A Framework for High Density Area Departure and Arrival Traffic Management

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An operational concept is proposed to improve high-density area departure and arrival traffic management that specifically accounts for complications arising in metroplex operations where multiple airports are located in close proximity. In the proposed concept, the roles and responsibilities are redistributed among the Traffic Management Coordinators in different facilities, which include the Air Route Traffic Control Center, Terminal Radar Approach Control, and the Airport Traffic Control Tower. The redistribution of roles and responsibilities facilitates improved decision making capabilities thereby increasing safe, efficient, and stable operation of departure and arrival traffic in the Next Generation Air Transportation System. This paper proposes a set of functions and capabilities needed to support the roles and responsibilities defined in the proposed concept. The decision support system framework defines three levels of decision making and incorporates an optimization methodology to assist decision makers at the different phases of the decision process. A detailed description of the decomposition and corresponding decision support system structure is presented and a description of the optimization models is provided. An analysis is performed on a realistic traffic example to demonstrate the optimization model and illustrate the concept.

Nomenclature

A	Set of all arcs
AR	Arrival (operation type)
ART	Set of available route-time nodes
C^C	Capacity utilization component of resource allocation optimization cost function
C^R	Route change component of resource allocation optimization cost function

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C^T	Time change component of resource allocation optimization cost function
DFR	Defer node
DMD	Demand node
DP	Departure (operation type)
$D_{r,t}^{a,p,o}$	A single unit of demand from aircraft *a* at airport *p* for route *r* in time bin *t* of type *o*
$D_{r,t}^{p,o}$	Aggregate demand from airport *p* of type *o* for route *r* in time bin *t*
FN	Set of individual flight nodes
FT	Set of fix-time nodes
$F(r)$	Mapping that yields fix *f* as a function of route *r*
J^C	Capacity utilization component of flight assignment optimization cost function
J^R	Route change component of flight assignment optimization cost function
J^S	Schedule change component of flight assignment optimization cost function
J^T	Time change component of flight assignment optimization cost function
K	Number of time bins for enroute resources in period of interest
$\bar{K}$	Number of time bins for surface resources in period of interest
MX	Mixed (operation type)
N	Set of all nodes
RRT	Set of requested route-time nodes
T_0	Start time of period of interest
T	End time of period of interest
$T_{max}^o(i)$	Maximum time bin difference allowed for a late assignment for request *i* of type *o*
$T_{min}^o(i)$	Maximum time bin difference allowed for an early assignment for request *i* of type *o*
TT_{max}^A	Maximum TRACON transit time for arrivals
TT_{max}^D	Maximum TRACON transit time for departures
$TT(r,p,o)$	Nominal transit time between route *r* and airport *p*, for operation type *o*
$U_{f,t}$	Capacity of fix *f* in time bin *t*
$U_{r,t}$	Capacity of route *r* in time bin *t*
$U_{r,t}^p$	Capacity allocated to airport *p* for route *r* in time bin *t*
$U_{w,t}^p$	Capacity of runway *w* in time bin *t*
$U_t^{p,o}$	Capacity of airport *p* in time bin *t* for operation type *o*
W^p	Set of runways at airport *p*
$W^p(r)$	Mapping that yields the runway at airport *p* that is associated with route *r*
a	Flight / aircraft
$c_{i,j}^{C,o_i}$	Cost per unit of flow from PRT node *i* to the defer node, given the operation type *o*
$c_{r_i r_j}^{R,o_i}$	Cost per unit of flow of assigning a request for route *i* to route *j*, given the operation type *o*
$c_{\mathrm{t}^i\mathrm{t}^j}^{T,o_i}$	Cost per unit of flow of assigning a request for time *i* to time *j*, given the operation type *o*
f	Coordination fix
f_i	Fix associated with node *i*
i	Node
j	Node
$j_{i,j}^C$	Cost of assigning flight *i* to the defer node
$j_{r_i r_j}^{\mathrm{R}}$	Cost of assigning a flight request for route *i* to route *j*
j_i^S	Cost of changing either the route or time (or both) of flight *i*
$j_{\mathrm{t}^i\mathrm{t}^j}^{\mathrm{T}}$	Cost of assigning a flight request for time bin *i* to time bin *j*
k	Enroute resource time bin number
$\bar{k}$	Surface resource time bin number

n	Total number of arriving and departing flights considered during period of interest
n^{po}	Number of flights to be assigned for airport *p* of type *o*
o	Operation type (departure or arrival)
o_i	Operation type associated with node *i*
p	Airport
p_i	Airport associated with node *i*
r	Departure, arrival, or mixed-use route
r_i	Route associated with node *i*
t_i	Time bin associated with node *i*
t^k	k^{th} enroute time bin
$\bar{t}^{\bar{k}}$	k^{th} surface time bin
w	Runway
w^C	Weight of capacity utilization component in resource allocation optimization cost function
w^R	Weight of route change component in resource allocation optimization cost function
w^T	Weight of time change component in resource allocation optimization cost function
$x_{i,j}$	The flow along the arc from node *i* to node *j*
α	Parameter defining the normalized location of the aggregate demand within its time bin
β^S	Weight of schedule change component in flight assignment optimization cost function
β^C	Weight of capacity utilization component in flight assignment optimization cost function
β^T	Weight of time change component in flight assignment optimization cost function
β^R	Weight of route change component in flight assignment optimization cost function
ΔT	Time discretization (time bin length)
(i,j)	Arc connecting node *i* to node *j*

I. Introduction

As a complex dynamic system, the National Airspace System (NAS) can be very sensitive to even small disturbances in the operating environment. Given the complexity inherent in high-density area departure and arrival traffic management, these small disruptions can propagate quickly, causing a significant loss in operational efficiency. In order to transition into the Next Generation (NextGen) air transportation system operating environment, it is critical that the entire NAS, and especially high-density area departure and arrival traffic management, be robust to such disturbances as efficient use of resources will be at a premium.

Previous research [1] identified two significant challenges facing today's departure and arrival traffic management system. The first challenge is the lack of integrated information presented to decision makers. Without an integrated picture that includes traffic, weather, and airspace resource information, large-scale Traffic Management Initiatives (TMIs) are often implemented to manage demand/capacity imbalances. To address this first challenge, an Integrated Departure Route Planning (IDRP) [2] tool was developed to improve the situational awareness of decision makers.

The second challenge is that the point of action is too far removed from the point of decision making. To address this challenge, it is necessary to move the locus of control to the most effective decision maker. For metroplex traffic management this requires a redefinition of the decision making processes within the Air Route Traffic Control Center (ARTCC), the Terminal Radar Approach Control (TRACON) and the multiple Air Traffic Control Towers (ATCTs).

In the proposed concept, the decision making authority in each of the above areas aligns with the information available to each decision maker and the impact of the decision on their operating environment. Specifically, requests for departures are provided to the TRACON by the ATCTs as they possess the best information regarding the status of these flights. Similarly, requests for arrivals are provided by the ARTCC to the TRACON. The TRACON Traffic Management Coordinator (TMC) is responsible for allocating the use of the departure and arrival routes to the different airports for departures and to the ARTCC for arrivals. However, given the uncertainties present in predicting flight readiness and arrival times, the TRACON does not assign specific departure and arrival slots to individual flights, instead assigning departure slots to the ATCTs and arrival slots to the ARTCC. The specific flight assignments are made locally at the ATCTs and ARTCC as deemed best for their individual operating environments. By decoupling the decisions of the individual ATCTs and the ARTCC, each area possesses increased flexibility to handle situations as they develop and therefore improves the overall efficiency of terminal airspace operations.

A primary research focus for terminal-area traffic management has been the development and analysis of improved scheduling techniques. Research into optimal runway use for departures [3, 4] or arrivals [5] has provided insight into improved single airport operations. However, for metroplex operations, the scheduling of the shared en-route resources, such as departure and arrival routes and fixes, can be the more challenging problem. Research that optimizes the assignment of flights to departure fixes [5] or arrival fixes [6, 7, 8] captures the interdependencies associated with managing competing resource demands from multiple airports. Integrating both en-route and airport runway scheduling for a single airport [9] or multiple airports [10, 11] captures the set of challenges inherent in the terminal area operational environment. Building on these complete models, decision support systems can be developed to aid traffic managers in managing complex operations [12] or investigate new techniques to for airspace management, such as dynamic terminal airspace [13].

Recent research has investigated metroplex interdependencies to better understand the complexities inherent in these operational environments. Techniques such as classification of operations [14], queuing model simulations [15] and system-of systems framework designs [16-18] have been used to identify and classify the dependencies.

By capturing the specific operational challenges in metroplex decision making, decision support systems can be tailored to meet the needs of these high density terminal areas.

Specifically, the research methodology proposed in this paper aims to streamline the decision making environment by decomposing the problem formulation into a resource utilization problem followed by a flight assignment problem. By extending the operational concept proposed in Reference 19 and the mathematical models proposed in Reference 20, this paper defines an integrated departure and arrival traffic management decision support tool specifically designed for metroplex operations. Section II briefly describes the proposed concept and associated framework for the High-Density area Departure and Arrival traffic Management (HDDAM) problem. Section III develops the underlying modeling approach and Section IV describes the mathematical models for the decision support system components identified in the HDDAM framework. To illustrate and analyze the merits of the mathematical formulation developed in Section IV, an example scenario based on real traffic data in the Potomac TRACON is described, and the results of the implementation are presented in Section V. The conclusions obtained and ongoing research areas identified from this analysis are presented in Section VI.

II. Proposed Concept

Within a metroplex, there are multiple airports competing for the same resources and multiple levels of decision makers, with varying degrees of insight into the operational constraints at other levels. The operational concept proposed in this research takes advantage of this distributed decision structure by segmenting the decision making process to align the point of impact of a decision with the appropriate decision maker. This process empowers each of the decision makers with autonomy as their scope of influence has been decoupled from other decision makers, which in turn increases flexibility while maintaining safe operations.

Figure 1 illustrates the shared resources in a metroplex environment and highlights the different and competing requests for these resources. The ARTCC is responsible for setting the capacity of the en-route resources, namely the departure and arrival fixes and routes. In addition, the ARTCC is responsible for defining the requests of arriving flights for both en-route and surface resources. The ATCTs are responsible for defining the surface resource capacities, namely the runway configurations and the associated airport usage rates. In addition, the ATCTs are responsible for defining the requests of departing flights for both en-route and surface resources. The TRACON is the central component of the metroplex decision environment, where competition for resources must be negotiated. Furthermore, as both the en-route and surface resources are at the boundary of the TRACON, the TRACON can negotiate the capacities of these resources, if TRACON-specific operations require.

Figure 2 provides the decision support framework associated with the envisioned HDDAM concept for a metroplex environment. The decision making process begins with the definition of capacity for both the en-route resources and the surface resources. The right side of Figure 2 shows the components that factor into the definition of the en-route and surface capacities, where the capacities are defined for a discrete period of time and may be time-varying. Highlighted here is that the TRACON contributes to the definition of these resource capacities as the TRACON airspace environment impacts their availability. The left side of Figure 2 shows the definition of the demand for resource utilization by arrivals, as determined by the ARTCC (top left), and the demand for departures, as determined by each individual ATCT (bottom left). It should be noted that both the ARTCC and ATCTs provide their requests for resource utilization as aggregate requests, as opposed to flight specific requests, as the TRACON TMC is only concerned with allocating resources in each time bin, not assigning individual flights to these resources.

The center of Figure 2 depicts the TRACON decision support tool (DST) which allocates the en-route resources, subject to both the en-route and surface capacity constraints, to the ATCTs and the ARTCCs, based on their requests. Since the resource utilization problem is now decoupled, the ARTCC DST and ATCT DSTs can independently assign individual flights to the allocated resources.

By decomposing this flight assignment problem into a multi-step decision process, the point of decision making is moved closer to the point of impact; thereby reducing coordination efforts. However, it is necessary to recognize that from a mathematical perspective, this decomposition is sub-optimal for a flight assignment problem when perfect knowledge of demand and capacity is provided. However, as HDDAM is envisioned as a planning tool to be utilized 30 minutes or more in the future, the level of aggregation is consistent with the information accuracy available in that timeframe. As such, the benefits of decomposition are believed to exist in the robustness of the solutions generated by this method when uncertainties, such as departure readiness times, are considered. Furthermore, this concept provides a strategic capability that enables advanced scheduling to promote the efficient use of available resources.

III. Problem Formulation

The concept described in the previous section defines a multi-level decision making architecture for assigning metroplex resources to individual flights. This problem definition can naturally be formulated as an integer programming problem; however an alternative formulation that provides the exact solution with less computational expense is a network flow problem [21]. Given the time-varying nature of the capacities, a time expanded network formulation is defined [22] which essentially replicates the physical or static network in time, enabling time varying parameters such as capacity to be effectively captured. In this section, we define the properties of the network models developed for both the TRACON capacity allocation problem and the ARTCC and ATCT flight assignment problem.

A. Problem Definition

We begin by defining the time discretization employed in the time expanded network. Specifically, we define the time period of interest as beginning at time T_0 and lasting until time T. By defining the time discretization ΔT, the number of time periods or time bins K can be computed as

$$K = \left\lceil \frac{T - T_0}{\Delta T} \right\rceil \qquad 1.$$

For $k = \{1,2, \dots K\}$, t^k is defined as the beginning of the k^{th} time bin where $t^1 = T_0$ and $t^K = T_0 + \Delta T * (K - 1)$.

Given the definition of the time bins, the capacities of the en-route resources, namely the departure and arrival routes and fixes, can be defined. The capacity of each route *r* for each time bin t is defined as $U_{r,t}$. The capacity of each fix *f* during each time bin t is defined as $U_{f,t}$. Each fix *f* has one or more routes connected to it, where the routes can either be departure routes, arrival routes, or mixed-use routes. The associated mapping between fixes and routes is defined by the function $F(r)$. It is important to note here that each resource may be of mixed-use (i.e. when a fix or route serves both departures and arrivals); however the mixture of departures and arrivals does not impact the capacity of the fix or the route.

The surface resource capacities are defined using the same time period discretization as the TRACON and align with the time bins t^k; however, as departures may takeoff prior to t^1 and arrivals may land after t^K, additional time bins are defined to account for the TRACON transit time between the ground and en-route resources. The TRACON transit time, denoted as $TT(r, p, o)$, provides an estimate of the average transit time between a runway at airport *p* and a route *r* for the specified operation type *o*, namely departure (*DP*) or arrival (*AR*). To define the length of the surface time horizon, we define TT^D_{max} as the maximum TRACON transit time for all departures and

TT^A_{max} as the maximum TRACON transit time for all arrivals. Given these values, the number of time periods needed is be computed as

$$\bar{K} = \left\lceil \frac{TT^D_{max}}{\Delta T} \right\rceil + K + \left\lceil \frac{TT^A_{max}}{\Delta T} \right\rceil \quad 2$$

For $\bar{k} = \{1,2, \dots \bar{K}\}$, $\bar{t}^{\bar{k}}$ is defined as the beginning of the $\bar{k}$th time bin where $\bar{t}^1 = T_0 - \left\lceil \frac{TT^D_{max}}{\Delta T} \right\rceil \Delta T$ and $\bar{t}^{\bar{K}} = \bar{t}^1 + \Delta T * (\bar{K} - 1)$.

To define the runway and airport resources mathematically, the capacity of each airport *p* in each time bin t for each operation type *o* is defined as $U^{p,o}_t$. Each airport *p* has one or more runways associated with it, where the runways can be departure-only, arrival-only, or mixed-use. As such, the set of runways associated with each airport *p* is defined as W^p. The capacity of each runway *w* for each time bin *t* is defined as $U^p_{w,t}$

The departure and arrival flights provide the demand for the capacitated resources. Each flight *a* is associated with an airport *p*, a route *r*, a time bin *t* and the operation type *o* (i.e. *DP* for departure or *AR* for arrival) and can be expressed as $D^{a,p,o}_{r,t}$. However, as the demand for the TRACON is provided for each airport *p* for each operation type *o*, as an aggregated request for capacity[§] for each route *r*, in each bin *t*, the TRACON demand can be expressed as shown in Equation 3.

$$D^{p,o}_{r,t} = \sum_a D^{a,p,o}_{r,t} \quad 3$$

B. TRACON Network Model

The TRACON network model represents the connectivity of demand to the en-route resources[**], where both the aggregate demand and en-route capacities are provided as inputs to the network. A depiction of the TRACON network is provided in Figure 3, which shows five distinct sets of nodes: Requested route-time nodes, available route-time nodes, fix-time nodes, a defer node, and a demand node. On the left of Figure 3 are the requested route-time nodes for the departures from each airport and the arrivals to each airport during each time bin. The supply incoming to these nodes represents the aggregate requested capacity from each airport for departures for each

[§] In the TRACON capacity allocation module, the demand incoming to the network is essentially the requested capacity over each route at each time. As such, the terms demand and requested capacity are used interchangeably.

[**] Although both the surface and en-route capacity constraints can be represented in a time expanded network formulation, critical information regarding the specific allocation of the resources to accommodate the requests would not be captured. Therefore, only the en-route resources are modeled within the network, and the surface constraints are added as side constraints to the resulting linear programming formulation.

route during each time bin and the aggregate requested capacity from the ARTCC for arrivals for each airport for each route during each time bin. It is important to note here that the model development analyzes arrivals in a similar fashion as departures. Although there are significant differences between arrivals and departures in terms of operational limitations, this concept proposes that all differences can be captured in the instantiation of the network connectivity, costs, and constraints as opposed to a different modeling formulation.

The requested route-time nodes are defined as belonging to the subset of nodes RRT, where $RRT(i)$ is the i^{th} RRT node. For every node $i \in RRT$, the following properties of the node are defined:

p_i= the port associated with the i^{th} RRT node.

o_i= the operation (i.e. departure (*DP*) or arrival (*AR*)) associated with the i^{th} RRT node.

r_i= the route associated with the i^{th} RRT node.

t_i= the time associated with the i^{th} RRT node.

The available route-time nodes, shown as the second set of nodes from the left, represent the different departure, mixed-use, and arrival routes available at each time bin. The available route-time nodes are defined as belonging to the subset of nodes ART, where $ART(i)$ is the i^{th} ART node. For every node $i \in ART$, the following properties of the node are defined:

r_i= the route associated with the i^{th} ART node.

t_i= the time associated with the i^{th} ART node.

o_i= the operation (i.e. departure (*DP*), arrival (*AR*), or mixed (*MX*)) associated with the i^{th} ART node.

The next set of nodes in Figure 3 depicts the fix-time nodes. The fix-time nodes are defined as being in the subset of nodes FT where $FT(i)$ is the i^{th} FT node. For every node $i \in FT$, the following properties of the node are defined:

f_i= the fix associated with the i^{th} FT node.

t_i= the time associated with the i^{th} FT node.

The node on the bottom of Figure 3 represents a defer node, which accounts for all requested capacity that cannot be accommodated, and the decision of how to allocate resources to fulfill these requests is deferred to a further analysis outside of the current time period. The defer node is defined as belonging to the subset of nodes DFR; however this is the only node in this subset. The node on the right of Figure 3 represents the demand node, which is where all demand exits the network. The demand node is defined as the only node belonging to the subset of nodes DMD.

Given the definition of the different types of nodes, we now define the set of allowable connections in the TRACON capacity allocation network. Specifically, the requested route-time nodes are connected to multiple available route-time nodes in order to allow the TRACON module to allocate resource capacities other than as requested, in order to satisfy the resource capacity constraints. Furthermore, restrictions on available use of different route resources, such as the prohibition on assigning departure requests to arrival routes, can be directly captured via node connectivity in this formulation. The directional arcs defined between the requested route nodes (RRT) and the available route nodes (ART) nodes belong to the set of all arcs A and exist under the following conditions.

$$(i,j) \in A \; iff \; \begin{cases} i \in RRT, j \in ART \\ o_i = DP \\ o_j \neq AR \\ T^o_{min}(i) + TT(r_j, p_i, o_i) - TT(r_i, p_i, o_i) - (1-\alpha)\Delta T \leq t_j - t_i \leq T^o_{max}(i) \end{cases} \quad 4$$

$$(i,j) \in A \; iff \; \begin{cases} i \in RRT, j \in ART \\ o_i = AR \\ o_j \neq DP \\ T^o_{min}(i) \leq t_j - t_i \leq T^o_{max}(i) \end{cases} \quad 5$$

where $TT(r,p,o)$ is the TRACON transit time associated with travelling on route r based on the configuration of airport p and the operation type o. $T^o_{min}(i)$ and $T^o_{max}(i)$ define the lower and upper positive time changes that can be incurred for each operation type o and can be specified separately for each node i; however it is assumed for the rest of this model development that a single value is provided for departures and a separate value is provided for arrival operations. The parameter α defines where in the time bin the demand is assumed to occur. By aggregating multiple capacity requests into time bins in the TRACON model, it effectively provides a point impulse of demand, as opposed to a distribution of demand across the time bin. Although consistent with the HDDAM concept, this approximation requires that the point of impact be defined.

Specifically, $\alpha \in [0,1)$ where $\alpha = 0$ implies the demand is located at the start of the time bin and $\alpha = 1^-$ implies that the demand is located at the very end of the time bin. Setting $\alpha = 0$ allows additional arcs to be included in the network which in turn provides the TRACON increased flexibility when allocating resources; however the individual ATCTs may not be able to utilize these slots as the individual flights may only be available later in the time bin. In contrast, setting $\alpha = 1^-$, ensures that every allocation provided by the TRACON to the

ATCTs can be utilized; however additional feasible options may not be considered. As such, α is defined as a parameter to be set by the decision maker.

The connections between the available route-time nodes and the fix-time nodes are defined by *F(r).* As it is assumed there are no transit times between routes and fixes, the route-time nodes connect only to their associated fix in the same time period. The conditions for arc existence between the available route time nodes (*ART*) nodes and the fix time nodes (*FT*) nodes are defined in Equation 6.

$$(i,j) \in A \; if \begin{cases} i \in ART, j \in FT \\ F(r_i) = f_j \\ t_i = t_j \end{cases} \qquad 6$$

The arcs connecting the route and fix-time nodes have a capacity equivalent to the route capacity during the time bin specified ($U_{r,t}$).

The node at the right of Figure 3 is the demand node (*DMD*) and there exists an arc in the network between every node fix time node (*FT*) and the demand node (*DMD*). The arcs connecting the fix-time nodes to the demand node have a capacity equivalent to the fix capacity during the time bin specified ($U_{f,t}$). Similarly, at the bottom of Figure 3 is the defer node (*DFR*). For every node in the requested route nodes (*RRT*) there exists a connection to the defer node (*DFR*), and there also exists a connection from the defer node (*DFR*) to the demand node (*DMD*).

C. ARTCC and ATCT Network Definition

The ARTCC and ATCT network models represent the connectivity of individual flights to the en-route resources, where the en-route resource capacities are provided by the TRACON allocation. It is proposed that the same general time expanded network formulation can be used for both arrivals in the ARTCC and departures in the ATCT flight assignment problems, as the operational differences are reflected in the parameters defining the specific formulation instance. As such, the general flight assignment network formulation is presented and any differences between the ARTCC and ATCT formulations are highlighted.

Figure 4 depicts the flight assignment network model, where four types of nodes are represented: flight nodes, route-time nodes, a demand node, and a defer node. On the left of Figure 4 are the flight nodes, which represent each flight requiring an assignment and are defined as having a single unit of supply. Each flight node is defined as belonging to the subset of nodes FN, where $FN(i)$ is the i^{th} FN node. For every node $i \in FN$, the following properties of the node are defined:

r_i= the route requested by the i^{th} FN node.

t_i= the time bin requested by the i^{th} FN node.

In the ARTCC and ATCT formulations, the set of routes that are permissible for arrivals in the ARTCC or departures from the given airport, respectively, are defined. In each model, the applicable route time nodes are defined as belonging to the subset of nodes RT, where $RT(i)$ is the i^{th} RT node. For every node $i \in RT$, the following properties of the node are defined:

r_i= the route associated with the i^{th} RT node.

t_i= the time associated with the i^{th} RT node.

The node on the bottom of Figure 4 represents the defer node, which accounts for all requested capacity that cannot be accommodated, and the decision of how to allocate resources to fulfill these requests is deferred to a further analysis outside of the current time period. The defer node is defined as belonging to the subset of nodes DFR; however this is the only node in this subset. The node on the right of Figure 4 represents the demand node, which is where all demand exits the network. The demand node is defined as the only node belonging to the subset of nodes DMD.

Given the definition of the different types of nodes, we now define the set of allowable connections in the flight assignment network. Each flight node is connected to the route-time nodes, where constraints on allowable assignments can be directly encoded in the network connectivity. It is noted here, that due to the specific operation type or departure airport being considered in each module, further descriptions of the nodes are unnecessary. In fact, the only difference between the ARTCC and ATCT formulations for assigning flight nodes to route time nodes arises in the definition of arc existence. Utilizing the same general definition for arrivals presented in the TRACON, the ARTCC connectivity is formulated in Equation 7.

$$(i,j) \in A \ iff \begin{cases} i \in FN, j \in RT \\ T^o_{min}(i) \leq \ t_j - t_i \leq \ T^o_{max}(i) \end{cases} \quad 7$$

The connectivity for ATCTs is defined using the same definition for departures presented in the TRACON formulation, as shown in Equation 8.

$$(i,j) \in A \ iff \begin{cases} i \in FN, j \in RT \\ T^o_{min}(i) + TT\big(r_j, p_i, o_i\big) - TT(r_i, p_i, o_i) - (1-\alpha)\Delta T \leq \ t_j - t_i \leq \ T^o_{max}(i) \end{cases} \quad 8$$

As these equations represent the connectivity for individual flights to allowable routes, both the ARTCC and ATCT formulations can include flight-specific preferences and constraints. Specifically, the minimum and maximum delays, T_{min}^{o} and T_{max}^{o}, can be defined for each individual flight for the specified operation type. In addition, further limitations on allowable reroutes can be defined for each flight. However, as these definitions require knowledge regarding specific operator preferences and equipage limitations, the general definition from the TRACON formulation is retained for the remainder of the paper.

Each route-time node is connected to the demand node, and the capacity of each connection is the capacity allocated by the TRACON to the ARTCC or ATCT for that route during that time bin, defined as $U_{r,t}^{p}$, where p is generalized in this context to represent the specific ATCT or ARTCC.

For every node flight node (*FN*) there exists a connection to the defer node (*DFR*) to accommodate flights not assigned a route during the time period considered. A connection also exists from the defer node to the demand node in order to satisfy the total outgoing demand, which is total number of flights n^{po} of operation type *o* at airport *p* for the time period under consideration.

IV. Optimization Model Development

The mathematical models that define the optimization problems for the resource allocation problem (TRACON) and the flight assignment problems (ATCTs and ARTCC) are presented in this section. Each model description begins with the definition of the objective function and is followed by the mathematical definition of the resulting optimization problem.

A. TRACON Optimization Model

The objective of the TRACON capacity allocation module is to efficiently allocate en-route capacity to each airport for departures and the ARTCC for arrivals, while satisfying the capacity thresholds of both the en-route and surface resources. To represent this goal, a multi-term objective function, derived from subject matter experts, is defined to capture an efficient and desirable allocation in cases where insufficient capacity exists to satisfy the requests. We note that although significant differences exist in the treatment of departures and arrivals, it is proposed that a generic objective function formulation that captures the inherent decision making concerns can be used for both, albeit with potentially different parameter values.

The first component of the objective function maximizes capacity utilization by penalizing any flow that between the requested route nodes and the defer node. Using the nomenclature provided in the previous section, the capacity utilization metric (C^{C}) of the TRACON objective function is defined as

$$C^C = \sum_{i \in RRT} \sum_{j \in DFR} c_{i,j}^{C,o_i} x_{i,j} \quad 9$$

where $c_{i,j}^{C,o_i}$ is the cost of assigning a request to the defer node for each operation type and can be defined differently for individual routes, time bin requests, or airports, and $x_{i,j}$ is the flow between node *i* and node *j*. However, this objective alone does not differentiate between an effective or ineffective allocation of capacity. As such, two additional metrics in the objective function are defined: time change and route change.

The time change metric captures the cost of an allocation that differs from the time period requested and includes limits on the feasible number of time bins that the allocation can differ from the request. Essentially, for each time bin before or after the request, a cost is associated with the assignment, which can be different for departures and arrivals, as illustrated in Figure 5. Figure 5 shows additional lines denoting the maximum and minimum time bin changes permitted, which are defined consistently with the definition of arcs described in Equations 4 and 5. As such, the TRACON time change metric (C^T) is defined as

$$C^T = \sum_{i \in RRT} \sum_{j \in ART} c_{t^i t^j}^{T,o_i} x_{i,j} \quad 10$$

where $c_{\mathrm{t}^i \mathrm{t}^j}^{T,o_i}$ defines the cost of moving assigning a request for time bin t^i to time bin t^j for operation type o_i and the value of the penalty is informed by subject matter expertise.

The route change penalty differentiates the desirability of allocating capacity on a different route than requested and captures the operational realities of the TRACON airspace. Specifically, reroutes that would only slightly modify the TRACON airspace operation (i.e. reroutes between neighboring fixes) may be penalized lightly while reroutes that significantly change TRACON operation (i.e. crossing streams of departure or arrival flows) are penalized higher. Given this definition, the TRACON route change metric (C^R) is formulated as

$$C^R = \sum_{i \in RRT} \sum_{j \in ART} c_{r_i, r_j}^{R,o_i} x_{i,j} \quad 11$$

where c_{r_i, r_j}^{R,o_i} defines the cost of allocating a request for route r_i to route r_j for operation type o_i and the value of the penalty is informed by subject matter expertise. The three metrics in the TRACON objective function are then combined in a weighted sum to provide the overall objective for the TRACON DST, as shown in Equation 12.

$$\min_{x} w^C C^C + w^T C^T + w^R C^R \qquad 12$$

The weights on each component of the objective function (w^C, w^T, and w^R) can be utilized to set the relative priority of the different objective function values; however for the purpose of this analysis, they are each assigned a value of one.

The objective in Equation 12 is subject to the following constraints. Specifically, Equations 13-15 represent the flow conservation constraints for the various sets of nodes in the TRACON network.

$$\sum_{\{j:(i,j)\in A\}} x_{i,j} = D_{r,t}^{p,o} \qquad \forall\, i \in RRT \qquad 13$$

$$\sum_{\{j:(i,j)\in A\}} x_{i,j} - \sum_{\{j:(j,i)\in A\}} x_{j,i} = 0 \qquad \forall\, i \in ART, FT, DFR \qquad 14$$

$$-\sum_{\{j:(j,i)\in A\}} x_{j,i} = -\sum_{k\in PRT} D_{r,t}^{p,o} = -n \qquad \forall\, i \in DMD \qquad 15$$

where n is the total number of capacity requests provided to the TRACON DST.

To capture the surface resource constraints, the following assumption is made. Each departure or arrival route is connected to a single runway at each airport and the function $W^p(r)$ defines the runway at port p associated with route r. Furthermore, to specify which flows are included in each constraint, the en-route time bins are mapped to the surface time bins (Equation 2), and the definition of the effective point of demand (α) within the TRACON time bin is utilized. Equation 16 defines the runway capacity constraints, and Equations 17 and 18 define the airport capacity constraints for departures and arrivals, respectively.

$$\sum_{\substack{\{i\in RRT, j\in ART:\\ (i,j)\in A\\ p_i=p\\ o_i=DP\\ W^{p_i}(r_j)=w\\ \bar{t}\le t_j+\alpha\Delta T-TT(r_j,p_i,o_i)\le \bar{t}+\Delta T\}}} x_{i,j} + \sum_{\substack{\{i\in RRT, j\in ART:\\ (i,j)\in A\\ p_i=p\\ o_i=AR\\ W^{p_i}(r_j)=w\\ \bar{t}\le t_j+\alpha\Delta T+TT(r_j,p_i,o_i)\le \bar{t}+\Delta T\}}} x_{i,j} \le U_{w,\bar{t}}^{p} \qquad \forall\, \bar{t}, w \in W^p, p \qquad 16$$

$$\sum_{\substack{\{i\in RRT, j\in ART:\\ (i,j)\in A\\ p_i=p\\ o_i=DP\\ \bar{t}\le t_j+\alpha\Delta T-TT(r_j,p_i,o_i)\le \bar{t}+\Delta T\}}} x_{i,j} \le U_{\bar{t}}^{p,DP} \qquad \forall\, \bar{t}, p \qquad 17$$

$$\sum_{\substack{\{i \in RRT, j \in ART: \\ (i,j)\in A \\ p_i = p \\ o_i = AR \\ \bar{t} \le t_j + \alpha\Delta T + TT(r_j, p_i, o_i) \le \bar{t} + \Delta T\}}} x_{i,j} \le U_{\bar{t}}^{p,AR} \qquad \forall\, \bar{t}, p \tag{18}$$

The bounds on the flow variable ($x_{i,j}$) are specified in Equations 19-21.

$$0 \le x_{i,j} \qquad \forall i, j \in N \tag{19}$$
$$0 \le x_{i,j} \le U_{r,t} \qquad \forall i \in ART, j \in FT \ s.t. (i,j) \in A \tag{20}$$
$$0 \le x_{i,j} \le U_{f,t} \qquad \forall i \in FT, j \in DMD \ s.t. (i,j) \in A \tag{21}$$

B. ARTCC and ATCT Optimization Model

Given that the TRACON DST considers all en-route and surface constraints when defining the allocation to each ARTCC and ATCT, the resource utilization and flight assignment problems have been effectively decoupled. As such, the ARTCC and ATCT modules can independently assign flights to routes and time bins, subject only to the allocation provided by the TRACON. This enables decision makers in each of these areas to define assignments that best minimize delay while accommodating the competing needs of each flight.

The objective of each flight assignment DST is to minimize the movement of flights from their requested routes and times while minimizing overall delay and maximizing the use of the TRACON allocated capacity. As such, four metrics for the flight assignment problem are defined: Schedule change, capacity utilization, time change and route change.

The schedule change metric penalizes any change in route or time in to order reward assigning the flight its requested schedule. Thus, changing the assignment of a flight in any way has an associated cost, which is intended to balance global delay minimization with schedule integrity. The cost of schedule change (J^S) is defined as

$$J^S = \sum_{i \in FN} j_i^S \sum_{\substack{j \in RT \\ s.t.\ r_i \ne r_j \\ t_i \ne t_j}} x_{i,j} \tag{22}$$

where j_i^S represents the cost of changing the schedule of the specific flight. The remaining three metrics are formulated similarly to the definitions presented in Equations 9-11. Specifically, the capacity utilization metric, which penalizes the flow from the flight nodes to the defer node, is defined as

$$J^{C} = \sum_{i \in FN} \sum_{j \in DFR} j^{C}_{i,j}\, x_{i,j} \qquad 23$$

where $j^{C}_{i,j}$ is the cost of assigning a flight to the defer node and can be defined differently for individual flights, routes, or time bins. The flight assignment time change metric J^{T} is defined as

$$J^{T} = \sum_{i \in FN} \sum_{j \in RT} j^{\mathrm{T}}_{\mathrm{t}^{i}\mathrm{t}^{j}} x_{i,j} \qquad 23$$

where $j^{\mathrm{T}}_{\mathrm{t}^{i}\mathrm{t}^{j}}$ defines the cost of moving a flight from time bin t^{i} to time bin t^{j} and can be specified for differently for each flight. The flight assignment route change metric (J^{R}) is formulated as

$$J^{R} = \sum_{i \in FN} \sum_{j \in RT} j^{R}_{r_i, r_j} x_{i,j} \qquad 25$$

where $j^{\mathrm{R}}_{r_{i,} r_j}$defines the cost of assigning a flight on route r_i to route r_j and can be specific to each flight. The four metrics in the flight assignment objective function are then combined in a weighted sum to provide the overall objective for the ATCT or ARTCC DST, as shown in Equation 26.

$$\min_{x} \beta^{S} J^{S} + \beta^{C} J^{C} + \beta^{T} J^{T} + \beta^{R} J^{R} \qquad 26$$

The weights on each component of the objective function (β^{S}, β^{C}, β^{T}, and β^{R}) can be utilized to set the relative priority of the different objective function values; however for the purpose of this analysis, they are each assigned a value of one. The objective in Equation 26 is subject to the following constraints. Specifically, Equations 27-29 represent the flow conservation constraints for the various sets of nodes (*FN*, *RT*, *DFR*, *DMD)* in the flight assignment network.

$$\sum_{\{j:(i,j) \in A\}} x_{i,j} = 1 \qquad \forall\, i \in FN \qquad 27$$

$$\sum_{\{j:(i,j) \in A\}} x_{i,j} - \sum_{\{j:(j,i) \in A\}} x_{j,i} = 0 \qquad \forall\, i \in RT, DFR \qquad 28$$

$$- \sum_{\{j:(j,i) \in A\}} x_{j,i} = -n^{po} \qquad \forall\, i \in DMD \qquad 29$$

and n^{po} defines the number of flight nodes in the set for airport *p* and operation type *o*, as it will differ between the various ATCTs and ARTCC. The variable bounds are specified in Equations 30-31.

$$0 \le x_{i,j} \qquad \forall i,j \in N \qquad 30$$

$$0 \le x_{i,j} \le U^{p}_{r,t} \qquad \forall i \in RT, j \in DMD\ s.t.\ (i,j) \in A \qquad 31$$

V. Analysis

The models defined in Section IV are implemented on a realistic traffic example in the Potomac TRACON. Figure 6 depicts the Potomac TRACON airspace and resources considered in this analysis. The traffic sample consists of the departing and arriving flights identified as using the resources depicted over a 6-hour TRACON time period, corresponding to 1100Z - 1700Z on January 28th, 2010, for three major Potomac TRACON airports: Baltimore Washington International (BWI), Ronald Reagan Airport (DCA), and Dulles International Airport (IAD).

Using this data, an analysis of the allocations provided by the TRACON and the resulting flight assignments defined by the ARTCC and ATCTs was performed for three resource constraint scenarios: nominal capacity, reduced en-route capacity, and reduced surface capacity. The nominal capacity scenario details the flow of information through the various DSTs and examines the decisions made in each. The reduced en-route and surface capacity scenarios highlight how the proposed concept enables an efficient use of the remaining available capacity. We note that the description provided in the nominal capacity scenario is the same as for the other two scenarios, except where explicitly noted.

The models described are implemented in the MATLAB programming language[††] (R2010a) and solved using the GNU Linear Programming Kit (GLPK v4.44.)[‡‡] via the GLPKMEX wrapper[§§]. All scenarios were run on a 64 bit Windows 7 dual core 2.66GHz Intel I7 M620 processor and 4.0GB of RAM. The TRACON allocation problem is solved in 5-7 seconds, depending on the scenario, and the flight assignment for all 3 airports takes approximately 2 seconds to solve, yielding a total solution time of 7-9 seconds per scenario.

A. Nominal Capacity Scenario

The nominal capacity scenario provides the baseline operational case where the departure and arrival demand for each airport and the nominal en-route and surface resource capacities are considered. The departure demand for each airport was taken from archived Traffic Flow Management System (TFMS) operational data, which provides the estimated gate push-back time and requested departure route for departures. The wheels-off departure time was calculated by adding an estimate of surface transit time[***], which can be unique to each airport and each departure

[††] http://www.mathworks.com/products/matlab/ Accessed 27 August 2012
[‡‡] http://www.gnu.org/software/glpk/ Accessed 27 August 2012
[§§] http://glpkmex.sourceforge.net/ Accessed 27 August 2012
[***] Defining surface transit times as a function of departure route provides a surrogate value for the potential variance in transit times to different runways.

route, to the gate push-back time. For this analysis, a single transit time value was provided by subject matter experts for each airport, where the surface transit time for BWI is five minutes, for DCA is six minutes, and for IAD is eight minutes. The arrival demand for each airport was also derived from TFMS traffic data which listed the estimated time of arrival (ETA) and filed route of each flight. The filed route was then mapped onto one of the defined HDDAM arrival routes for each arriving flight.

In this analysis, the runway capacity constraints (Eqn. 16) are not implemented, and therefore it is assumed that the only active surface constraints are the departure and arrival rates for each airport, where the implemented rates were obtained from the Aviation System Performance Metrics (ASPM) database. By aggregating the demand into the surface time bins for each airport, we compare the requested rates with the surface capacity constraints, as shown in Figure 7. Over the surface time horizon, which begins at 1030Z and lasts until 1715 Z, Figure 7 shows a few time periods where the request for departures or arrivals is in excess of the airport departure and arrival rate constraints. Figure 7 also shows that DCA has an overall demand for departures and arrivals that is close to the capacity for each operation type during the entire surface time horizon.

The en-route resources considered in this analysis are shown in Figure 6. Figure 6 highlights seven departure routes where each route is assumed to have a capacity of three departing aircraft per 15 minute time bin. Furthermore, it is assumed that each departure route has a unique departure fix which has a capacity of three aircraft per 15 minute time bin[†††]. The arrival routes, shown in Figure 6, are specific to each airport and are assumed to each have a capacity of six aircraft per 15 minute time bin[‡‡‡]. It is noted here that for arrival routes that share the same geographic location but are altitude separated by airport, alternate names are utilized, thus allowing each route to be utilized at full capacity, which is consistent with operations. Unlike the departure routes, there exist arrival fixes that correspond to more than one arrival route. As it is assumed that each fix has a capacity of 6 aircraft per 15-minute time bin, the allowable throughput on these routes is coupled. For BWI, both SABBI and CSN utilize the same fix. DCA has two pairs of routes sharing fixes, namely DOCCS and SHAAR and RIDGY and LAFLN. IAD also has two pairs of routes sharing fixes, specifically PRTZL and DELRO and KERRE and VERNI. To compute

[†††] The departure route and fix capacity was derived by subject matter experts as follows. Assuming that the nominal sector Monitor/Alert Parameter (MAP) value is 12 and that 6 aircraft are currently occupying the sector, the remaining capacity of 6 was divided between the 2 departure fixes that, on average, are associated with a departure sector.

[‡‡‡] The arrival route and fix capacity was derived by subject matter experts assuming a nominal spacing between flights of 10 miles at approximately 250 knots. This spacing corresponds to a rate of one aircraft per 2.5 minutes or 6 aircraft per 15 minutes.

the demand for the departure and arrival routes in the TRACON, the TRACON transit time between each airport and the requested route is estimated by subject matter experts, where the values chosen are displayed in Tables 1 and 2. To determine the requested departure capacity for each route and airport, the TRACON transit time is added to the wheels-off time for each flight, and the resulting demand in each TRACON time bin is aggregated, as shown in Figure 8. To compute requested arrival capacity for each route, the TRACON transit time is subtracted from the estimated time of arrival, and the resulting demand is aggregated, as shown in Figure 9.

Examining Figures 8 and 9 shows some route and time bin combinations highlighted, where a light-grey colored box indicates route demand that is equal to the available capacity and a dark-grey colored box indicates demand that exceeds the available capacity. In cases where the demand exceeds the capacity, the TRACON module will need to reallocate the requested demand to available routes or time bins.

1. Potomac TRACON Capacity Allocation

The TRACON DST seeks an efficient allocation of the available capacity to the ARTCC and the ATCTs subject to the surface and en-route resource constraints. As discussed in Section IV, there are three metrics considered within the TRACON optimization model, namely capacity utilization, time change, and route change, and the parameter values utilized in this analysis are defined by subject matter experts as follows. The capacity utilization penalty is set as 1000 for departures and 9999 for arrivals, where the higher penalty for arrivals represents the larger operational penalty associated with diversions. The time change penalties, shown in Table 3, provide the cost of allocating a request to a different time bin. Examining Table 3 shows that there are different values for departures and arrivals. Furthermore, a '-' indicates an infeasible allocation and early departures or arrivals are prohibited.

Table 3. TRACON Capacity Allocation Problem Cost Parameter Values

Time Bin Change	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9	+10	+11	+12	+13
Time Change	-15	0	+15	+30	+45	+60	+75	+90	+105	+120	+135	+150	+165	+180	+195
Departures	-	0	15	30	45	60	75	90	120	150	210	270	330	390	-
Arrivals	-	0	30	60	-	-	-	-	-	-	-	-	-	-	-

The route change metric specifies the feasibility and desirability of moving the demand from one route to another and is defined as the sum of the rerouting penalty and the positive TRACON transit time difference. The rerouting penalty represents the operational acceptability of moving demand to a different route and the specific penalty values are defined by subject matter experts. Table 4 provides the rerouting penalties for departures from all airports in this analysis, although separate values can be assigned to different airports. As the arrival routes in this example are defined as airport-specific, and few reroutes are allowed, Table 5 provides the rerouting penalty values for BWI, DCA, and IAD. Again, it should be noted that a reroute penalty cost of '-' implies that the reroute is infeasible and is not included in the network definition. Examining Table 5, we see that some reroute penalties are not symmetric; however these parameter values were defined by subject matter experts and reflect the realities of the Potomac TRACON airspace. The TRACON transit time difference simply distinguishes between reroutes of similar operational acceptability; however only longer reroutes are penalized and shorter reroutes are not rewarded.

Table 4. TRACON Capacity Allocation Problem Departure Route Change Penalty Values

Departure Routes	DAILY	HAFNR	FLUKY	LDN	AML	BUFFR	JERES
DAILY	0	40	40	-	-	-	-
HAFNR	40	0	20	40	40	-	-
FLUKY	40	20	0	40	40	-	-
LDN	-	40	40	0	20	40	40
AML	-	40	40	20	0	40	40
BUFFR	-	-	-	40	40	0	20
JERES	-	-	-	40	40	20	0

Given the nominal capacities and the relative costs associated with modifying allocations from their requests, the optimal allocation is computed for departures and arrivals and is shown in Figures 10 and 11, respectively. Figure

10 compares the allocation of departure routes (shown as solid lines) to the requests for capacity (shown as dashed lines) for the entire Potomac TRACON and each of the ATCTs. Comparing the overall Potomac TRACON departure requests and allocations reveals that the TRACON DST provides an allocation that generally matches the requests over the time horizon considered, with the exception of 1400Z. Referring back to Figure 8, we see that during this time period, many routes have requests much higher than the available capacity, which requires the TRACON DST to allocate additional capacity in future time bins to satisfy demand. Reviewing the allocations to each ATCT shows that BWI has the closest agreement between requested and allocated capacity and IAD has the worst agreement. The largest discrepancy between IAD departure requests and allocations is at 1400Z.

Table 6 provides a description of the request modifications made by the TRACON for each airport. Examining Table 6 shows that all three airports receive approximately the same number of request modifications, where the number of modifications correlates to the number of scheduled flights. Although there were certain instances where the demand requests by each airport exceeded the surface constraints, most of the changes were necessary to satisfy the departure route capacities. Specifically, DCA and IAD were given more reroutes since much of their demand requests were for over-capacitated routes and time bins. In contrast, the BWI demand requests were more evenly spread over departure routes and times bins and therefore could be satisfied with delay-only allocations.

Figure 11 compares the allocation of arrival routes (shown as solid lines) to the requests for capacity (shown as dashed lines) for the entire Potomac TRACON and each of the airports. Comparing the overall Potomac TRACON arrival requests and allocations shows that the TRACON DST provides an allocation that very closely matches the requests. Reviewing the allocations for arrivals into each ATCT reveals that BWI receives an allocation exactly matching its request while DCA and IAD are closely matched.

Table 7 provides a description of the modifications made and reveals that all changes to the requests were delays, which is consistent with the penalty values provided. It is interesting to note that the two modifications for IAD are a result of PRTZL and DELRO sharing a fix, where the request for each route is within each route's capacity but the overall request for the fix is in excess of the fix capacity. The four modifications for DCA are a result of the aggregation of demand in the TRACON and the specific value of α chosen (0.99). Referring back to Equation 18 shows that the surface constraints are defined by this parameter, as opposed to the actual wheels-off times for the flights. As such, the TRACON amends the requests to satisfy the perceived constraint, as opposed to the actual arrival rate, and therefore modifying the α parameter value can influence the resulting capacity allocation.

2. ARTCC and ATCT Flight Assignment

The ARTCC and ATCTs determine the assignment of flights to departure and arrival routes based on the capacities allocated to each by the TRACON. As discussed in Section IV, the flight assignment objective function is similar to the TRACON objective function, but includes the schedule change metric. For this example, the schedule change penalty is assigned a value of five for all departures and zero for all arrivals, and the remaining metrics utilize the same general parameters defined for the TRACON optimization.

Table 8 summarizes the actions taken within each ATCT to assign departing flights to departure routes based on their capacities allocated by the TRACON. Examining Table 8 shows that the assignment actions are decomposed into delay only, reroute only, and both delay and reroute, where the ground delay for a flight is calculated as the difference between the flight's originally scheduled departure time and the start of the assigned departure time bin, if later than requested. The air delay is the difference between the TRACON transit time of the route requested and the route assigned, if the assigned route has a longer transit time.

Table 8. Summary of ATCT flight assignments

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Ground Delay	Total TRACON Air Delay
BWI	16	1	0	190 min.	0 min.
DCA	13	6	2	187 min.	0 min.
IAD	13	6	1	203 min.	4 min.

Examining Table 8 shows that the total ground delay is 580 minutes and the total TRACON air delay is four minutes. The negligible TRACON air delay reveals that most reroutes required less TRACON transit time which ensures that the flight can meet the allocated resource time constraint. Comparing the aggregate ATCT actions, shown in Table 8, with the TRACON allocation changes, defined in Table 6 reveals that the schedule change penalty in the ATCT influences the solution obtained. Specifically, the ATCTs modified the assignment request of 58 flights as compared to 70 slot modifications in the TRACON, which highlights that the concept enables individual ATCTs to manage their flight assignments by choosing the relative importance of the various metrics in a given operational situation, independent of the TRACON objectives.

Similarly, Table 9 summarizes the actions taken by the ARTCC to assign arrival flights to the arrival routes for each airport. Examining Table 9, shows the assignment changes decomposed into the same categories as in Table 8.

Furthermore, the ARTCC maintains the same allocation as the TRACON for assigning arriving flights to arrival routes and time slots since the schedule change penalty is zero for arrivals.

Table 9. Summary of ARTCC flight assignments

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Arrival Delay
BWI	0	0	0	0 min.
DCA	4	0	0	30 min.
IAD	2	0	0	6 min.

B. Reduced En-route Capacity Scenario

The second scenario examined analyzes the impact of a set of en-route resource capacities being temporarily reduced, for example due to weather. Figure 12 defines the reduced capacities over three arrival fixes and one departure fix during the TRACON time period of 1330-1500Z. Given the same demand, remaining resource capacities, and parameter values defined in the nominal scenario, an analysis of the impact of the capacity reductions in the TRACON environment is conducted.

The reduced en-route resource capacities shown in Figure 12 create demand/capacity imbalances for departures at all three airports, as well as for the BWI-bound arrivals on SABBI and the DCA-bound arrivals on OJAAY. The reduced capacity on BRV does not impact the arrivals into IAD as the reduced capacity is sufficient to accommodate the requested demand. The TRACON allocation of the remaining capacity to the ATCTs for departures and the ARTCC for arrivals is summarized in Tables 10 and 11, respectively.

Comparing Table 10 to the nominal capacity scenario allocation shown in Table 6 reveals that the reduced en-route capacity resulted in only one additional request modification; however longer delays, more reroutes, and more reroutes with delays were incurred. By rerouting more flights onto routes with existing capacity, fewer delays can be incurred and the TRACON resources can be utilized as efficiently as possible. Examining Table 11 shows that BWI now has five modifications and IAD retains the same number of modifications, as expected; however many DCA arrival requests have been modified by delays or reroutes. Referring back to Figure 9 reveals that during the time period when the capacity of OJAAY is reduced, there are many scheduled arrivals on this route. The

TRACON has modified these requests by moving some of the demand onto other routes and delaying the rest incrementally. Together, Tables 10 and 11 show an operationally sound response to the reduced-capacity event.

Tables 12 and 13 depict the flight assignments defined by the ATCTs and ARTCC, respectively. Examining Table 12 shows that as in the base case, the ATCTs modify the requests of fewer flights than the TRACON. Comparing Table 12 to the ATCT flight assignments made under the nominal capacity scenario (Table 8) shows that the total ground delay is increased to 709 minutes and the TRACON air delay is increased to 6 minutes; however much of the additional ground delay occurs at BWI. During the affected time period, most of the requests for DAILY capacity are from BWI flights, and therefore the reduction in capacity on DAILY causes additional ground delay to be accumulated. In contrast, DCA and IAD have little demand for DAILY during this time period, but have significant demand on other routes and previously used DAILY for additional capacity. The loss in DAILY capacity requires additional reroutes and reroutes with ground delay to be assigned, resulting in small increases in ground delay for DCA and IAD.

Examining Table 13 shows that the ARTCC modifies the requests of fewer flights than the TRACON, resulting in a total arrival delay of 172 minutes. The difference is a result of the ARTCC choosing to delay fewer arrivals by slightly increasing the arrival delay on already delayed flights. Furthermore, of the 15 flights delayed, 11 were delayed no more than 15 minutes and the remaining 4 were delayed no more than 30 minutes. In addition, four DCA-bound flights were assigned to an alternate arrival route. Given the large demand for OJAAY at the beginning of the affected time period, rerouting these flights was appropriate and highlights the flexibility of HDDAM to adjust to off-nominal events.

Table 12. Summary of ATCT Flight Assignments for En-route Capacity Reduction

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Ground Delay	Total TRACON Air Delay
BWI	18	1	0	278 min.	0 min.
DCA	12	5	4	213 min.	2 min.
IAD	11	9	2	218 min.	4 min.

Table 13. Summary of ARTCC Flight Assignments for En-route Capacity Reduction

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Arrival Delay
BWI	4	0	0	44 min.
DCA	9	4	0	122 min.
IAD	2	0	0	6 min.

C. Reduced Surface Capacity Scenario

The final scenario examined in this paper involves a temporary reduction in the surface capacity at an airport, namely BWI. Figure 13 defines the allowable airport capacity profiles for both departures and arrivals for the impacted time period (the profiles overlap in the figure). Using this modification, while retaining the original demand and en-route capacity profiles, an analysis of the impact on the TRACON allocations to the ATCTs and ARTCC can be conducted as described in Tables 14 and 15, respectively.

Examining Table 14 reveals that BWI is allocated a number of departure slots later than requested in order to satisfy the flights delayed by the reduced surface capacity available at the airport. In turn, the TRACON allocates these slots to DCA and IAD, reducing the number of capacity request modifications at both airports. Examining Table 15 shows that only one request for an arrival slot at BWI was delayed in order to satisfy the surface capacity requirements. This single modification is a result of both the low demand for arrivals at BWI during the constrained time as well as the representation of the surface constraint within the TRACON through the parameter α. Furthermore, given that the arrival routes are specific to an airport, both DCA and IAD receive the same arrival slots as in the nominal capacity scenario.

Tables 16 and 17 depict the flight assignments defined by the ATCTs and ARTCC, respectively. Examining Table 16 shows that, as before, the ATCTs modify fewer flights than the TRACON. Comparing Table 16 to the ATCT flight assignments made under the nominal capacity scenario (Table 8) shows that the total ground delay is increased to 677 minutes from 580 minutes. Specifically, BWI has an additional five flights receiving a modification to their requested departure, resulting in an additional 132 minutes of ground delay and four minutes of TRACON air delay; however the overall solution delay is only 97 minutes higher than in the nominal capacity scenario, which can be attributed to the previously assigned BWI resources being redistributed to DCA and IAD. Examining Table 17 reveals that the ARTCC assigned the arrival slots as specified by the TRACON, resulting in a total arrival delay of 39 minutes. Furthermore only a single arrival flight into BWI was delayed as a consequence of the reduced surface capacity.

Table 16. Summary of ATCT Flight Assignments for BWI Capacity Reduction

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Ground Delay	Total TRACON Air Delay
BWI	18	1	2	322 min.	4 min.
DCA	10	6	1	154 min.	0 min.
IAD	12	6	0	201 min.	0 min.

Table 17. Summary of ARTCC Flight Assignments for BWI Capacity Reduction

Airports	# of Delayed Flights	# of Rerouted Flights	# of Delayed and Rerouted Flights	Total Arrival Delay
BWI	1	0	0	3 min.
DCA	4	0	0	30 min.
IAD	2	0	0	6 min.

VI. Conclusions

The concept proposed in this paper seeks to address a current deficiency in the high-density area departure and arrival traffic management system, namely that the point of action is too far removed from the point of decision making. This paper describes a methodology and defines a decision support system structure for departure and arrival management that both alleviates this issue by realigning the locus of control to the appropriate decision maker and empowers decision makers in all areas to most effectively make the decisions under their control. Drawing on network optimization theory, the underlying models of the decision support system were defined as a dual stage capacity allocation and flight assignment problem.

The model developed was implemented for three resource capacity scenarios. Analyzing the results showed that resources could be efficiently distributed, and that once decoupled, the Air Route Traffic Control Center and Airport Traffic Control Towers could independently utilize their assigned resources as best fit their local needs. The results further showed that in the presence of disturbances, the model was able to effectively reassign capacity, increasing the throughput of the system and minimizing the overall impact of the event.

The ultimate of objective of the High Density Departure and Arrival Traffic Management concept, framework, and decision support tools developed is to reduce the workload of each decision maker while achieving a more efficient use of resources. Decoupling the problem as proposed limits the propagation of disturbances, and creates a more robust departure and arrival management system. Given the uncertainty that exists in flight schedules, it is necessary to develop a robust optimization approach, as opposed to a point-optimal schedule. As such, this concept will be further developed to consider rolling time horizons, where uncertainty in demand estimates, as well as available capacity predictions, are subject to change. Analyzing these effects will be of great importance in validating the concept and realizing the benefits envisioned.

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