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Collaborative Decision Making in Air Traffic Management: Current and Future Research Directions

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Abstract: Collaborative Decision Making (CDM) embodies a new philosophy for managing air traffic. The initial implementation of CDM in the US has been aimed at Ground Delay Program Enhancements (GDP-E). However, the underlying concepts of CDM have the potential for much broader applicability. This paper reviews on-going and proposed CDM research streams. The topic areas discussed include: ground delay program enhancements; collaborative routing; performance monitoring and analysis; collaborative resource allocation mechanisms; game theory models for analyzing CDM procedures and information exchange; collaborative information collection and distribution.

1 Introduction

Advances in the technology underlying communications, navigation and surveillance are leading the way toward Free Flight, an architecture in which the responsibility for the safe progress of an aircraft through the airspace can be shared between the pilot and the air traffic controllers. Collaborative Decision-Making (CDM) is a concept that goes hand-in-hand with Free Flight. Under CDM, the management of traffic flows and the associated resource allocation decisions are conducted in a way that gives significant decision making responsibility to the Airline Operational Control Centers (AOCs). Under the pre-Free Flight and pre-CDM paradigms, the air traffic controllers and traffic flow managers were viewed as a central planning authority with total responsibility both for the short term control of an aircraft to insure its safety and for the longer term management of flight schedules to insure effective traffic throughput. Free Flight and CDM are based on the principles of information sharing and distributed decision making. The overall objectives of CDM can be summarized as:

- generating better information, usually by merging flight data directly from the Airspace System with information generated by airspace users;
- creating common situational awareness by distributing the same information both to traffic managers and to airspace users;
- creating tools and procedures that allow airspace users to respond directly to capacity/demand imbalances and to collaborate with traffic flow managers in the formulation of flow management actions.

CDM was initially conceived in the mid-1990s within the FADE (FAA Airlines Data Exchange) project. The FADE project, as well as the initial operational implementation of CDM, has been aimed at the development of new operational procedures and decision support tools for implementing and managing ground delay programs (GDPs). However, it has become clear that the CDM philosophy and principles can, and should be, applied to a much broader class of problems in air traffic management.

In this paper we describe on-going CDM research and propose future research directions. The research areas we review are grouped as follows:

- Ground Delay Program Enhancements
- Collaborative Routing
- Performance Monitoring and Analysis
- Collaborative Resource Allocation Mechanisms
- Game Theory Models for Analyzing CDM Procedures and Information Exchange
- Collaborative Information Collection and Distribution

2. GDP Enhancements

The primary focus of CDM in the US has been the modification and improvement of GDP procedures, known as GDP enhancements. The collaboration between government and industry was born out of the FAA's need for real-time operational information from the airlines and the airlines' desire to gain more control over their operations during a GDP, especially in matters with economic consequences.

The major enhancements made to GDPs by the CDM working group to date are (see [Wambsganss 1997] or [Hoffman et al 1999] for details):

- the removal of (unintentional) disincentives for the airlines to report up-to-date flight status and intention information;
- the development of a mechanism (the Compression algorithm) to perform dynamic, inter-airline slot swapping that utilizes arrival slots vacated by canceled or delayed flights;
- the ability of traffic flow managers to revise program parameters during a GDP that are dependent upon stochastic conditions (e.g., airport acceptance rate);
- the dissemination of accurate aggregate forecasts of arrival demand at all major airports in the US to all traffic flow managers and to all airline operational control centers (AOCs);
- the distribution of a uniform sett of tools for formulating an analyzing GDPs to the Air Traffic Control System Control Center (ATCSCC) and to all AOCs - these tools are packaged in decision support tool known as the Flight Schedule Monitor (FSM).

A number of relatively short-term research projects are underway to enhance the basic application of CDM to GDPs. An area of general importance involves modeling the stochastic aspects of a GDP. In any traffic flow management setting the two key quantities of interest are demand and capacity. The relevant capacity for GDPs is the airport acceptance rate (AAR). Current GDP procedures are deterministic in nature and use a single AAR vector as their input. The AAR of an airport is determined largely by the runway configuration and the type of flight rules in effect, instrument flight rules (IFR) or visual flight rules (VFR). Each of these factors is dependent upon weather conditions which are, of course, highly stochastic. GDP planning in the context of CDM with stochastic AAR inputs, has been dealt with in [Ball et al 1999a]. Further work is on-going to develop the required inputs (AAR distribution).

Although the airlines are now reporting cancellations and delays in real-time, not all of these can be known hours in advance, when a GDP is first formulated. Also, there can be last-minute additions to the schedule of incoming flights (called popups), largely stemming from general aviation and military aircraft. In general, GDP planning requires an accurate estimate of the arrival demand profile. Recent work has developed improved methods for estimating departure times, which in turn leads to improved estimates of the timing of flight arrivals (see [Chaabouni 1999] and [Pujet 1999]). All work to-date on demand estimation builds upon single (deterministic) estimates of individual flight departure times. We see a need to develop stochastic demand estimation models, which build upon individual flight arrival time distributions.

Current GDP planning is done in a single airport, arrival-oriented setting. In practice however, there is a trade off between an airport's arrival and departure capacities. A rich area of research is to explore various strategies for incorporating departures into the planning of a GDP. In [Hall 1999], the CDM paradigm is extended to include departures. In essence, each airline is allowed to balance its share of the departure resources at a GDP airport along with its share of arrival resources, thus distributing among the airlines the decisions required for balancing arrivals with departures. We view the practical application of this approach a promising next step for CDM.

3. Collaborative Routing

CDM has been successfully implemented for GDP planning and control. The next major challenge area for practical implementation is flow management in the en-route airspace. The emerging area of Collaborative Routing (CR) refers to the application of CDM technologies and practices to near-real-time route planning and route adjustment. In this section, we discuss the fundamental research issues related to Collaborative Routing and cite the differences between the GDP and en-route settings that make the transfer of CDM technology from one to the other challenging.

3.1 User Needs

At this time in the US, the traffic flow management tools for controlling en-route traffic consist of (1) time-based metering, which controls the time an aircraft is to pass over a geographical point, (2) distance-based metering, which places a limit on how closely one aircraft can follow another, (3) ground delays. The form of distance-based metering most commonly used is miles-in-trail (MIT), which specifies a minimum separation (in miles) between aircraft moving in the same direction. Currently, there are few decision support tools to aid airspace managers in formulating these control actions and little collaboration between airspace users and managers in the formulation of such actions. We have formulated the following three need categories to guide a future research agenda.

The need for a shared global picture of predicted capacity and demand for various airspace resources: In the recent past, airspace users have typically not been informed of those MIT restrictions that are in place or those that are planned. In cases where such restrictions lead to high delays along certain routes, airlines (with prior knowledge) would file alternate routes to avoid such delays. Thinking longer term, a basic tenet of the CDM philosophy is to broadly share information about anticipated resource utilization to allow users to independently react and alter demand patterns. Thus, a goal should be for a common view of anticipated airspace demand and capacity restrictions to be shared among users and managers.

The need for real-time models that predict the impact of potential control actions and user decisions: Today airspace managers must make decisions regarding MIT restrictions and the rerouting of aircraft with little or no analytical support. Airspace users also lack models to predict the impact of their route planning decisions on their own delays and overall airspace congestion. Evaluation models for both groups are clearly called for.

The need for collaborative resource allocation mechanisms: The process of airline route planning and then the subsequent spatial or temporal modification of planned routes by airspace managers today is done as a two step process with little or no analytic support. This is clearly a place where new collaborative resource allocation mechanisms are called for. The successful GDP procedures should provide a starting point for this development.

3.2 Research Topics

The needs described in the previous section have led us to define the following research areas.

Aggregate Flow Models and the Prediction of Capacity-Demand Imbalances. In order to meet the fundamental information need discussed above, it is necessary to predict traffic flows on time scales any where from minutes to a few hours in advance. These predictions in turn would lead to the identification of congestion caused by capacity-demand imbalances. We feel that the only way to properly address this need would be through the development of stochastic airspace flow models. Such models would track the flow of aircraft into and out of airports and through the airspace. Most likely it would be appropriate to deal with flows at an aggregate level and to take into account delays resulting from congestion within the airspace or at airports. The models should operate in real-time and should continuously monitor, and react to, airspace conditions. Thus, the models should be built around the available real-time data sources and their characteristics. Of particular interest would be issues related to the merging of airline data sources with air traffic control data sources. The accurate prediction of capacity-demand imbalance requires good estimation of capacity constraints. Thus, models in this area should build upon research which estimates the capacity of airspace componnets, e.g. sector capacity models.

Estimation of Impact of Control Actions. Models for predicting traffic flows and airspace congestion, would provide airspace managers and users with alerts to the need to take corrective actions. The obvious second level of tool support would be to provide decision makers with feedback on the implication of any proposed action. For example, airspace managers would like to know the impact of proposed MIT restrictions or traffic reroute strategies. Airline operational control personnel would like to know the congestion-induced delays associated with various alternate flight paths and even the system impact of major changes in route structure. Models of this type would be natural add-ons to the aggregate flow models described above.

Collaborative Resource Allocation for the En-route Airspace. The most sophisticated level of decision support would involve the development of collaborative resource allocation mechanisms. A direct application of the CDM processes used for GDPs to Collaborative Routing (CR) might be:

A: An iterative process takes place between the airlines and traffic flow management (TFM). An iteration would consist of the airlines assigning routes to flights followed by TFM scheduling flights, i.e. assigning takeoff times and en-route delays, if appropriate. TFM would also have the ability to assign alternate routes under certain conditions.

Preliminary research [Goodhart and Yano (1999)] and practical use of CR suggest the following process:

B: The airlines provide inputs on their preferred routes and route alternatives, together with criteria for choosing among the routing alternatives. TFM then assigns routes to flights taking into account the criteria provided by the airlines.

For either approach the following research issues would have to be addressed:

Characterization of airline preferences and trade-off criteria. airlines must specify criteria for choosing among the alternatives specified. For a single flight there might be a tradeoff between waiting on the ground in order to take a shorter route with less fuel burn and taking off immediately but using a longer, more expensive route. Additionally, criteria would be required in order to determine how to allocate delay among several flights.

Definition of fair allocation principles. M will typically be faced with decisions regarding the allocation of delays among flights of competing airlines. Criteria are required to do this in a fair fashion (e.g. analogies to ration-by-schedule and compression).

For approach B, it is necessary to represent a variety of routing alternatives and to choose amongst them, leading to the following additional topics.

Characterization of routing alternatives acceptable to an airline. In the simplest case, an airline might specify a route and a small number of alternate routes. However, given the combinatorial growth of route alternatives through the airspace, a robust, flexible system should allow more flexible ways of specifying alternatives, which could capture many possible alternatives in a compact way.

Development of route generation algorithms. Given the issues discussed above, one is left with a complex route choice problem. When compared with existing literature on such problems, e.g. [Bertsimas and Stock (1998), Bertsimas and Stock- Patterson (1998)], one is faced with airline-specific route alternatives and new classes of objective functions that involve fairness criteria (see [Goodhart and Yano (1999)] for CDM related work).

The development of resource allocation mechanisms for the en-route airspace would not doubt build upon and employ many of the ideas presented in Section 5.

4 Performance Monitoring and Analysis

As efforts increase to make more efficient use of airspace resources and to move toward a more decentralized decision making paradigm, there is an increasing need for quantitative assessments of conditions within the airspace and for the evaluation of new programs and initiatives. CDM has dramatically highlighted these needs. The two main stumbling blocks in the development of the necessary tools are (1) the measurement of cost effectiveness in monetary terms or in terms of airspace resources such as capacity or throughput and (2) the inherent difficulty in evaluating the contrasting hypothetical case, (i.e., what would have happened had an initiative not been made or done using prior technology). The areas of concern can be roughly divided into three categories:

(i) Single-event predictions: The issue here is how to evaluate, both on an aggregate and individual basis, the quality of information being submitted for an event that will occur at some future point in time. For instance, given a stream of ETAs (estimated time of arrival) for a single flight made over, say, a 12-hour period, how does one evaluate the quality of the stream? In this case, a metric such as IPE (integrated predictive error) can be used to assign one performance number to the entire stream of predictions (see [Hoffman 1999] for details). This integration-based metric is robust with respect to isolated instances of bad predictions and aggregates easily over multiple flights. Other events of concern are the departure time of a flight, the number of aircraft that will arrive at an airport during a given hour, and the number of aircraft that will pass through a fixed region of the airspace.

(ii) Value of CDM Data and Decision Processes: CDM procedures create new information streams by combining airspace manager (FAA, EuroControl, etc) and user (airlines, GA, etc.) data sources. This information is then distributed to both airspace users and managers. For instance, under the CDM flow of information, the FAA now receives early cancellation notices on individual flights. Prior to CDM, cancellation notices were delivered on a sporadic basis and on-the-average after a flight's scheduled departure time (see [Ball et al 1999b]). Research topics of interest are the assessment of the added value of this new information stream when compared to its predecessor, and the impact of creating common situational awareness by distributing this information to all parties. Due to the use of procedures such as compression, overall GDP delay has been reduced by CDM (see [Ball et al 1999b]). A possibly more significant impact of CDM processes is that airlines are able to exercise more control over the allocation of delays to their own flights and to do so in a more timely fashion. Placing a value on this capability is a challenging problem.

(iii) Program performance: Although a GDP is planned by traffic flow managers, its success is contingent upon a wide variety of actions such as: departure compliance, inter-airline and intra-airline arrival slot allocation, the submission of timely data, weather forecasting, local traffic control, en-route time estimations, and the incorporation of unscheduled flights (e.g., general aviation, and military flights). Given all these components, how does one rate the success of the overall GDP? Can a single metric be developed for this and how should it vary over time as GDP procedures become more refined?

Some inroads to this has been made with the development of the rate control index (RCI), which compares, post facto, the flow of traffic into the terminal space of an airport (or on the runways) against the flow rate that was planned in the GDP (see [Hoffman and Ball 1999]). The RCI factors out the quality of the forecast upon which the GDP was based and the ultimate conditions at the airport during the GDP. This allows it to rate execution of a GDP independent of the appropriateness of the underlying plan. It is not designed, however, to measure the effects of airborne holding during a GDP or the ability of traffic flow managers to dynamically revise GDP parameters.

5 Collaborative Resource Allocation Mechanisms

The broad application of CDM to resource allocation decisions is a rich and challenging, research domain. At one extreme, the Air Traffic Control/Traffic Flow Management can be viewed as a centralized authority that controls the actions of all aircraft. This point of view, traditionally taken in work on air traffic flow management, naturally lends itself toward the application of optimization models (see, e.g., [Andreatta 1987] and [Bertsimas and Stock 1998]). On the other hand, the classical approach to the analysis of ground transportation problems views each vehicle as an autonomous agent. This view lends itself toward the application of network equilibrium models to determine demand distributions. (see, e.g., [Florian and Hearn 1995]). In the aviation setting, the individual commercial aircraft are owned and operated by the airlines. CDM has initiated a shift away from the central authority paradigm by acknowledging that the airlines should play a substantial role in air traffic management. Thus, CDM resource allocation falls somewhere between the central controller and autonomous agent perspectives. This suggests a hybrid approach toward research in resource allocation involving techniques from optimization, game theory, distributed control and related disciplines. The applicability of this research will most likely extend beyond the context of air transportation.

In the context of ground delay programs [Hoffman et al 1999, Wambsganss 1997], the CDM paradigm has led to several new operational procedures and algorithms, in particular, the introduction of airport arrival slot rationing through the ration-by-schedule (RBS) algorithm and the introduction of inter-airline arrival slot swapping through the Compression algorithm. The main principle underlying these procedures has been the consensus notion that each airline implicitly owns the arrival capacity allocated to it weeks in advance in the Official Airline Guide (OAG) schedule.

At the start of a GDP, the RBS algorithm honors this ownership by initially rationing available arrival capacity in accordance with the OAG schedule. Later in the GDP, the airlines have the opportunity to reallocate slots among their flights to meet their respective economic objectives. When flights are canceled or delayed, slot vacancies can be created that are not usable by the vacating airline, thus leading to globally sub-optimal use of airport resources. The Compression algorithm rectifies this by reassigning these slots to competing airlines, while at the same time, rewarding the vacating airline with other slot assignments that it can make effective use of. This acts as an incentive for airlines to submit cancellation and delayed flight information.

RBS and Compression successfully comprise a resource allocation mechanism that shifts decision responsibilities to the AOCs, while ensuring globally optimal resource utilization (i.e. minimization of overall delays). Yet, their specific designs make it hard to incorporate incentive mechanisms and fairness considerations in more complex resource allocation decisions that occur in the en-route airspace or even in more advanced models for the allocation of resources in GDPs (e.g., [Hoffman 1998]). Therefore, a current area of research considers how to incorporate the incentive and fairness considerations employed by RBS and Compression into a model-based approach which is more closely related to the optimization models developed for the pre-CDM environment.

We have developed a goal-programming based model [Vossen and Ball 1999] that closely matches the reallocation of arrival slots that occurs in Compression. Slot ownership is defined by creating a set of goals or targets for each airline that represent the airline's ideal" utilization of its slots, which may not be attainable due to flight cancellations or delays. The model aims to minimize the maximum deviation from the defined sets of goals in such a way that no airline can increase its benefits without reducing the benefits of other airlines. An earlier model that uses goal satisfaction is a multi-commodity extension of the (single-commodity) basic GDP optimization model [Butler 1998]. This movement away from an approach defined only by a procedure (Compression) to an optimization-based allocation model allows for easier analysis of hypothetical changes to the allocation procedure and yields a greater potential for the migration of the reallocation process to more complex settings.

A suggested area of research is the redesign of the reallocation process itself. For instance, the reallocation of landing slots in Compression can be viewed as a situation in which airlines trade resources so as to achieve mutual benefits. From this perspective, Compression finds a subset of all possible trades, using delay minutes as a measure of airline benefits. Hence, it would be worthwhile to investigate whether it is possible to (a) extend the trading options in the reallocation process and/or (b) extend the measure of benefits for airlines within this framework. While such extensions would not affect overall resource utilization, they would likely be of great significance to the airlines, given the potential to increase flexibility and enhance economic trade-offs. This work will likely require concepts from game theory, such as fairness, stability in trades and coalition formation.

Another possibility is to relax the notion of resource ownership by allowing the airlines to competitively bid for resources. The relation between applicability of auctioning vs. trading mechanisms in a collaborative resource allocation environment is an interesting question in its own right, which could lead to important insights on the broad application of CDM. We emphasize that any comparison of resource allocation mechanisms should take into account the ease of implementation and the actual decision making capabilities of the entities involved.

6 Game Theory Models for Analyzing CDM Procedures and Information Exchange

Due to the limited number of decision makers and the diversity of objectives (or interests), each airline's decision has potential effects on the performances of other airlines' objectives and tends to provoke modifications of their decisions. Therefore, the decision making processes of the airlines are mutually dependent. Economists suggest that Game Theory can be used to analyze the interdependent decision makings within air transportation (see [Evans and Kessides 1994] and [Gibbons 1992] for background on the ideas discussed below).

CDM members provide and share accurate delay/cancellation information and create consensus weather information in order to make better and more synchronized decisions. In addition, through Compression, airlines exchange their unusable slots at arrival airports to avoid wasting valuable resources and to improve mutual benefits. Thus, it is through mutual cooperation (and trust) that CDM is able to improve the system-wide performance.

Under the CDM paradigm, there are three basic forces that keep an airline from deviating from cooperative behavior. Firstly, there is the goodwill towards the CDM. This has been a powerful force to support the cooperation. However, from an economics point of view, this force may be too weak to be sustained in the long run, given the competitiveness within the industry paradigm. Secondly, there is the peer pressure as described by the "Contestablity Theory" in the economics literature [Bailey and Panzar 1981]. This theory says that in multiple-market environment, an oligopoly company will neither raise its price too high to attract market entries nor cut its price too low to provoke price wars in other markets. This theory suggests that an airline may adhere to cooperative behavior simply to avoid provoking non-cooperative reprisals from competitors. Thirdly, the FAA performs (limited) supervision and enforcement functions on top of the system.

However, these forces may not be strong enough to support the cooperative paradigm in the long run, especially once the airlines become intimately familiar with their roles in the new procedures invoked by CDM. In game theory parlance, the current CDM paradigm is not supported by a stable cooperative structure, much like the prisoners in the famous Game Theory model - the Prisoner's Dilemma. For instance, an airline could potentially gain more delay reduction if it unilaterally delays the announcement of its delays and cancellations than if it cooperatively provides timely information. Since most airline information is proprietary, it is hard to detect whether an airline is gaming the situation through manipulation of the information that it supplies.

In the short run, cooperative behavior in the CDM paradigm can be enhanced by employing more non-cooperative behavior monitoring and correction devices. For example, a mechanism can be imbedded into the Flight Schedule Monitor tool to force flight substitutions on the behalf of bridge-only airlines who do not make use of arrival slots (the bridge-only status exempts an airline from certain flight movements that would naturally occur in the Compression Algorithm). Failure to submit flight arrival delay notices can be detected by checking for delays in flight departures that would inevitably lead to arrival delays. Also, a shortening of the compression cycle may reduce the damaging effects of erroneous or omitted flight information, thus removing some of the incentive to withhold information.

In the long run, the cooperative paradigm is best supported by the provision of economic incentives for the airlines to release timely information rather than the administration of punitive actions. This requires that an individual airline's interest be aligned with the interests of the overall system. Fairness issues should be addressed when designing the new incentive structure. In addition, the definition of the measurements for the objectives to be optimized is another important issue. The difficulty lies in the measurements of efficiency, safety, and costs. The trading or auctioning-based procedures mentioned in the prior section may contain appropriate incentive structures.

7 Collaborative Information Collection and Distribution

One of the maxims of collaborative decision making is that more information is better. However, individuals can become swamped with too much or inappropriate information. Airspace managers are particularly susceptible to this because many of them are making real-time decisions under pressure with potentially devastating consequences both in terms of resources and safety. CDM has been enormously successful at generating common situational awareness through information dissemination. However, more research in air traffic management is required with regard to the following human-factors issues.

- Which parties need which information and in what form?
- Should all parties have the same information?
- At what point does operational information become proprietary?
- At what point does information availability become counterproductive?
- How do we measure the value of information dissemination and how do we weigh it against the costs of start-up and ongoing maintenance?

The predecessor of CDM, the FADE program, successfully addressed these issues for one facet of air traffic management. In particular, it showed that the dissemination of a common aggregate picture to both traffic flow managers and airline dispatchers could have a positive impact on the decision making processes involved in the planning and maintenance of a GDP (see [Wambsganss 1997]). Research into these issues must be combined with long-range planning to produce directives for future information gathering and distribution.

In addition to distributing decision making a key aspect of CDM, which many would argue is the most important, is information sharing. In the present implementation of CDM, flight status information generated by the airlines is merged with FAA generated information to produce a higher quality picture of the system-wide status. Furthermore, both the FAA and the airlines using the Flight Schedule Monitor (FSM) decision support tool share a common view of this higher quality information. It is only because both the FAA and the airlines had a strong desire for the merged information stream and because both brought substantial value to the table that the effort was successful. Now the broader aviation community, including airports, general aviation, related ground-side transportation concerns, etc., has expressed a desire to gain access to this information resource. There is resistance to providing such access due to information privacy concerns and also, the simple acknowledgment that this information has value and should not simply be given away. This environment is an example of the growing importance and value of information within our society and of the associated economic complexities. The extension of CDM to a broader group of players requires research into economic models of information providers and consumers with the objective of providing a solution that can be applied within the air transportation setting.

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