THE GENERALIZED ARRIVAL PLANNER (GARP): MODELING AND ANALYSIS FOR ARRIVAL PLANNING

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Abstract

In this paper we describe the Generalized ARrival Planner (GARP) and demonstrate its use in an arrival management simulation. The paper will motivate the problem, describe the optimization-based sequencing and scheduling algorithm, and provide simulation-based analysis results. GARP is a new and efficient N-point planning algorithm for arrival management planning.

1 Introduction and Motivation

The effective use of airport capacity depends on the optimum use of all available runways. Even for a single runway there is much to be gained from the proper sequencing and scheduling of aircraft coming from different meter fixes. Certain sequences of aircraft of differing weight classes can be unfavorable due to the separation constraints imposed because of the wake vortex phenomenon. The most effective landing sequences tend to be “homogenous” by weight class in order to minimize the required separation times between successive landings. When there are multiple runways at a given airport there is an even greater opportunity to create effective landing sequences through runway re-assignment. Optimal runway assignment can have the effect of achieving this homogenization by segregating aircraft of a given weight class to the same runway, as well as to balance the traffic across the runways.

The Multiple Runway Planner (MRP) is a tool that has been developed at Boeing for representing Center planning processes in our exploration and system effectiveness analysis of alternative arrival management operational concepts. Given a set of arrivals within the planning scope, with pre-determined meter fix assignments and estimated times of arrival (ETA), and with delay options for the center and/or TRACON, the algorithm determines an output plan consisting of runway assignments and preferred sequences and schedules at the fixes and at the assigned runways. This output plan seeks to minimize the total arrival delay at the runways while maintaining feasibility with respect to separation constraints imposed at the meter fixes and at the runways. The Boeing MRP can be designated a 2-point scheduling algorithm due to the fact that each arrival is subject to separation constraints imposed at both the meter fix and at the runway. Similarly, the NASA Traffic Management Advisor (TMA) is a 2-point scheduling algorithm. The Boeing MRP algorithm uses an optimization-based approach which can be configured to represent a variety of objective functions and levels of automation beyond those specified above. For example, the algorithm can also be configured to emulate the TMA. Several years ago the MRP was used extensively at Boeing to explore concepts for collaborative arrival management. Since then the MRP has been integrated into the Boeing Trajectory Analysis and Modeling Environment (TAME) simulation environment, to represent arrival planning functions while the aircraft is still in the center airspace.

Beyond center planning there has been a desire to also model a second-stage TRACON planning process to address both arrival prediction errors along with potentially complex

TRACON route geometry. Addressing complex geometry typically translates into the need to address more general N-point planning and often with N>2. The GARP model is the result of recent Boeing research and development efforts and was initially aimed at the development of a TRACON planner. This TRACON planner, along with the MRP for Center planning, was to be included within TAME and also within a new stochastic simulation called the "Monte-carlo Schedule Effectiveness Model (McSEM)". Fortuitously, the development of GARP resulted a planner which can be configured as both an improved Center planner and, also, as a TRACON planner. In fact, the GARP algorithm can be configured in many different ways and can address an extremely wide range of arrival planning problems besides the TRACON planning problem which drove its initial development. Thus, GARP will replace the MRP for Center planning and will also serve, in a different configuration, as the TRACON planner within both TAME and McSEM. As such, GARP does, in fact, provide for a general capability for N-point Center and/or TRACON planning, with N>2 as needed, in order to more effectively address complex geometry wherever it may occur.

At this point in time, we have completed the implementation and testing of GARP and have integrated it into TAME, a test simulation for GARP, and into the McSEM simulation environment. Our initial analysis, utilizing GARP, has so far been focused on a Denver-based scenario. This scenario contains very complex geometry in the TRACON including several different kinds of scheduling points. The result is a problem requiring N-point scheduling for N>2 which means that a single arrival may pass thru N>2 scheduling points from birth to runway. In some cases, the value of N in this scenario is as large as N=6 which is well beyond the scope of 2-point planners such as the MRP or the TMA.

2 Related Work

NASA has reported a large body of work on arrival management. Many of the basic concepts concerning arrival sequencing and scheduling along with a representation of a CTAS TMA-like planner are taken from [1].

NASA has also reported on arrival management collaboration between air traffic and airlines. The CTAS tool was built to assist air traffic service providers, and Collaborative Arrival Planning (CAP) to assist air carriers by leveraging and expanding the capabilities of CTAS (see [2-6]) and to provide for information exchange which is the key to collaborative arrival management and can lead to improvements in both ATM and AOC operational effectiveness. In [7] a method for "priority scheduling" was explored to exploit airline-preferred arrival orders.

The Boeing MRP is described in [10] and has been integrated into the Boeing TAME model [9]. The MRP has been used to perform several analyses including meter fix balancing, an MRP/TMA comparison, collaborative arrival management benefits, and a study of continuous versus discrete delay options.

More recently, [12] describes research underway to improve the TMA by addressing TRACON merge points. A stochastic model, the Stochastic Terminal Area Simulation Software (STASS), is utilized in [13] to explore separation buffers. Sequencing and scheduling algorithms themselves are a primary focus in [14-15] with [14] comparing heuristic algorithm effectiveness to optimized schedules derived using integer programming while [15] explores potential real-time approaches for addressing discrete delays.

3 Problem Definition and Solution

In this section we will describe the problem formulation and solution methodology for the general arrival planning problem. It is assumed that the reader has a general familiarity with the arrival planning problem and especially as it has been defined for Center planning (solvable by the NASA TMA or the Boeing MRP) and also as it is defined in the conventional approach to 2-stage planning. References such as [1] and [10] are good places to start a review of these problems. We will also briefly describe what we mean by conventional 2-stage planning later in this section. For a detailed discussion of this 2-stage planning concept the reader is also referred to [11]. Most importantly, we will see that our general GARP formulation is capable of supporting a single stage arrival planning problem, which would consider the Center and TRACON plans as a part of a single all-encompassing plan or, alternatively, can be used to represent a first stage Center planner and a second stage TRACON planner in a two-stage approach to arrival planning. In any of these cases, the same GARP model can be utilized to provide for each of the planning functions by configuring its input to represent each different planning function.

Arrival Route Network

Perhaps the most fundamental element of the GARP approach, which provides for the great variety of different planning function representations, is that the underlying mathematical structure for representing the arrival route network is a very general network specification of nodes and arcs. The nodes are points in space such as birth nodes, meter fix nodes, runway nodes, along with other nodes that might be useful in defining this network. An important aspect of nodes is that some of them are designated as scheduling points so that separation constraints can be levied against consecutive arrivals passing thru these points. In GARP, any node in the network other than a birth node can be a scheduling point.

In addition to the nodes are the arcs, which we sometimes refer to as “legs”, which constitute segments of flying from one node (the upstream node) to another node (the downstream node). For each leg, we can define on input the nominal travel time as a function of aircraft performance type. Additionally, we can define for each leg the available delay authority. This can consist of an optional specification of holds plus either a continuous or discrete set of delay options also differentiated by aircraft performance type. These inputs result in a maximum delay authority for each leg. Legs are “directed” and are flown from upstream to downstream so that we are dealing with what is known in mathematics as a directed network. Related to this directionality, and given the specific “topology” (shape and/or structure) of these networks, the network has the important property of being “acyclic” meaning that these networks do not contain cycles. That is, there cannot be sequences of arcs (all in the same downstream direction) beginning at one node and ending at the same node. But this condition for an acyclic network is not, in general, limiting since this property is quite natural in considering an arrival network which is the basis for defining the different ways that arrivals can fly from their birth nodes to their destination runways. A cycle would simply represent an arrival flying in a circle and is not consistent with always flying in the downstream direction. Thus, the only reasonable purpose for such a cycle might be to represent a holding pattern, but these can be provided for in the simple way described later in this section and not requiring an explicit representation as a cycle of arcs. Thus, cycles are prohibited, but without loss of modeling flexibility insofar as we have another way to provide for holding.

As mentioned earlier, nodes in this network will often denote points of special importance in the overall arrival network. We have already stated that an important category of nodes are those denoted as scheduling points which are important because it is at these points that we will define separation constraints. Thus, the output sequence and schedule of GARP will guarantee that the schedule for consecutive arrivals at the same scheduling point will be separated (temporally) by an amount greater than or equal to a minimum separation value defined on input for these points. Birth nodes are also important as they define the point at which we will begin considering an arrival as a candidate for inclusion into the arrival planning problem. There is an additional process called “scoping” which determines exactly which arrivals are to be considered by the planner at each time designated for arrival planning. Scoping involves estimating the time it would take for an arrival to reach a runway along some kind of “nominal” route and then comparing that time to a temporal scoping window formed from an input “influence horizon” and an input "freeze horizon". Thus, at any particular planning time, the planning process considers those arrivals which have estimated flying times within the scoping window. In this regard, it should be clear that we would not always want to consider an arrival as part of our problem all the way back to its originating airport. Similarly, once an arrival gets sufficiently close to its destination runway (or even close to a meter fix or other defined point of interest) it is not practical or sometimes not even feasible to continue to re-plan arrivals. Such arrivals become "frozen" and are no longer subject to further planning. Nevertheless, frozen arrivals can constitute "constraints" for trailing arrivals to the extent that an arrival in scope and scheduled to cross a particular scheduling point must be scheduled in such a way as to achieve a minimum separation with respect to the leading aircraft crossing the same point whether the lead aircraft is also in scope or frozen.

M-Stage Planning

In some cases, certain points (for example, the meter fixes in two-stage planning) are important in the sense that they represent points of transition where an arrival crosses from one kind of controlled airspace (for example, the Center airspace) to another kind of controlled airspace (the TRACON airspace). It is usually desirable to designate these points of transition as scheduling points. This is, in fact, the case in two-stage planning where the meter fixes serve as these points of transition. This kind of 2-stage planning can be generalized to M-stage planning for M>2 (note that M-stage planning refers to a different aspect of arrival planning than the N-point planning discussed earlier). An obvious way to accomplish more general M-stage planning is to identify additional sets of transition nodes lying at the boundary of other adjacent subspaces of the overall arrival airspace. GARP is capable of supporting this kind of M-stage planning and we have already utilized it to support 2-stage as described above. In the first stage of planning, the planner functions as a Center planner and considers both the meter fixes and the runways as scheduling points. In the second stage, the planner treats the meter fixes as (dynamic) birth nodes, and considers the runways and possibly other points within the TRACON as scheduling points.

Routes and Route Sets

Another key aspect of GARP is that each arrival may possess a route set. A route is essentially a path thru the network from the arrival's birth node, along a sequence of arcs so that each arc is traversed in the proper direction from upstream to downstream, and which ultimately passes thru exactly one allowable runway. In some cases, to guarantee the existence of feasible solutions, the network may contain an artificial "diversion" runway along with the associated diversion routes. We have already noted that GARP is able to address N-point planning for N>2 since routes are allowed to pass thru any number of scheduling points so long as the route is compatible with the arrival network topology, compatible with the directionality of the arcs, and as long as the route does not possess a cycle. Thus the route set defines all routes that a given arrival is allowed to fly from its birth node to an allowable runway. The ability to represent N-point scheduling for N>2 is the key to being able to address complex airspace geometry.

Finally, besides the obvious nodes and arcs defined to represent the airspace network, the modeler is permitted to add additional "artificial" nodes and arcs to the network and utilize some of these nodes as additional scheduling points. The clever use of these artificial nodes and arcs greatly expands the set of planning problems which the modeler can address with GARP. One such example was provided earlier with respect to modeling diversions. Another such example is the ability to address runway dependencies which are of great importance in concepts for closely spaced parallel runways. There are other examples.

Example Arrival Route Network

Figure 1 illustrates an example arrival route network based on a model of the Denver airport

TRACON airspace and traffic patterns. This case has 8 meter fixes and 3 runways. It also clearly possesses complex TRACON geometry. Besides the meter fixes and runways, which need to be designated as scheduling points, there can be seen to be many other points interior to the TRACON that are merge and demerge points. These points will need to designated as scheduling points if the planner is to have any hope of generating an arrival sequence and schedule that safely separates the arrivals at all of these points.

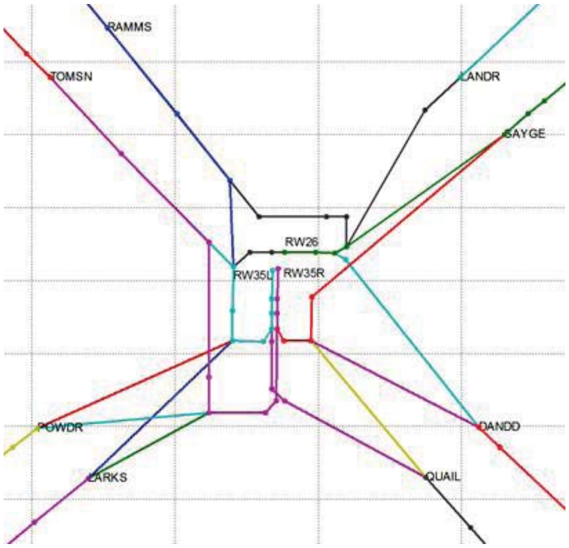

Figure 1 – Denver Scenario

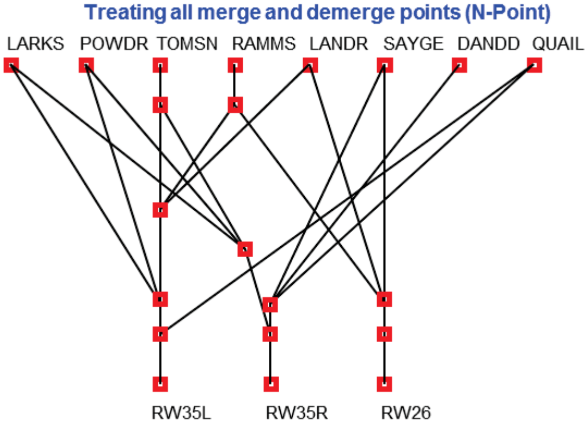

Figure 2 – Denver Scenario Abstracted

Figure 2 is an abstracted version of the same scenario but in a manner more easily recognized as (the TRACON part) of an arrival route network of the type utilized within the mathematical framework of the GARP algorithm. The 8 nodes at the top are the meter fixes and the 3 nodes at the bottom are the runways. Besides the meter fixes and the runways there are an additional 10 merge and demerge points. If we visualize this network from the standpoint of a Center planner then we must first realize that there are birth nodes upstream from the meter fixes and additional network components connecting the birth nodes to the 8 meter fixes. Assuming, also, that there are no other scheduling points in the Center airspace then the Center planning problem would ideally consider all of the 8 meter fixes, 3 runways, and 10 merge / demerge points interior to the TRACON as scheduling points. Furthermore, note that a route going from a birth node thru RAMMS to RW35L involve a minimum of 6 scheduling points (1 meter fix, 1 runway, and 4 additional merge / demerge scheduling points). Thus, in order to address the full-blown Center problem, we need to consider N-point planning for N at least as large as 6. This is well beyond the scope of the Boeing MRP or the NASA TMA.

Finally, consider Figure 3 in which the same network is simplified in a manner consistent with the Center planning representation normally used by 2-point planners.

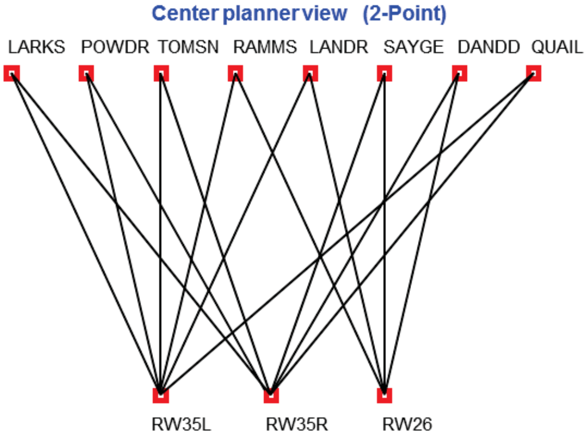

Figure 3 – Abstracted Scenario Simplified

This network is greatly simplified as seen by comparing Figures 2 and 3 where numerous merge and demerge points ignored as scheduling points. This kind of airspace geometry is a good example of how complex geometry benefits greatly from a capability for N-point planning with N>2.

The General Arrival Planning Problem

The general arrival planning problem can now be stated. The problem is to determine an optimal or approximately optimal sequence for scheduling arrivals, an assigned route for each arrival, and a feasible schedule at points along the route in order to minimize the total arrival delay. The feasibility of the schedule is with respect to satisfying minimum (temporal) separation constraints between consecutive arrivals at each scheduling point, and with respect to the flying time along each leg being feasible respect to leg flying times and leg-delay allocations being consistent with the defined delay authority for each leg. We will see later in this section that there are also a variety of optional additional constraint types can be added to the problem in order to enhance the model. GARP will also ensure that the output sequence and schedule is feasible with respect to any of these additional constraints.

Solution Methodology for the General Problem

The GARP solution methodology, in a way similar to the MRP model, is based upon an implicit enumeration or, equivalently, a branch and bound approach. The method extends and improves upon the MRP method [10] which already extended and improved upon a similar approach described in [8].

Implicit enumeration is a technique for finding optimal solutions to optimization problems through an exhaustive (or "implicitly" exhaustive) enumeration of all feasible alternatives. Typically, a bounding technique is utilized to reduce the search space by eliminating or "pruning" large numbers of feasible solutions without direct examination. Suppose, for example, that a partial sequence and schedule (say the first X of Y arrivals) has been constructed. If it can be shown (by a bounding argument and by comparison to a current "best" feasible solution) that no extension of this partial sequence could possibly be optimal, then every extension of this partial sequence can be eliminated from further consideration. These extensions are then considered to have been implicitly enumerated without resorting to direct examination.

The implicit enumeration approach used here makes use of such a bounding argument and further controls the computation by constraining the search of feasible alternatives to be close to the first-come-first-served (FCFS) sequencing approach. This approach, where the search is constrained to consider only sequences sufficiently close to FCFS, is called "restricted" branch and bound. FCFS is defined by consideration of a scheduling order based upon the runway ETAs for an arrival assigned to a nominal route and in consideration of a non-interference assumption. Non-interference just means that, for the purposes of this particular ETA calculation, we assume no delays would be incurred as the result of separating this arrival from all others. Closeness to the FCFS sequence is measured through the concept of "position shifts" as described in [1] and [10]. In general, constraints on position shifts can be levied in a variety of ways. Use of position shift constraints can provide flexibility in defining the degree of automation or optimality in the planning process and can also be used to avoid excessive computation, as is the case in our restricted branch and bound method. The approach also utilizes a moving or sliding window to be employed within the branch and bound and which provides for additional and substantial runtime reduction. The moving window idea is briefly described in [8] and has been adapted for use in both the MRP and GARP. Other details about branch and bound, position shifts, and/or the moving window can be found in [1,8,10].

The approach taken in GARP, as an extension to the MRP, is based upon the view that a complete arrival plan can be considered an ordered sequence of individual decisions involving the assignment of an arrival aircraft to a route from its route set. Viewed this way enables each decision to be considered as:

1 The assignment of a route to the arrival.
2 Stipulating this arrival to be the next arrival scheduled at each and every scheduling point along its route.
3 Permitting the efficient calculation of the scheduled time of arrival (STA) for this arrival at each scheduling point.

The STAs for this next arrival can be efficiently computed in (2) because the previously scheduled arrivals at each scheduling point along the route were already computed in prior scheduling steps. "Pushback" occurs when the STAs at some downstream scheduling point require a delay in excess of the maximum delay authority on the leg immediately prior to the scheduling point. When this happens the delay is immediately "pushed back" to one or more upstream legs having sufficient maximum delay authority. If this is impossible then that particular route assignment is deemed to be infeasible and the algorithm considers a different route in the same route set. If all routes are infeasible then a diversion will take place if the modeler provides for diversions. Otherwise, the algorithm calculates an artificial hold, which we also call a dynamic hold infeasibility, flags the case as infeasible, and continues processing. The branching logic of the method controls the exploration of sequences. This logic, in GARP, is similar to what is used in the MRP except that additional constraints can be modeled. There were also some additional runtime enhancements discovered and implemented within GARP. Note that in 2-point scheduling we often refer to runway assignment. In the more general framework, enabling N-point scheduling for arbitrary N, we focus instead on route assignment, wherein a route will always include an allowable runway but can also include additional scheduling points. The most profound difference between GARP and the MRP, from an algorithmic point of view, concerns the 3-step scheduling logic described above. This is considerably more complex in GARP due to the fact that GARP addresses, in great generality, N-point scheduling for arbitrary values of N>2.

Additional Constraints

Additional optional constraints are provided for in GARP. Their purposes are for modeling flexibility and/or computational efficiency. Most of these are new enhancements in GARP versus the MRP and are included here to illustrate the additional flexibility of using GARP. A partial list of constraints includes:

- Proper Ordering Constraint – any two consecutive arrivals assigned routes that do not share a common scheduling point should be scheduled in FCFS order. This constraint has a large impact on runtime because it eliminates the generation of identical cases within the branch and bound search.
- Equivalence Class Constraint – arrivals can be designated to be in the same equivalence class if they have the same route set and are otherwise operationally equivalent. The constraint forces arrivals belonging to the same equivalence class to maintain their relative order with respect to the FCFS sequence. In a manner similar to the Proper Ordering Constraint, this can result in a large runtime improvement with little or no impact on optimality.
- Arrival Family Constraint – arrivals can be classified as belonging to a family (for example, airline could be an example of a family). The constraint dictates that arrivals within a family can only use the same sequence positions as utilized by that family in the FCFS sequence (while the ordering of specific arrivals within those positions is not constrained). One application of this constraint is for equity between airlines.
- General Ordering Constraint – a set of arrivals can be given a relative order as a constraint. This generalizes the equivalence class constraint.
- Same Route Constraint – a set of arrivals can be constrained to be assigned the same route (without saying which route).

Additional Modeling Capabilities

A wide array of new capability is provided for in GARP from a modeling point of view. We end this section with a partial list of these new capabilities:

- Configurability – the same GARP model can be configured through its input to represent a variety of different planning functions.
- N-point Planning for Arbitrary N – GARP enables optimal or nearly optimal plans even when routes have more than two scheduling points at nodes along the route.
- GARP can address many different kinds of scheduling points including merges, demerges, crossing routes, and wake vortex.
- GARP can address runway dependencies by, for example, requiring staggered arrivals between adjacent runways.
- GARP can address diversions in order to guarantee the existence of feasible plans.
- GARP can address meter fix re-assignment in Center planning.
- GARP contains a special simplified mode which represents one way in which the idea of the NASA TMA can be extended for cases involving N-point planning with N>2.
- GARP can address M-stage planning.

4 Scenario for Analysis Based on Denver

The scenario utilized for the analysis presented in the next section is the same Denver airport scenario already discussed in Section 3 (see, in particular, Figures 1 and 2). The associated airspace network is able to support comparisons involving Center planning, TRACON planning, and 2-stage planning. Besides the scenario geometry already discussed in the previous section the scenario utilizes a set of 83 arrivals defined by the OAG scheduled arrival times, at Denver airport, between 7am and 8:30am in a February 2008 schedule. Specific birth times for these arrivals are generated from the OAG schedule using a random perturbation method.

5 Analysis of Alternative Concepts

In this section we illustrate the use of GARP in comparing four different arrival management concepts. These results have been obtained using the test simulation for GARP. The focus is on comparing the deterministic scheduling results of the planning output when configuring GARP in four different ways to represent alternative concepts as follows:

- Concept 1: One stage planning but without treating the points interior to the TRACON as scheduling points. This concept should produce the smallest delays but could also be infeasible with respect to minimum separation at the ignored points.
- Concept 2: One stage planning and treating all points as scheduling points. This concept uses the full power of GARP as an N-point planner for N>2. The results should minimize delays and maintain feasibility. The delays will be higher than in Concept 1 since Concept 1 allows for infeasibilities.
- Concept 3: Two stage planning. In the first stage, the meter fixes and runways are taken to be scheduling points while the points interior to the TRACON are ignored in terms separation constraints. In the second stage, the input is conditioned by the output of the first stage and, in this second stage, all points downstream from the meter fixes are treated as scheduling points.
- Concept 4: Two stage planning. Similar to Concept 3 except with a very simple second stage wherein re-scheduling is permitted with respect to the first stage but not re-sequencing.

We compare these four concepts first, while allowing for holds (Figure 4), and again without holds (Figure 5). Each concept is evaluated under an assumption of discrete delays and then compared to a continuous delay assumption. Discrete delays should result in more average delay than for continuous delays.

First of all, and as a test of the algorithm, it is found that all of the delay results behave as expected. Each successive concept should generate more delay and this is seen to be the case. Discrete delays result in greater average delay than continuous delays. Enabling holds results in less average delay than relying on diversions to provide for feasibility (which was an indication that, without holds, diversions were, indeed, needed in this scenario). Diversions were defined in such a way as to have a large associated diversion delay.

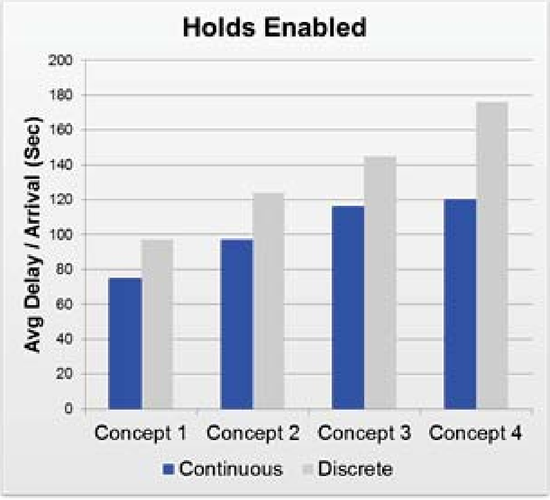

Figure 4 – Concept Comparison (Holds)

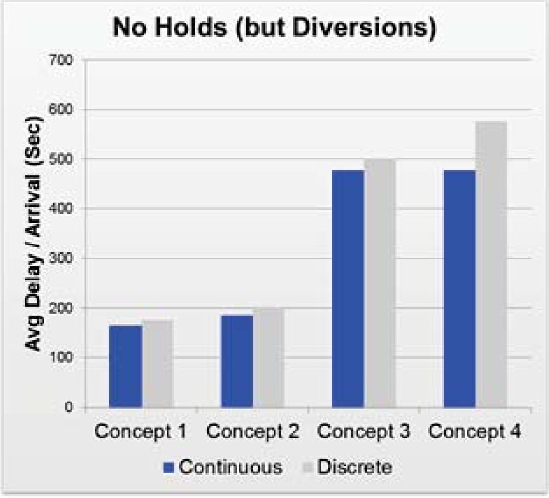

Figure 5 – Concept Comparison (No Holds)

Although not shown in the figures, ignoring the interior TRACON scheduling points (in Concept 1) resulted in over 20 instances of infeasibility in the form of lost separation events. The fact that only modest delay increases are seen between Concepts 1 and 2 illustrates the effectiveness of GARP in minimizing delays while completely providing for feasibility at all the scheduling points including the ones ignored in Concept 1.

Concepts 3 and 4 illustrate the use of GARP in addressing 2-stage planning. Without stochastic effects it is seen that Concept 2 performs better than either of Concepts 3 and 4. This is because, in Concept 2, the optimizer has complete knowledge of all the constraints in the problem. It remains to be seen whether or not Concept 2 is superior to Concepts 3 and 4 in the presence of stochastic effects (since, in 2-stage planning, there is an opportunity to refine the estimated times of arrival at the boundary of the airspace addressed in the second stage of planning). It should also be noted that Concepts 3 and 4 do not address feedback. In principal, feedback should make a significant difference in 2-stage planning and especially when some scheduling points are ignored in the first stage of planning.

6 Next Steps

The next steps in this research will be focused in two main areas. First, in the use of GARP within both TAME and McSEM, to explore the effectiveness of alternative arrival management concepts in the presence of stochastic effects. Second, in the use of these same models to explore M-stage planning both with M=2 and M>2. This second area of research will also require addressing the feedback question.

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