Dynamic Slot Exchange Mechanisms in Air Traffic Management

Michael Ball* Thomas Vossen†

*Robert H. Smith School of Business and Institute for Systems Research
University of Maryland
College Park, MD 20742 USA
mball@rhsmith.umd.edu

†Leeds School of Business
University of Colorado
Boulder, CO 80309-0419 USA
Thomas.Vossen@Colorado.edu

1 Introduction

Collaborative Decision Making (CDM) has now emerged as the fundamental basis for new air traffic management procedures and systems within the U.S. The widespread acceptance of CDM principles is based on its successful application to the planning and control of Ground Delay Programs (GDPs) (see [1],[3]). While CDM has several underlying philosophical components, its essential elements can be summarized as improved communications and improved resource allocation procedures. Using CDM-Net, FAA and airline data are merged to produce improved prediction of airspace demand patterns. The new resource allocation procedures have not only produced better equity and system utilization but, in addition, they are an essential driver of the improved communication. Prior to CDM, the airlines felt that they were not being treated equitably and that the information they provided could be used to provide benefits to their competitors. As a result, they were reluctant to provide up-to-date information. By instituting resource allocation methods that were based on an agreed-upon standard (ration by schedule) and by allowing the airlines to derive benefits for the provision of cancellation information (the compression algorithm), the airlines were induced to provide up-to-date intent information through the CDM-Net.

In achieving an allocation that is equitable and independent of flight status information, ration by schedule (RBS) produces an allocation of slots that might not be fully usable by an airline. The compression algorithm adjusts the allocation so that each airline can assign flights to all the slots it has been allocated. Specifically, whenever an airline has a slot it cannot use due to a flight cancellation or severely delayed flight, the compression algorithm executes a series of exchanges that gives the unusable slot to another airline while freeing up the earliest possible slot that that airline can use. While compression can be viewed as a procedure for optimizing slot utilization, it can also be interpreted as an inter-airline slot exchange procedure. This point of view is reinforced by recent research that interprets compression as mediated inter-airline bartering [2], and by the newly implemented slot credit substitution (SCS) procedure. SCS is a real-time transaction-oriented process in which airlines submit conditional offers to exchange an (earlier) slot freed up by a cancellation or delay for a (later) slot. The motivation for the offer is that the airline is unable to use the earlier slot because it has no flights that can arrive at that slot time, but it is does have flight(s) that can be assigned to the later slot.

2 Advanced Slot Exchange Mechanisms

In this paper, we use the slot exchange concept as a starting point to present and analyze two advanced exchange mechanisms. First, we replace the current one-for-one exchange mechanism, i.e. compression, with a two-for-two exchange mechanism. Subsequently, we add the possibility of monetary side-payments to the exchange. Implementation of the the two-for-two exchange mechanism requires the solution of a mediator problem, which must determine the set of two-for-two offers to accept. The incorporation of monetary side payments represents a fundamental shift from barter to a true marketplace. Supporting such a marketplace requires the development of an appropriate auction mechanism. In both cases, the effectiveness of the exchange mechanisms should be measured by comparing the efficiency of the allocations the mechanisms can achieve with a globally optimal allocation. Each of these topics represents an interesting research challenge, which we have addressed.

2.1 Mediated Bartering Model

We first analyze the bartering model, where each airline submits a set of offers consisting of desired slot exchanges. The offers are then examined by the mediator, who determines the offers to accept based on an appropriately defined global criterion. In the one-for-one trading case, the mediator's problem can be formulated and solved as an assignment problem (see [2]). In the general, k-for-n case, the mediator's problem can be formulated as a set partitioning problem. For the 2-for-2 case, we have developed a specialized integer programming model that has the structure of a network with side constraints. In this model, multiple offers were embedded within certain aggregate structures. In a set of computational experiments using GDPs from Boston's Logan airport, the model always solved in less than one minute with a standard Cplex implementation.

2.2 Market Mechanisms

The incorporation of monetary side payments introduces a challenging market design problem. Within the context of GDPs, the marketplace contains multiple buyers and sellers, and typical participants wish to both buy and sell multiple goods. In fact, the typical transaction is not a pure buy/sell, but rather a true exchange where a pair (or set) of slots is exchanged together with a monetary side payment. In theory, such exchanges could be decomposed into a series of buy-sell transactions. However, such an approach is not practical due to the risks involved: typically, an airline would not be willing to sell a slot (currently occupied by a flight) unless it was assured of (later) buying another slot that the flight in question could use. We describe a basic exchange procedure that supports this environment; it is an adaptation of a recently developed 2-sided auction mechanism.

2.3 Evaluation of Potential Benefits

Probably the most important aspect of this research involves the evaluation of the potential benefits that these two exchange mechanisms provide. We note that, if stochastic problem aspects are ignored, then system-wide efficiency (i.e. optimal throughput) is achieved as long as each of the GDP slots is assigned a flight. Thus, system-wide efficiency can be achieved without the use of any complex exchange mechanism. The value of an exchange mechanism (or any market mechanism) comes in its ability to simultaneously improve the individual performance of multiple participants. To evaluate such improvements, the internal objective functions of participants (airlines in our case) must be considered. In a set of experiments involving a large set of GDPs from Logan airport, three simple airline objective functions were considered: i) airlines maximize on-time performance (# number of flights with less than 15 minutes of delay); ii) airlines minimize total passenger delay; iii) airlines minimize a step-wise passenger delay function meant to model the impact of discrete time events, e.g. when baggage misses connections, when passengers miss connections, when the crew times out, etc. Experiments show that the 2-for-2 trading mechanism provides a substantial improvement over the (existing) 1-for-1 mechanism and, in fact, comes very close to achieving the best system-wide performance. For cost functions ii) and iii), the 2-for-2 trading mechanism provides substantial improvement over the 1-for-1 but does not come nearly as close to the system-wide optimal as in case i). When one considers the details of this environment it is clear why this is the case. In particular, for the Boston-Logan data set we used (and for most airports) there are several small carriers who predominately have small (in terms of number of passengers) flights. In these experiments, these carriers can "protect" their slots so that they remain assigned to flights with small numbers of passengers. Of course, when side payments are allowed, it is quite possible that smaller carriers would be willing to exchange earlier slots for later slots for a sufficient side payment. It also seems clear that a larger carrier would be willing to pay significant amounts to reduce delays on large aircraft. We are now in the process of implementing an auction mechanism and also of generating additional airline cost functions. These results as well as those previously mentioned will be reported on at the meeting.

References

[1] M.O. Ball, R. L. Hoffman, D. Knorr, J. Wetherly and M. Wambsganss, "Assessing the Benefits of Collaborative Decision Making in Air Traffic Management", in *Air Transportation Systems Engineering*, G. Donohue and A. Zellweger, eds., 239-250, American Institute of Aeronautics and Astronautics, Inc., Reston, VA., 2001 (a preprint appeared in *Proceedings of 3rd USA/Europe Air Traffic Management R&D Seminar*, 2000).

[2] T. Vossen and M.O. Ball, "Optimization and Mediated Bartering Models for Ground Delay Programs," submitted for publication, working paper, Robert H Smith School of Business, University of Maryland, 2002, available at http://bmgt1-notes.umd.edu/faculty/km/papers.nsf.

[3] M. Wambsganns,“Collaborative Decision Making Through Dynamic Information Transfer,” *Air Traffic Control Quarterly*, 4, 107-123 (1996).