajectory option for each FCA, although there could be more options for each one.

The CTOP assignment algorithm can be summarized in six steps (GOLIBERSUCH, 2012). The exempt flights are defined as international flights and flights *en* route at the time CTOP demand is created.

1. Determine which flights are included in the CTOP;
2. Determine which flights are exempt from the CTOP;
3. Assign trajectories to exempt flights;
4. Sort remaining flights by their IAT;
5. Considering flights in their IAT order and the available capacity, assigns the available flights to slots based on their TOS;
6. Send assignments to airlines.

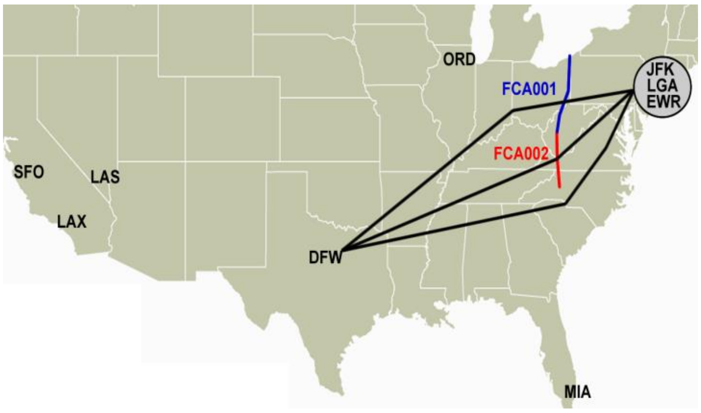

Figure 1. CTOP Overview (Cruciol et al., 2015)

Considering the above algorithm, during the first step the involved airlines in the CTOP demand will receive information about which flights were captured, i.e., each carrier will only have information about its own flights. Thus, the airline will need to decide which TOS to send for each flight. The airline does not need to send TOS for its exempt flights, since those flights will have preference and firstly assigned in the available slots, i.e., a determined available time to fly by the FCA.

A TOS example is presented in Table 1. It contains information such as Aircraft Identification (ACID), origin and destination airports, Initial Gate Time of Departure (IGTD), aircraft type, Earliest Runway Time of Departure (ERTD), Relative Trajectory Cost (RTC), Required Minimum Notification Time (RMNT), Trajectory Valid Start/End

Time (TVST/TVET), altitude, speed and route.

The FCA concept means that the demand is over the capacity to fly by that area, i.e., some flights will not get an available slot to fly by that area and it will receive a NOSLOT response. This condition does not require a waiting time to departure since it will not fly by a restricted area, however it could receive other kind of restriction such as Ground Delay Program (GDP) due other conditions, e.g., airport restriction.

In the fourth step, the slot allocation is based on the IAT order, i.e., the TOS message sent for each flight will interfere directly in the final sort and the required delay for the flights of each airline. Considering this, if the airline sends only the second best trajectory option for one flight, its global delay would be reduced because the gain for other flight would be greater.

TABLE I. TOS EXAMPLE

ACID	ORIG	DEST	IGTD	TYPE	ERTD	
F#14	ATL	JFK	09/1800	B738	09/1812	
RTC	**RMNT**	**TVST**	**TVET**	**ALT**	**SPEED**	**ROUTE**
0	-	-	-	350	430	DOOLY7 GRD J209 SAWED J121 SIE CAMRN4
15	-	-	-	350	430	DOOLY7 GRD J209 DARRL J209 SAWED J121 SIE CAMRN4
30	-	-	-	350	425	DOOLY7 GRD J209 RDU ORF J209 SAWED J121 SIE CAMRN4

By the airline perspective, the CTOP decision process could be considered complex because there is a high amount of unknown variables to plan its best possible group of TOS messages, e.g., the amount of captured flights of other airlines, the demand and capacity rate of each schedule window, the demand of each FCA, the strategy used by other airlines to define their TOS, and others.

2.2. Game Theory

Game Theory (GT) makes it possible to model strategic decision-making scenarios, where there are two or more agents involved in negotiations regarding limited resources. The game may be cooperative, where both players support themselves to achieve better results together; or non-cooperative, where each airline will try to maximize its results without any cooperation with the other one (VON NEUMANN and MORGENSTERN, 1944; NISAN et al., 2007).

It can be divided into two types regarding the way it is played, as static or dynamic. In the static, the players take decisions based on their strategies at the same time, i.e., without knowledge about the strategies of other players for that game round.

In the dynamic game, there are interactions regarding the decisions taken by each player during the game, i.e., after the first player has taken its decision, the second player will consider that move to define its own next move in the game.

When players have knowledge about the strategies and payoffs of the other players, the game is defined as complete information. On the other hand, when players do not have any information, the game is defined as an incomplete information game.

A game can be played once or repeatedly in the time allotted. The game timing can be finite, i.e., the number of game rounds that will be played is known by the players. In the infinite case, the players do not have knowledge about when it will happen the last game round. This definition interferes directly how the players will define their strategies.

There is a greater probability that players will make more cooperation when they do not know when it is the last round at the game. This process will create the reputation of each player, which is used by the other player to define its own strategy.

The strategies are basically defined into two types: pure or mixed. A pure strategy is used by the player in all situations. In other words, no matter the actions of its opponent, its strategy will not be changed. A mixed strategy could be defined based on the history of previous actions. Basically, there are five elements in a game:

- Players: the group of involved agents in a game.
- Strategy: the way each player will act considering the current game scenario.
- Interaction: how a player's action will affect another player's move.
- Rationality: every player in a strategic game will pursue their best possible results.
- Payoff: the gain each player will receive from each move.

An important concept regarding the players' decisions and their strategies is known as the Nash Equilibrium (NASH, 1950). For example, one player decides to maximize its results and choose the best results for itself. Considering that maximizing its results is rational for an airline, it is assumed that the other player will do the same and try to improve its results. However, when both airlines act in this non-cooperative way in a dispute over limited resources, both airlines will not achieve their best results.

If the first player changes its strategy to cooperate with the second player, there are two possible cases: the second player cooperates and both could try to improve their results or the second player rejects the cooperation with the first player and achieve better results than with the cooperation scenario. Considering this possibility, it is rational to think that both airlines would betray the other to achieve better results, even though it is possible that each player will not achieve the best possible results. When no player wants to change its strategy unilaterally, it is defined as Nash Equilibrium in the game.

A classic example about the Game Theory and Nash Equilibrium is the Prisoner's

Dilemma. The Prisoner's Dilemma overview is presented in Figure 2.

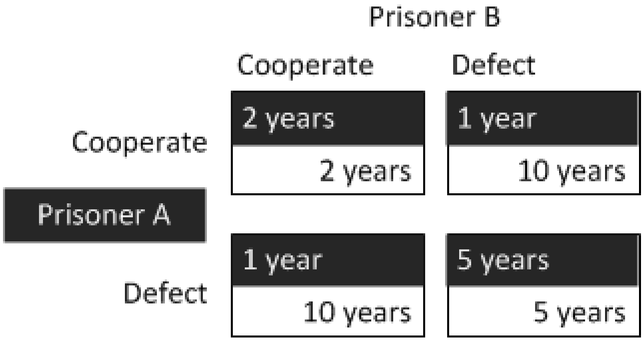

Figure 2. Prisoner's Dilemma Overview

If both prisoner A and B cooperate and stay silent, they will be sentenced to two years.

If one prisoner betrays the other, and the other one stays silent, the betrayer prisoner will be sentenced to one year and the betrayed prisoner will be sentenced to ten years.

If both prisoners betray each other, they will both be sentenced to five years.

Thus, it is possible to verify that Nash Equilibrium happens in the case when both prisoners betray. This non-cooperation option will carry worse results for both. Each prisoner decides for its best result, which it is betray and stay arrested for one year. However, when both prisoners choose their rational option, they would achieve and equilibrium, which no one has interest to change its strategy unilaterally.

Thus, the CTOP negotiation process regarding the TOS planning between the airlines can be considered a game, which there are two airlines playing to get their best group of available slots to fly by a FCA.

It is assumed that each airline has rational strategies and aims to reduce its costs. These costs include direct costs such operational costs increased by congested airspace sectors or airports; and indirect costs such as lack of confidence of its passengers. It is possible to apply this approach to improve the airline gains in general by the balancing of possible results for each airline.

3. OPTIMIZATION IN CTOP

The proposed model was called as SG-CTOP and regards a dispute of available slots between airlines A and B called players, and it only captured flights is used in the CTOP demand.

As for the player’s strategies, two cases regarding the TOS messages are defined. Each airline could send only the best flight trajectory for its flights or send the best option for each FCA. So, each airline may send one or two trajectory options for each flight, considering that two FCAs exist. Each airline takes its decisions based on its own flights, i.e., Airline A does not know the schedule of the other airline.

In a CTOP environment, there is no interaction between airlines during the TOS planning, i.e., each carrier does not have knowledge about the competitor's flights and how its own strategies will interfere in the final game result.

It is supposed that each airline will send the best trajectory option set for each flight.

However, it does not mean that an airline will send always the best TOS for one flight, if this would achieve worse global results when it has considered all its CTOP captured flights.

As soon as a flight plan is approved to fly by an established route and a CTOP demand is created, there is a known estimated time for each flight to enter in each defined FCA. By this information, the airline may prefer to fly only by one FCA or for a longer route to give preference for its other flight. For example, the airline may prefer to fly by FCA001 if the delay will be up to 30 minutes, otherwise its better option is to fly by FCA002. These preferences are stated by TOS messages and its payoff is being defined as the minutes of delay to enter in the assigned FCA when compared with the original estimated entrance time for each flight.

Thus, the Prisoner's Dilemma game was chosen to model the TOS planning, which is presented in Figure 3. The payoff is based on the minutes of delay for each airline, regarding their CTOP captured flights (Cruciol et al., 2015).

	Airline B		
Airline A	NOSLOT (1054) NOSLOT (510)	NOSLOT (1054) 1 Trajectory + NOSLOT (513)	NOSLOT (1054) 2 Trajectories + NOSLOT (471)
	1 Trajectory + NOSLOT (1012) NOSLOT (510)	1 Trajectory + NOSLOT (1033) 1 Trajectory + NOSLOT (477)	1 Trajectory + NOSLOT (1102) 2 Trajectories + NOSLOT (489)
	2 Trajectories + NOSLOT (980) NOSLOT (510)	2 Trajectories + NOSLOT (1002) 1 Trajectory + NOSLOT (511)	2 Trajectories + NOSLOT (1007) 2 Trajectories + NOSLOT (481)

Figure 3. SG-CTOP Optimization Model (Cruciol et al., 2015)

Analyzing the Figure 3, it is possible to verify some points. For Airline A, it is better to send two trajectories options, which will achieve better results, regarding of Airline B strategy. For Airline B, it will achieve the best result if it sends two trajectories options. However, if Airline A sends one trajectory, it is better to send one trajectory.

Considering that both airlines are rational, they would send two trajectories options. So considering the planned schedule and the published schedule, Airline A would have 1007 minutes of delay in its flights and Airline B would have 481 minutes of delay in its flights.

In this example, the Nash Equilibrium happens in the case of both airlines sending two trajectory options for each flight. Both airlines would not achieve better results change their strategies unilaterally.

During the TOS planning process some uncertain points are considered by each airline to define the best strategy for all its flights. For example, how much better would it be to avoid flying by one FCA, or how many trajectory options send for each flight or FCA, (DE ARRUDA et al., 2015; CRESPO et al., 2012; MEHTA et al., 2013; FRANKOVICH and BERTSIMAS, 2013).

4. CASE STUDY

To support and improve the airline decision process regarding CTOP, a case study is conducted to verify how the game theory approach behaves in different cases and relative to the combinatorial approach. The GT approach was chosen due to the uncertainty involved in this decision process and, particularly the lack of information each carrier needs to treat before defining its TOS messages.

4.1. Environment

The CTOP demand was defined in the interval between 04pm and 08pm and considered the flights of two airlines, A and B, with a minimum of one feasible Estimated Time of Arrival (ETA) before 08pm in one FCA. This paper considers two FCAs, FCA001 and FCA002, and flights for LaGuardia Airport (LGA), Newark Liberty International Airport (EWR) and John F. Kennedy International Airport (JFK) from Chicago O'Hare International Airport (ORD), Miami International Airport (MIA), Dallas/Fort Worth International Airport (DFW), Los Angeles International Airport (LAX), McCarran International Airport (LAS) and San Francisco International Airport (SFO).

The case study was divided into three scenarios:

- Airline A has more CTOP captured flights than Airline B. In this case, there were 152 flights. The Airline A had 94 flights and Airline B had 58 flights.
- Airline A has the same amount of Airline B CTOP captured flights. In this case, there were 190 flights. The Airline A and Airline B had 95 flights each one. The Airline A had 1 exempt flight and Airline B had 2 exempt flights.
- Airline A has fewer CTOP captured flights than Airline B. In this case, there were 257 flights. The Airline A had 95 flights, including 1 exempt flight and Airline B had 162 flights, including 2 exempt flights.

The interval was divided into 16 time windows of 15 minutes each. The windows were defined from 04:00pm to 7:45pm. The capacity for each window was defined as 3, i.e., in each 15 minutes 3 aircraft could fly by FCA001 or FCA002. Thus, there were 48 available slots in each FCA during the CTOP demand.

It is possible to verify that in the three scenarios the demand of aircraft to fly by the FCA is between 58 and 167%, at least in the global environment, considering the best case that each flight would have the same reward to fly for any FCA. In the case that a flight has one trajectory option to fly by one FCA, certainly the local demand would increase in one FCA.

This case study presents an optimization model based on a game theory approach to improve the planning of TOS messages for each flight and measure with a combinatorial approach, e.g., Airline A needs to decide which trajectory options will maximize the reward for each flight. When the airline considers only local optimization, it is not guaranteed that it will achieve the best rewards for all its flights on global optimization. In other words, it is possible that Airline A indicates its preference for the 2nd best route for one flight because the global reward will be better for the airline.

Some assumptions were made to perform the case study Airline A could send only a trajectory option, its earliest IAT; or send two trajectory options, its earliest IAT for each FCA.

In this approach, the Prisoner's Dilemma was considered to model similarly the scenario. Thus, there are nine possible moves in the game. Each move is composed of the number of trajectory option for each flight using the airline sequence of moves (AB).

- Move (00): Both airlines send no slot for each flight;
- Move (01): Airline A sends no slot for each flight and Airline B sends one trajectory option for each flight;
- Move (02): Airline A sends no slot for each flight and Airline B sends two trajectory options for each flight;
- Move (10): Airline A sends one trajectory option for each flight and Airline B sends no slot for each flight;
- Move (20): Airline A sends two trajectory options for each flight and Airline B sends no slot for each flight;
- Move (11): Both airlines send one trajectory option for each flight;
- Move (22): Both airlines send two trajectory options for each flight;
- Move (12): Airline A sends one trajectory option for each flight and Airline B sends two trajectory options for each flight;
- Move (21): Airline A sends two trajectory options for each flight and Airline B sends one trajectory option for each flight.

4.2. Results Analysis

Some important points to understand how CTOP games behave are summarized below:

- When *Airline A* had 67% or 75% of CTOP captured flights, the first half of IAT was composed with 100% of *Airline A*'s flights, and *Airline B* strategy was send NOSLOT for all its flights, *Airline A* would achieve better results in 43% by sending NOSLOT option and in 57% by sending two trajectories plus NOSLOT. In other cases, if *Airline B* strategy was send NOSLOT for its flights, *Airline A* would achieve better results by sending two trajectories plus NOSLOT in 98% at least.
- Whatever was *Airline B* strategy, *Airline A* did not achieve more than 6% of best global results by sending one trajectory plus NOSLOT option.

- When *Airline A* had 75% of CTOP captured flights, minimum global delay would be achieved in about 44% by sending NOSLOT and in about 55% by sending two trajectories plus NOSLOT option, if *Airline B* strategy was send one or two trajectories plus NOSLOT option for its flights.
- When *Airline A* had 50% of CTOP captured flights, minimum global delay would be achieved in 44% by sending NOSLOT and in about 53% by sending two trajectories plus NOSLOT option, if *Airline B* strategy was send one or two trajectories plus NOSLOT option for its flights.
- The minimum global delay for *Airline A* was identified in 100% of cases by sending two trajectories options, when the *Airline B* sent a NOSLOT option for all its flights.
- It is possible to verify that in some cases the difference when *Airline A* sends NOSLOT could be 7x higher than sending two trajectories plus NOSLOT.

Considering the SG-CTOP results after 100 SG-CTOP demands and accumulated delay in hours, the normal probability distribution function (PDF) for SG-CTOP and others possible strategies for *Airline A* is presented in Figure 4, considering the first category.

It is possible to verify that SG-CTOP is highly related to two trajectories option strategy. The SG-CTOP keeps achieving better results than others strategies by the time and reducing the accumulated delay.

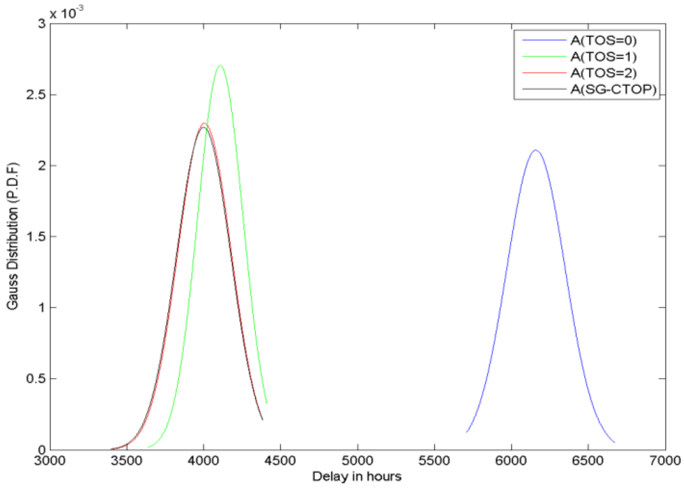

Figure 4. SG-CTOP Optimization Model (Cruciol et al., 2015)

5. CONCLUSION

The Trajectory Option Set planning process handles a large uncertainty involving how many options per TOS and which is the best strategy to choose. The TOS messages sent by each airline will determine the assignment sort for each available time slot to fly by a Flow Constrained Area. When a CTOP demand is created, each airline has only information about its own flights to take its decisions.

The TOS planning model achieved satisfactory results using the SG-CTOP, demonstrated by the performed case study. After 100 SG-CTOP demands the best strategy was achieved when it was sent two trajectories option for each FCA plus a NOSLOT option to fly around. This strategy achieved a global delay of 53% less than NOSLOT strategy.

When this strategy was compared with the proposed SG-CTOP model, *Airline A* would achieve a global delay less than this strategy, or equal, in 97% of CTOP negotiations representing a reduction in accumulated delay of 537 hours for *Airline A.*

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