BOEING CAPACITY-INCREASING ATM CONCEPT FOR 2020

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Abstract

This paper presents a capacity-driven, integrated, gate-to-gate air traffic management (ATM) operational concept for the US National Airspace System (NAS) in 2020. The concept defines five core services for ATM: airspace, flow, traffic, separation and information management. Flow, traffic and separation management are the services that directly influence air traffic movement, while airspace management determines the physical resources available to accommodate traffic demand. The planning and control authority of flow, traffic and separation management is determined using a partitioning of planning time horizons to each service. The paper describes four design alternatives for the separation management service, with varying levels of responsibility allocated to the aircraft. A scenario illustrating interactions between the traffic services is provided.

1. Introduction

This work was performed in the context of the NASA Virtual Airspace Modeling and Simulation (VAMS) project[1] in collaboration with NASA Ames. This gate-to-gate, integrated air traffic management concept represents further development of the Boeing ATM operational concept first published in [1], built on foundations laid in [2-3]. The concept is driven by requirements collected by the Boeing ATM Working Together Team [4], with particular focus on the capacity-related objectives.

The authors have been active participants in the developments of a number of related ATM operational concepts [5-9]. Thus, this concept has a number of features in common with others, with an emphasis on the integration of a hierarchical set of services around a 4-D trajectory basis. This paper presents a summary of the Boeing ATM 2020 operational concept, which is described in detail in [10].

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2. Objectives and Assumptions

The focus of the Boeing gate-to-gate operating concept is the provision of IFR services for the 2020 system operation. The driving objective of the concept is capacity to meet the predicted demand. Furthermore, in real-time operation, the concept addresses the primary objectives of system users and the service provider. For the user, the primary operational objective is flight schedule integrity. The flight schedule is the user's statement of operational objective. For the provider, the operational objective is safety, expressed as preventing the overloading of system resources or the close proximity of flights. The Boeing operational concept is based on the following assumptions:

- 2020 traffic demand projections require action to relieve a major system capacity problem.
- Airport development will keep pace with the traffic demand across all user types. This concept addresses the airspace problem that remains.
- Airspace definitions and operating rules will change to support implementation of the concept.
- An information system exists that is capable of handling the required data exchange between system agents.
- This concept is not constrained by political considerations.

3. Operational Concept Overview

A representation of the 2020 concept functional structure is shown in figure 1. The concept includes five core ATM services: airspace, flow, traffic, separation and information management. A fundamental attribute of the Boeing 2020 operational concept is the allocation of the core air traffic management services to time-horizons and geographical domains. Another key aspect of the concept is that the functions base their problem detection on different levels of fidelity, starting with flow considering airport arrival and departure rates and sector loads, traffic considering groups of aircraft inside sectors across multiple sector areas, and separation detecting conflicts between pairs of aircraft. All services rely on assessment of current operating state, prediction of that state based on the current set of 4-D trajectories, and a projection of the traffic load onto key system resources such as runways or sectors for flow, routes and airspace segments for traffic, and spatial proximity for separation. The services alert where overloading is detected, and generate a new plan to remove the overload condition.

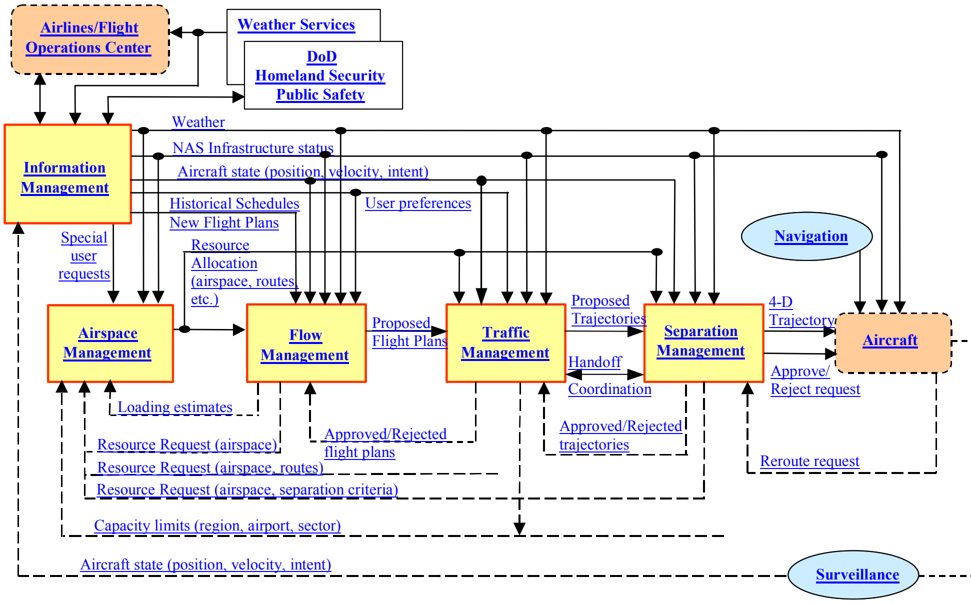

Figure 1 2020 ATM Operational Concept Functional Flow

A key distinction between current NAS operations and this concept is that each function operates directly on individual trajectories to solve detected problems on its time horizon. In the current US and European systems, with the exception of flow management ground delay allocations, the services up-stream from the sector act only indirectly on flight plans, by taking actions such as miles-in-trail spacing rules, airport ground stops, re-route advisories, and so on. While often effective in reducing system overloads, these actions can work at cross purposes, cause under-utilization of resources, and make the progress of individual flights through the system unpredictable. Therefore, an operational concept that allows each function to schedule and route individual flights, based on a hierarchy of operational goals, is expected to enable significantly higher system performance than currently achieved, enabled by an integrated functional architecture and an extensive information and automation infrastructure.

A fundamental attribute of the operational concept is the allocation of the core air traffic services to planning time-horizons. A presentation of the 2020 concept services and associated time-horizons is shown in figure 2. The prediction time-horizons (PH) identify the overall temporal scope of a service. For example, re-routing around large convective weather areas in flow management will require a PH on the order of hours to capture the effects of a new plan, while collision avoidance is considered on a very short time-horizon. System uncertainty generally limits the usability of predictions for planning purposes, and thus it is important to limit the accuracy of a planning objective to the quality of the data used for problem prediction. The prediction time horizon for the system functions may need to be adjusted dynamically, depending on system predictability for a given condition, and thus the boundaries between the services can vary with condition. Additionally, system predictability depends on the phase of flight and/or operational domain, e.g. the differences between pre-departure and in-flight state, and thus the time horizons are adjusted to operational domain and location.

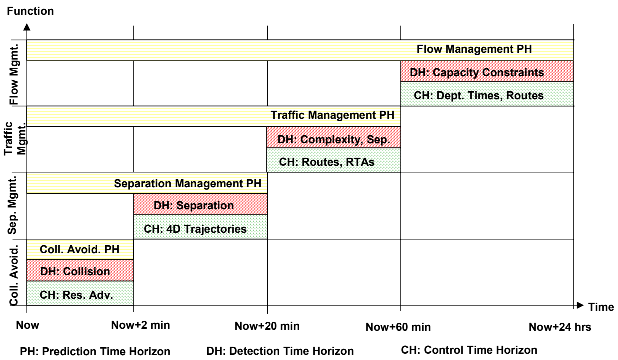

Figure 2 Time Horizon Partitioning for Services

The detection time horizon (DH) in figure 2 defines the future time period within which a service detects problems and determines a plan to achieve its objectives. For flow management this implies that it looks at the time period beyond 60 minutes to detect airport and sector overloads, and does not concern itself with problems prior to 60 minutes. The lower level service, traffic management, is at the same time actively examining situations prior to 60 minutes. The control time horizon (CH) in figure 2 specifies the time frame in which a service can modify its control variables. This implies that traffic management is allowed to modify the route and/or required time of arrival of a flight starting 20 minutes from now, to solve a problem in its detection horizon. Conversely, traffic management is not allowed to reach inside the separation management time horizon with a trajectory change.

The division of control based on time horizons illustrated in figure 2 is designed to avoid ambiguity in control authority. Section 8 presents a scenario that points to a number of details of the time horizon construct. The scenario brings to light coordination requirements between the functions, which, for the sake of clarity, are not illustrated in figure 2. A structure such as this holds the key to the overall functional architecture of the future gate-to-gate system to ensure a logically coherent integration of services, procedures, and ATM automation aids.

4. Flow Management Service

The primary objective of the flow management service is the determination, communication and monitoring of a flow plan that supports the user's flight operations center (FOC), traffic and separation management in providing services with minimal disturbances from weather and congestion events. The flow management service detects capacity and demand imbalances across the NAS over a 24-hour time horizon, and proposes resolutions that balance users schedule integrity with the risk of overloading system resources while considering user preferences and equity. The resources of concern to flow management include airport arrival and departure rates, gate availability and airspace sector capacities.

Flow plan negotiations allow airlines to manage their schedules, to minimize the risks of delay propagation, cancellations and re-positioning flights. Inputs used by flow functions include the current state of aircraft, wind data for trajectory predictions and resources capacity information for use by the capacity allocation functions, as indicated in figure 3. The flow management service is continually executed with an update rate sufficient to safely support other down-stream services. Depending on the dynamics of the NAS, weather or system disruptions may cause reduced predictability down to a few hours. Flight plan modifications in flow management are performed from 60 minutes in the future up to the flow management prediction time horizon.

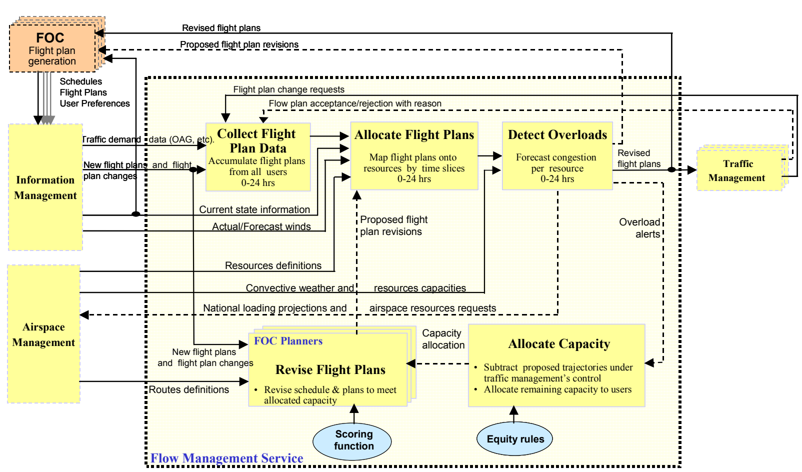

Figure 3. Flow Management Service

Collect Flight Plan Data: Accumulate flight plans for the planning horizon.

Allocate Flight Plans: Map flights onto resources by time slices. The allocate flight plans function predicts all aircraft positions and trajectories and maps flight plans onto resources for each time slice in the flow manager's planning horizon.

Detect Overloads: Compare traffic loads with resource capacities. The detect overloads function checks for resources capacity overloads over the flow planning horizon. If no capacity overload is detected, the user's flight plan is accepted by the flow manager and forwarded to the traffic manager, available for flight plan clearance at departure time. If capacity overloads are detected, a flow resolution action is initiated.

The resolution action is performed in an iterative and collaborative fashion between the allocate capacity function and multiple FOC planner functions. The resolution includes a feedback loop through the allocate flight plans, detect overloads, allocate capacity, and the multiple FOC planner functions.

Allocate Capacity: Allocate capacities to individual users. The allocate capacity function first reduces available capacities by predicting usage by committed flights. It then computes a time-dependent capacity constraint matrix for all resources and partitions the constrained resources to individual FOC planners using equity rules.

Revise Flight Plans: Negotiate revised schedules and flight plans among users. Individual flight operation planner functions use strategies and automation aids to examine their allocated capacity matrix and revise their schedules and flight plans to meet the allocated capacities. Each individual FOC planner uses its own objective function to balance re-routes with departure delays and cancellations and closely collaborates with the allocate capacity function to maximize capacity utilization and schedule integrity. The user objective function assigns value to each individual flight and considers such factors as number of seats or amount of cargo on board, the distance flown, the amount of delay incurred during the day or other cost and revenue related components of a flight. To account for delay propagation during the day, the revise flight plan function accesses the airlines flight planning databases. It has access to schedule connectivity information such as the equipment and passenger flows assigned to each flight. Once all flight plans have been allocated to resources and no overloads exist, revised flight plans are distributed to traffic managers and FOC agents.

The frequency of flow plan updates will be limited by the time needed to recompute a flow plan, the number of flights and airlines to be considered and data communication performance. The ability to compute and execute such a flow plan is subject to a number of sources of uncertainty. They include the ability to accurately predict and continually update aircraft intent, the ability to predict departure times, the ability to collect and store 4-D trajectory based flight plans and to determine their intent in the face of traffic and separation actions to deal with local congestion. Models for these uncertainties will be used to compute a prediction performance metric to guide flow management strategies. High levels of prediction uncertainty may require more frequent updating of flow predictions. Flow replans may be triggered at fixed time intervals and executed continuously to account for the latest convective weather forecasts. Other strategies may be needed to deal with sudden system events, such as runway closures, where the objective of the flow replan is to minimize down stream effects on traffic and separation services and to ensure flow plan stability. Alternatively, replans can be initiated reactively when a flow conformance deviation from the current plan has been detected.

5. Traffic Management Service

The primary objective of the traffic management service is the determination, execution and monitoring of a traffic plan that reduces traffic complexity and maximizes throughput under spacing constraints across a regional area, based on a flow plan as determined by flow management. The traffic management service fills the gap between strategically oriented flow management and tactical separation management.

The traffic management service consists of four functions, as illustrated in figure 4. Traffic assessment compares the current traffic situation with the traffic plan and evaluates the need for a replan. 4-D trajectory predictions for each airplane form the basis for the computation of complexity measures and aircraft spacing, which permits the identification of complexity overloads or spacing goal violations. If a new traffic plan is required, the traffic replan function maximizes a throughput metric with traffic complexity and spacing constraints in the planning time-horizon and the multi-sector region.

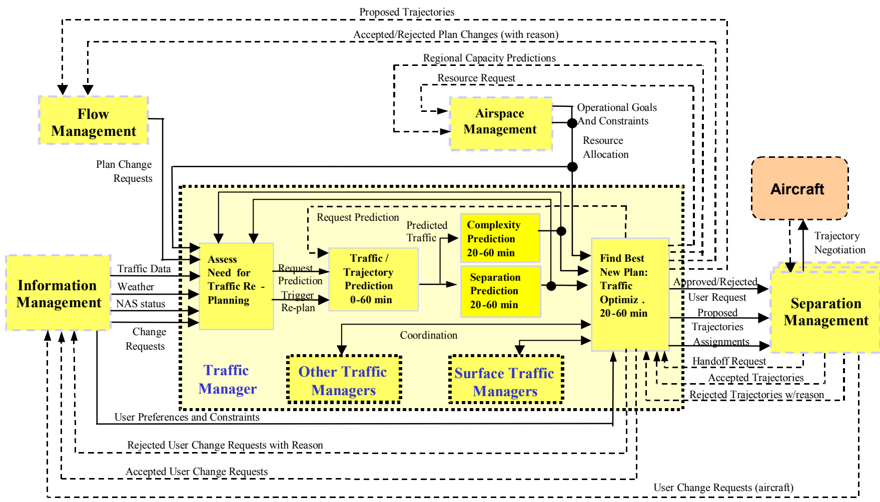

Figure 4. Traffic Management Service

Assessment of Replan Need. Based on a composite view of the surface and air-borne traffic situation, traffic monitoring tracks compliance with the plan that is in effect, and evaluates whether a new traffic plan needs to be generated. Traffic replans may be triggered pro-actively or executed continuously. Alternatively, replans can be initiated reactively when a traffic conformance deviation from the current plan has been detected. Proactive triggering aims at continuous efficiency improvement using a scoring function that compares benefits between a new plan and the existing plan. A threshold will determine whether to activate the new plan. Reactive triggering compares traffic deviations against a defined complexity tolerance to determine need for a replan. The triggering tolerance thresholds are subject to trades between throughput, efficiency, stability, and communication loads. A traffic replan can also be activated via external requests. For example, flow management may request the acceptance of a new flow plan. Separation management may reject proposed traffic plans or request the incorporation of trajectory modifications.

Trajectory/Traffic Prediction. Information for prediction is composed of the planned trajectory, procedures and the time horizon over which the path has to be calculated. Path prediction also requires predicted environmental conditions such as wind and temperature, as well as a model of airplane performance. Prediction performance is a key aspect of reliable planning. Models for prediction uncertainties will be used to compute uncertainty bounds for the prediction. This metric is essential for the computation of overall traffic plan stability and the determination of achievable prediction time horizons.

Complexity and Spacing Detection. Based on predicted airplane paths, complexity and spacing predictions are computed. Complexity and spacing performance goals are inputs from airspace management. Comparison of these goals with the predicted metrics permit the determination of constraint violations. The computation of the spacing constraints may be based on pair-wise distances between aircraft, or represented in a combined complexity and spacing metric.

Traffic Optimization. A new plan is computed by maximizing an efficiency metric that is subject to operational constraints expressed in terms of traffic complexity, spacing goals and user preferences. Sub-functions of traffic optimization include:

- Computation of the efficiency metric for traffic planning.
- Determination of constraint compliance.
- Definition of a new trial plan considering user preferences, inputs from other planning functions, constraints and performance goals.

The traffic management service either initiates the generation of a new trial plan or issues requests for new resources from airspace management. When a new plan has been found that satisfies all constraints and performance goals, the new plan is presented to the human traffic management agent for acceptance, and is subsequently communicated to flow and separation management.

The traffic management service will integrate planning of arrival, departure and en route traffic within the multi-sector region and is tightly coupled with surface traffic management to ensure efficient arrivals and departures and maximized airport throughput.

Traffic Management Control Mechanisms. Traffic management services modify 4-D trajectories in the control time horizon from 20 to 60 minutes. The following control mechanisms are defined for traffic management:

- Departure times of aircraft and surface traffic trajectories at airports for the surface traffic manager.
- Route selection for aircraft within the multi-sector region, for the airspace traffic manager.
- Dynamic 4-D trajectory allocation via waypoint designation and associated timing targets.
- Sequencing of aircraft through merges and intersections.

Inter-Sector Handoff and Coordination with other Traffic Managers. The traffic manager is responsible for handoff coordination between sectors as well as across multi-sector boundaries. This task includes short- to medium-term conflict detection on airspace boundaries, and the generation of resolution strategies. Conflicts on boundaries internal to the multi-sector region are handed over to separation management for resolution. Conflict resolution on boundaries with other multi-sector regions are negotiated and resolved in cooperation with other traffic managers.

6. Separation Management Service

The objective of the separation management service is to plan, communicate and monitor 4-D aircraft trajectories that ensure no violation of the minimum allowed separation between pairs of aircraft, while contributing to full utilization of airspace and airport resources by operating as close to the minimum as feasible. The separation management service is the sole point of trajectory change communication between the aircraft and the ground-based ATM functions after pushback from the gate. Separation management coordinates directly with traffic management and airspace management to achieve its operational goals.

The following assumptions are made regarding separation minima in 2020, driven by the goal of accommodating the predicted traffic demand:

- En route: 5 nm.
- Terminal area: 3 nm, extending significantly farther from the airport than the current TRACON airspace.
- In-trail final approach in VFR: determined by runway occupancy time.
- In-trail final approach in IFR: limited only by low visibility runway exit performance.
- Closely spaced parallel approaches: independent operations down to 750 ft centerline distance.
- Vertical – 1000 ft all altitudes.

Figure 5 illustrates the functions in the separation management service. The prediction time horizon for separation management is 20 minutes, and it is continually executed with an update rate sufficient to safely support the separation standard in use. The detection and control time horizons for the separation management service are bounded below by 2 minutes. The service produces a conflict-free 4-D trajectory for every aircraft in the sector or airport surface, out to the 20-minute prediction horizon, and communicates this 4-D trajectory as a clearance to the aircraft. The aircraft flight manager assesses the ability to execute the trajectory within the given tolerances for the procedures in use at the time, and if able transmits an acceptance message and flies the trajectory. If the trajectory is infeasible, the flight manager notifies the separation manager of rejection with a reason for the rejection by stating the constraint, or by proposing a modified trajectory for consideration.

The 4-D trajectory definition is a collection of 3-D (x, y, z) points in space, with associated estimated or required future time values. Associated with the trajectory definition is a 4-D conformance bound. The separation manager generates trajectories for each aircraft such that if they stay within their 4-D tolerance it is ensured that conflicts will not occur. The ability to execute such a plan is subject to a number of sources of uncertainty, and thus there is a certain probability that a plan will require updates within the 20-minute time horizon upon which it was initially based. It is expected that the longitudinal intervention rate will be higher than the vertical and lateral rates, but all need to be sufficiently low to ensure stability, and computational and communication feasibility.

Figure 5 illustrates that the separation manager continuously monitors each aircraft's conformance to the cleared 4-D trajectory through the conformance monitoring function. The conformance monitoring function will detect and alert the need for plan updates in cases when aircraft exceed the given conformance limit, and in cases when an unexpected change in aircraft intent is communicated.

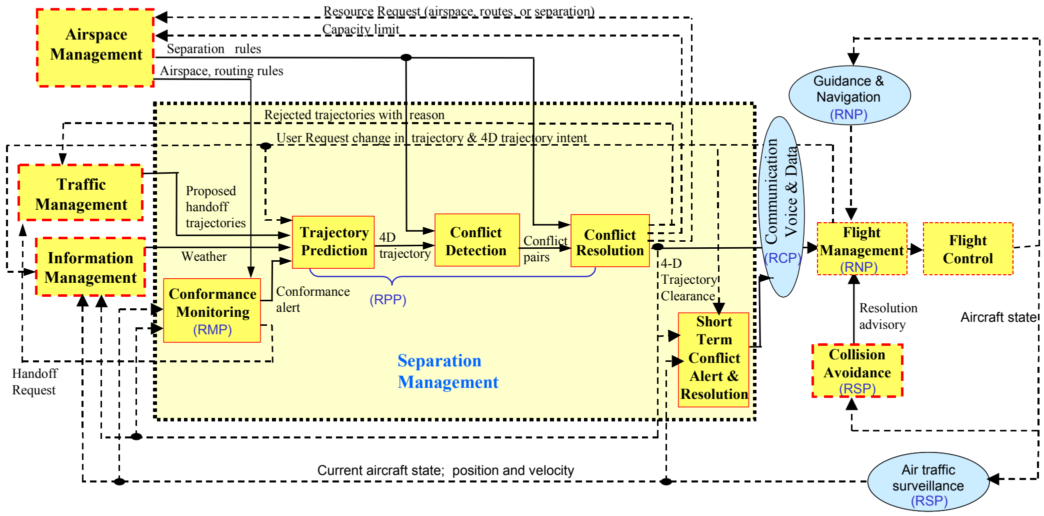

Figure 5. Separation Management Service

Due to the computational complexity of the 20-minute 4-D trajectory planning process, and the likely stringent safety and certification requirements on the separation management function, it may be necessary to include an independent function for short-term conflict detection. Four concept alternatives are proposed for short-term plan update functionality, one based on allocating it to the ground element, the other three allocating it to the airborne element.

Alternative 1. A short-term function (1- to 5-minute time horizon) is added to the separation management service to enable rapid automated detection of trajectory deviation and impending conflicts. This short-term conflict alert (STCA) function relies on current state and trajectory intent information from the 4-D trajectory planner, the independent surveillance sensors and from downlinked aircraft state and intent data. In response to a short-term conflict alert, the STCA function determines a resolution action and a new trajectory is up-linked to one or more aircraft. The separation manager is alerted to the conflict and voice communication with the crew is used to ensure immediate action to resolving the conflict. The crew verifies the resolution on a graphical display and has final execution authority.

Alternative 2. The short-term conflict alert and resolution function is allocated to the aircraft. This function uses the current state and trajectory intent of own aircraft, along with state and intent information from surrounding aircraft from the surveillance and communication systems, to detect a conflict in the 1-5 minute time horizon. This functionality is as described for protected airspace zone (PAZ) alerts and resolutions in [11] The function generates an alert and conflict-resolution maneuver to the pilot in the form of changes in heading, climb/descent rate and/or speed change. Note that this removes the aircraft from 4-D trajectory mode and implies the use of manually dialed settings. PAZ-generated resolution advisories are coordinated with other airborne conflict management systems involved. The resolution maneuvers are immediately communicated to the separation manager, who updates his trajectory predictions and generates 4-D trajectory updates for all aircraft in the sector that are consistent with the short-term maneuvers, continuous with the original flight plan, and conflict free.

Alternatives 1 and 2 both assume that the airborne collision avoidance function remains independent and performs like current Airborne Collision Avoidance System (ACAS) functions, with approximately 1-minute time horizon.

Alternative 3. In this alternative it is assumed that the ground-based conflict-free 4-D trajectory planning process performed by the separation management service performs adequately to ensure safe separation, with only an enhanced airborne collision avoidance function that provides a 2-minute alert and resolution. The collision avoidance function relies on automatic dependent surveillance data from surrounding traffic and additional intent information to contain false alarm rate to a minimum even in the most dynamic terminal areas. The collision avoidance function is integrated with the ground and airborne 4-

D trajectory management systems so that it generates compatible advisories and communicates those advisories to the separation manager.

Alternative 4. Assuming the enhanced collision avoidance function as in alternative 3, the airborne element assumes the added responsibility of maintaining spacing with respect to other aircraft identified by the separation manager, according to the 4-D trajectories issued. This results in significantly lower air/ground communication bandwidth requirements by eliminating the need for the separation manager to issue clearances to fine-tune 4-D plan execution. The separation manager uses larger conformance bounds on its monitoring function, and intervenes with a new plan only when significant changes result from unexpected plan execution.

A safety and collision risk assessment will determine which of the concept design alternatives listed above can satisfy overall separation management and collision avoidance requirements. Ground and airborne architecture cost will also be a significant driver on the trade study outcome.

7. Airspace Management Service

The airspace management service is responsible for long-term activities, such as the definition and planning of airspace resources, and short-term activities, including the dynamic allocation of airport and airspace resources. Long- to medium-term responsibilities include determining the physical definition and operating rules of the airspace, airways, and airport assets, including air traffic and flight procedures. Short-term responsibilities include dynamic allocation of these resources to the flow, traffic and separation services based on predicted total system performance levels [12].

As illustrated in Figure 6, airspace management will forecast required and available air traffic service levels for the day. Airspace management will decide the partitioning of prediction, detection and control time horizons for the flow, traffic and separation services based on an assessment of prediction uncertainty. Airspace management will adjust sector boundaries, establish routings and spacing targets, and allocate other key NAS resources to flow, traffic and separation.

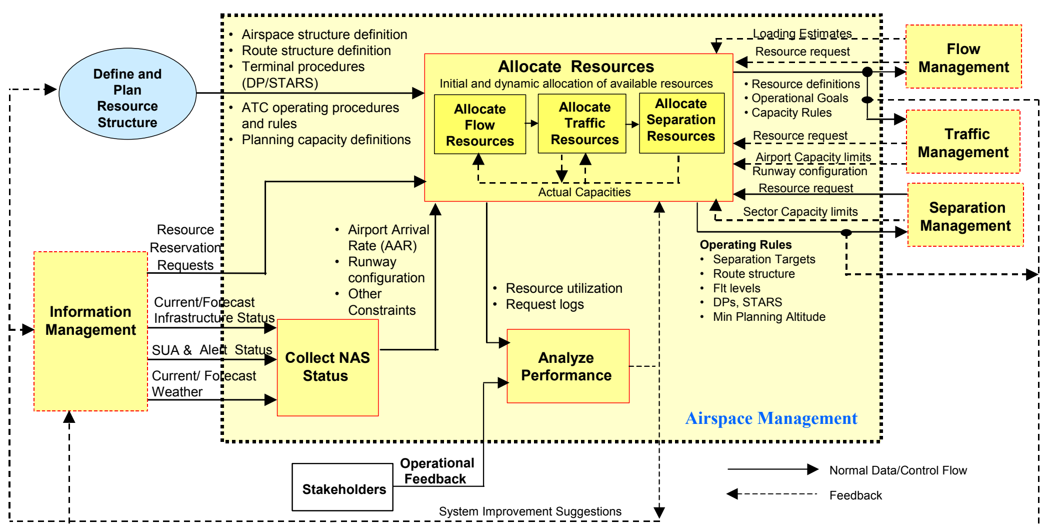

Figure 3-9 Airspace Management

Collect NAS Status. Airspace management gathers information on the status of resources that will effect the day's operation. Communications, navigation and surveillance equipment status and planned outages, runway repairs, weather forecasts, etc. are collected to form the basis for an assessment of actual system performance levels (ATSP). A grid of ATSP by time of day will be provided via the manage information service for all NAS users.

Allocate Resources to Flow, Traffic and Separation Services. Based on the traffic demand and weather picture for the day's operation, the function allocates resources to the other services. The airspace management service also establishes time horizons for flow, traffic and separation services.

Sector boundaries, routes and spacing targets are determined in real-time. All airspace is defined in terms of RTSP-based criteria consistent with operational needs.

Analyze Performance. The airspace management function will analyze overall system performance on an on-going basis. A performance baseline of NAS operations will be developed and a dynamic process for statistical analysis of trends and causal factors will be established to provide performance feedback to management and users.

8. Scenarios

Figure 7 illustrates how the ATM functions operate from the point of view of a single flight through the system. The horizontal time line starts with "now" being at the flight's pushback time, TD. Prior to this time, the flow and traffic management functions have evaluated the flight plan for potential problems, and generated re-plans as required. Thus the current plan, assuming that situations unfold as predicted, will result in acceptable traffic loading on all the resources that this flight is planned to use.

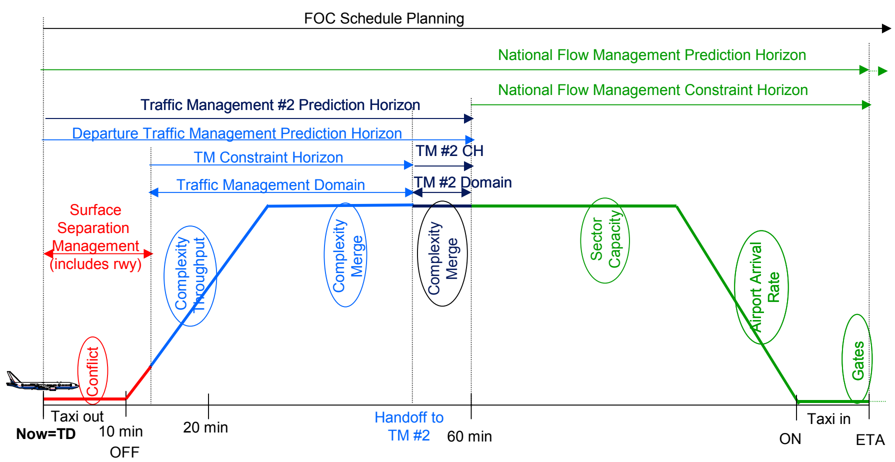

Figure 7. Scenario with Service Time Horizons

At the time of departure, TD, the surface separation manager has generated a taxi plan for the aircraft, which provides a near-unobstructed taxi path, except for a few tactical interventions at taxiway crossings, merges and runway crossings. He communicates the taxi plan to the aircraft and continues to monitor and guide the aircraft to the runway. The time horizon assigned to the surface separation manager is adapted to the size of the airport surface, in most cases less than 20 minutes. Figure 7 indicates that the surface separation manager's scope includes the departure runway and the start of climb-out.

At the same time, the departure traffic manager continues to evaluate departure throughput and traffic complexity from initial climb-out to 60 minutes into the flight. He plans an unrestricted climb trajectory, sequences the aircraft into the overhead stream and ensures that sector complexity limits are not violated. In keeping with the time horizon structure in figure 2, this resolution should not modify the aircraft's plan until 20 minutes from now. However, given that a significant airspace problem that has just been detected can jeopardize safety, an allowance should be made for coordination between traffic and separation on a resolution action before takeoff. Thus, if a trajectory adjustment is necessary, the traffic manager generates a new trajectory, and notifies the surface separation manager, who checks for impact on the current taxi situation. The possible impact and resolution on the surface plan performed by the surface separation manager includes:

- Delay a few minutes: absorb in the airspace to avoid delaying other aircraft on taxiways.
- Delay of more than several minutes: move the aircraft to a surface holding area, if available.
- Airspace re-route implying a runway change: check for feasibility of directing the aircraft to the other runway. If feasible, clear the aircraft to the other runway and update its trajectory to alert the other departure separation manager of new trajectory. If infeasible, alert the departure airspace separation manager of need to accommodate the re-route through his domain.
- Airspace re-route using same departure runway: no change in current taxi plan.

Concurrently, at the time of departure, the flow manager is monitoring for potential capacity overloads beyond the 60 minute time horizon across the entire NAS. If the flow manager detects a sector overload condition or an arrival airport overload, he may propose a ground delay or re-route for the aircraft, and alert the departure traffic manager with a trajectory update. The traffic manager checks any impact on his domain, adjusts trajectory as needed and transmits to the surface separation manager, who checks for surface hold feasibility, and communicates the new trajectory to the aircraft.

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