ESTIMATING CAPACITY REQUIREMENTS FOR AIR TRANSPORTATION SYSTEM DESIGN

Shannon Zelinski[1] and Tom Romer[2]
NASA Ames Research Center, Moffett Field, California, 94035, USA

Abstract

This paper discusses a method for estimating the minimum airport and airspace capacities required of an operational concept to meet flight demand needs to satisfy given delay constraints. A demand profile for each individual airport and airspace facility is used to estimate a facility's minimum required capacity subject to given maximum delay constraints. The scalability if the required capacities produced in this analysis are validated using a simulation of the air transportation system. The capacity estimating method was developed to efficiently analyze demand and establish minimum concept design requirements for an air transportation system design process. This demand analysis focuses air transportation concept design while ensuring complementary developed flight demand schedules. The capacity requirements for several demand models are estimated and compared demonstrating the use of this method for demand analysis.

Nomenclature

i	=	bin index
Δt	=	bin size in minutes
n	=	total number of bins
$D(i)$	=	demand profile
$E(i)$	=	number of flights that need to be shifted
$\alpha_\circ(i)$	=	initial number of flights that may be shifted
$\beta_\circ(i)$	=	initial number of flights that may not be shifted
$\alpha(i)$	=	new number of flights that may be shifted
$\beta(i)$	=	new number of flights that may not be shifted
d_f	=	maximum delay per flight in minutes
d_a	=	maximum daily average delay in minutes
c	=	capacity
ρ	=	demand/capacity ratio

[1]Computer Engineer, Aerospace Operations Modeling Office.
[2]Aerospace Engineer, Aerospace Operations Modeling Office.

1 Introduction

Demand on the air transportation system is forecasted to increase between two and three times by 2025. Current efforts [1],[2] are defining future operational concepts that increase capacity to accommodate increasing demand. Because many factors affect future demand growth, the spectrum of scenarios, and therefore capacity design requirements, is extremely broad. Reference [3] initially decoupled individual concept and demand growth development. The concepts and demands were integrated for the first time in the system design and analysis phase. This was done through simulations in a trial and error approach to refine the concept with little or no modification to flight demand. A means to analyze demand requirements and guide both concept and demand development beyond a "trial and error" approach is needed.

This paper discusses a method for efficiently estimating minimum required capacities that can serve as first order requirements for air transportation system design. The method analyzes future demand scenarios to establish minimum airport and airspace capacity levels that future concepts must supply. These capacities are then used in trade studies balancing the physical, technological and economic constraints of concepts against the proposed flight demand. In turn, constraints are established on demand growth that narrow the breadth of scenarios requiring consideration. This method takes the view that concepts and demand scenarios must be designed in parallel to create balanced and realistic solutions. The Required Capacity Estimator described in this paper provides a quick and simple demand analysis, playing a vital role in the iterative design process.

Section 2 discusses the motivation of this research, incorporating the Required Capacity Estimator into an iterative future demand and capacity system design process. Sections 3 and 4 discuss the method used to estimate minimum required capacity and the simulation test matrix used to validate the method. The delay results from the validation simulations are discussed in section 5. In section 6 the Required Capacity Estimator is applied to several different demand profiles generated by varying growth and business models. The capacity requirements for these different types of future demand, are compared and their implications on future concept requirements are discussed.

2 System Design Process

A recent preliminary evaluation of integrated future operational concepts using system wide simulations failed to meet a two times current day capacity with acceptable delay by today's standards[3]. The evaluation results showed that future demand had to be appropriately balanced with concept capacity across the National Airspace System(NAS) to reach this goal. For example, one concept increased airport capacity by utilizing closely spaced parallel runways to perform parallel landings. The concept was applied to a limited number of airports due to the high cost of building new runways. This concept had to be balanced with the future demand scenario used to ensure that it was applied to airports that required the most capacity. In balancing the demand to capacity, many simulation runs were performed using the Airspace Concept Evaluation System (ACES) [4]. Metrics were derived from each run and the concept capacities and demand were modified followed by additional simulations.

System wide simulations include many models and are computationally intensive, especially as demand increases. They require a significant amount of simulation and analysis resources. The Required Capacity Estimator discussed in this paper may be used to iteratively design a balanced future demand and concept without running high fidelity simulations. Once a reasonable balance has been found, fewer simulations will be needed to validate and analyze the effects of interacting NAS elements with the proposed future concept and demand.

Figure 1 shows how the Required Capacity Estimator can be incorporated into an iterative future demand and concept system design process. A set of potential demand scenarios is proposed. Each demand is evaluated using the process described in this paper, establishing the minimum level of capacity required by a concept to satisfy the demand. The estimated capacities that a single concept or integrated set of concepts being evaluated can provide are compared with the required capacities. Metrics based on the capacity differences may be fed back into the demand generation process, reducing excess demand where required levels are not achievable physically, technologically and/or economically. The metrics may also be used to refine the concept to better meet the capacity requirements. A concept that reasonably meets the requirements of a demand scenario may be simulated to study the effects of interacting NAS elements. Simulation results may lead to further demand and concept refinement. As concepts mature, the iterative process continues. The results are concepts designed to meet required levels of capacity and satisfying realistic demand sets.

3 Required Capacity Estimator

The Required Capacity Estimator estimates the minimum capacity required for a given demand profile. Estimates are made individually for each airport departure, arrival, and total capacity and for each sector capacity in the National Airspace System.

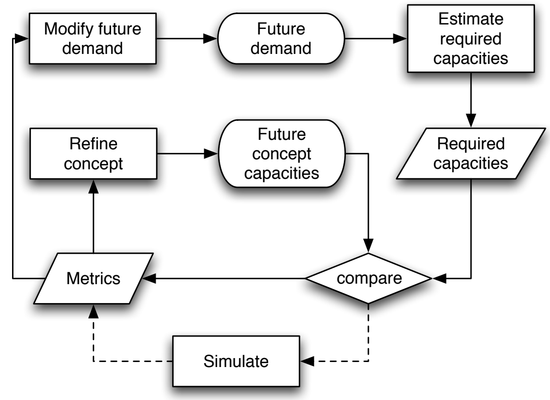

Figure 1: Future demand and concept design process.

The demand profile ($D(i)$) is the number of desired airport operations or average sector loading for each i. Each i represents a bin size of Δt and the total number of bins is given as

$$n = 1,440/\Delta t$$

in order to cover a 24 hour (1,440 minute) day. Given $D(i)$, the Required Capacity Estimator finds the minimum capacity (c) subject to the maximum delay constraints, d_f and d_a. The Δt is always greater than or equal to d_f. Let $\alpha_\circ(i)$ be the number of flights that occur in the last d_f minutes of i that may be delayed to $i+1$ (shifted to the next bin). Let $\beta_\circ(i)$ be the number of flights that occur in the first $\Delta t - d_f$ minutes of i that may not be delayed (shifted) to $i+1$ such that

$$D(i) = \alpha_\circ(i) + \beta_\circ(i).$$

Beginning with $\beta(0) = \beta_\circ(0)$, the algorithm steps though each i calculating the number of flights that need to be shifted as

$$E(i) = max(\alpha_\circ(i) + \beta(i) - c, 0).$$

If $E(i) \leq \alpha_\circ(i)$ or $c \geq \beta(i)$, then

$$\alpha(i) = \alpha_\circ(i) - E(i)$$
$$\beta(i+1) = \beta_\circ(i+1) + E(i).$$

Otherwise, c is insufficient and fails. If c fails, increment c and repeat the algorithm until all n bins have passed and the following requirement on d_a is met.

$$d_a \geq \sum_{i=1}^{n} E(i)/n$$

Figure 2 shows a graphical representation of the required capacity estimator algorithm as it steps through i for $c =$

14. $E(1)$ is calculated and transfered from $\alpha_\circ(1)$ to $\beta(2)$. Then $E(2)$ is calculated and transfered from $\alpha_\circ(2)$ to $\beta(3)$. $E(3) > \alpha_\circ(3)$ and so $c = 14$ fails and must be incremented.

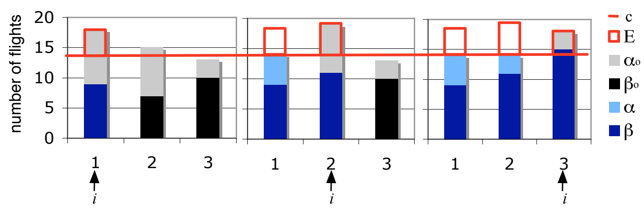

Figure 2: Graphical representation of the required capacity estimator algorithm.

The algorithm is used similarly for estimating both airport and sector capacities. The differences lie in how $D(i)$ is created, how Δt is chosen with respect to d_f, and the interpretation of c.

A zero-delay ACES simulation is performed to produce unimpeded flight tracks and flight times. For each airport, the unimpeded takeoff time for each flight departing from the airport and landing time for each flight arriving at the airport are counted for each i to create departure and arrival $D(i)$ profiles. The sum of the two is the total operations $D(i)$ profile. Even though hourly capacities are specified in the inputs, ACES applies airport capacity restrictions quarter hourly, dividing the given hourly capacity by four. Therefore, the resolution for interpreting airport capacity in ACES is 15 minutes. For this reason, the Δt used for estimating airport capacities in ACES should be no less than 15 minutes. The estimated required capacity for airports is an hourly capacity equal to $60c/\Delta t$.

The unimpeded flight tracks identify the sector that a flight is occupying for each minute in flight. These flight tracks are used to calculate the average instantaneous number of flights occupying each sector for i to create sector loading demand profiles. These average instantaneous sector loading demand profiles may then be used as $D(i)$s to find minimum required sector capacities. Sector capacity is an instantaneous flight count limit and is equal to the algorithm output c. The resolution for interpreting sector capacity is the same as the flight track resolution of one minute. The only restriction on Δt used for estimating sector capacities is that it be an integer.

All airport and sector $D(i)$s are considered independent in this algorithm. Delays are not propagated to other airports and sectors.

For this study, required capacities were designed for both airports and sectors with $d_f = 15$ and $d_a = 3$.

Figure 3 shows an example of required capacity estimation where $d_f = 15$ and $d_a = 3$. Figure 3(a) shows the original demand in flights per quarter hour. The algorithm begins with test capacity equal to the average demand for the day $c = 13$ seen in Figure 3(b). The test capacity fails at $i = 63$ where there are more than 13 shifted flights that cannot be moved again. Figure 3(c) shows the next iteration where test capacity 14 passes for the entire day for $d_f = 15$. The average flight delay for the day for $c = 14$ is 2 minutes which satisfies the requirement $d_a = 3$.

Because these capacities are designed per facility with no buffer for delay propagation between facilities, real system delays are expected to exceed d_f and d_a. First attempts to simulate NAS-wide traffic using minimum required sector and airport capacities designed for the demand resulted in excessively large delays. Reference [8] analyzes delay vs. demand/capacity ratios at high demand US airports and shows how most of these airports operate at a demand/capacity ratio between .6 and .8. The demand/capacity ratio ρ is taken as an average over the peak 18 hour operating period for a facility. The requirement that each facility have $\rho \leq .7$ was added to the minimum required capacity design. Reference [3] incorporated this requirement in their iterative demand design as well. For the example shown in Figure 3, $\rho = .57$ which is sufficient. Facilities with more evenly distributed demand over longer periods of the day had $\rho > .7$ and their required capacities were increased to lower ρ to .7.

4 Demand Scenarios for Validation

All future demand scenarios discussed in this paper were created using *AvDemand*[5]. *AvDemand* uses a baseline flight demand schedule and modifies the schedule according to various user parameters such as projected airport growth rates and point-to-point business strategies.

A set of 5 demand scenarios was designed and simulated using ACES to validate the required capacity estimation method. The demand set included a current traffic demand scheduled processed from 7/7/2006 Aircraft Situation Display to Industry data[6, 7]. 7/7/2006 was a good weather and moderately high traffic day. The current traffic demand (1x) was used as the baseline in *AvDemand* to create 1.5x, 2x, 2.5x, and 3x traffic homogenously grown across airports, meaning that growth ratios were the same at all airports. Figure 4 shows the hourly departure demand profiles for this demand set.

Minimum required departure, arrival, and total operations capacities were estimated for over 1600 US airports, and sector capacities were estimated for 354 High and Super Sectors. All capacities were estimated using $d_f = 15$, $d_a = 3$, and maximum allowed $\rho = .7$. The lowest required airport capacities allowed were the ACES IFR default rates for a single runway. These default departure, arrival, and total rates are 30, 30, and 53 flights per hour, respectively.

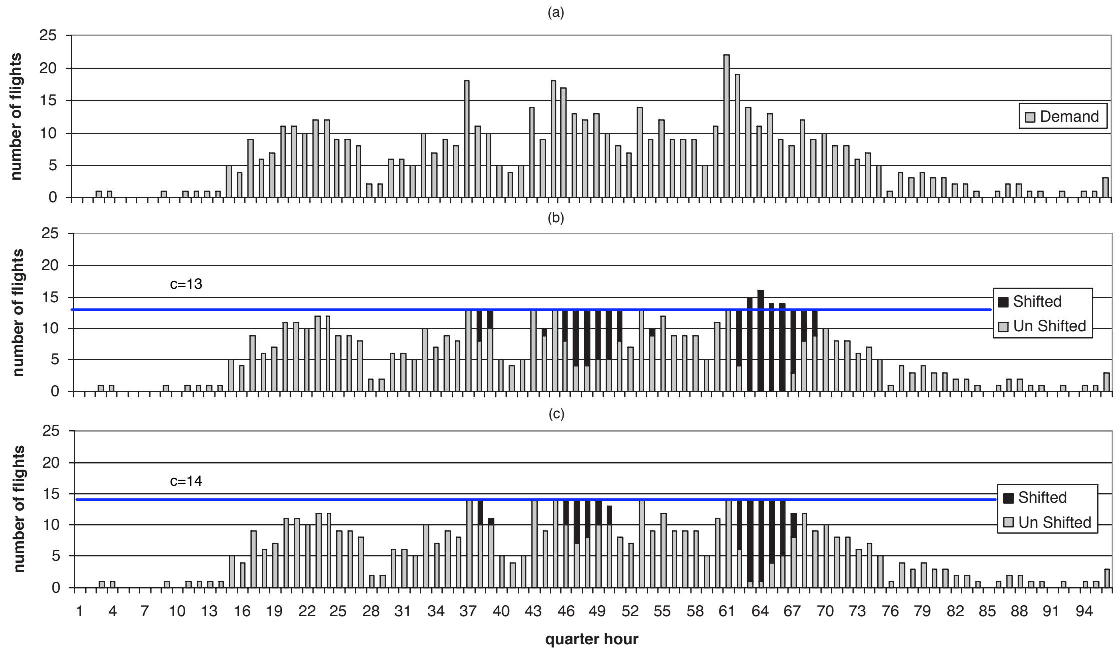

Figure 3: Required capacity estimation example with a maximum delay per flight of 15 minutes and a maximum average flight delay across the facility of 3 minutes. (a) Demand profile. (b) Unshifted flights and shifted flights for a test capacity of 13 flights. (b) Unshifted flights and shifted flights for test a capacity of 14 flights.

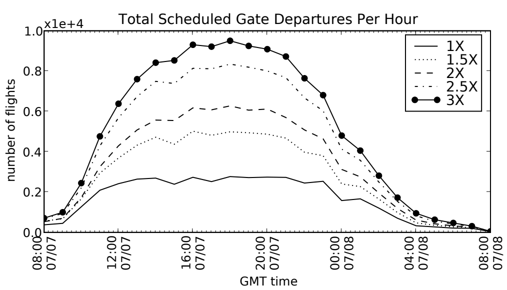

Figure 4: Departure demand profiles for 1x, 1.5x, 2x, 2.5x, and 3x homogeneous growth based on 7/7/2006 traffic.

Less than 100 airports were estimated to require capacities greater than these defaults for any of the demand cases. Default current day sector capacities came from FAA adaptation data. Required sector capacities less than half the default sector capacities were not allowed.

Figure 5 shows histograms of facility required capacity as a percentage of the 2004 Benchmark Report[9] airport capacities and FAA adaptation data sector capacities. The 1x demand set would not have been represented at all in Figure 5 if the current day default capacities were adequate for current day demand. However, six airports and two sectors require between 100% and 150% of the current day capacity. For both sectors and airports, the number of facilities and percentage range of default capacity increases rapidly as the demand increases. The airport that consistently had the greatest required capacity and percentage of default capacity for this demand set is Atlanta International Airport (KATL). The 3x required capacity for KATL is 634 total operations per hour. The two sectors that consistently had the greatest required capacity and percentage of default capacity for this demand set and the only two that are greater than 100% default for 1x demand are two adjacent high sectors in Chicago center ZAU75 and ZAU76. The 3x required capacities for these sectors are 71 and 61 flights, respectively.

5 Validation Results

The five demand scenarios discussed in section 4 were simulated in ACES three times: 1) with both airports and sectors constrained to their required capacities, 2) with just airports constrained and sectors unconstrained, and 3) with just sectors constrained and airports unconstrained as shown in the following test matrix table.

simulation run	airport constraints	sector constraints
1)	constrained	constrained
2)	constrained	unconstrained
3)	unconstrained	constrained

ACES enforces these constraints with very simplistic traffic flow management. Flights are not rerouted to avoid congestion. Delay is propagated back from the constraints using

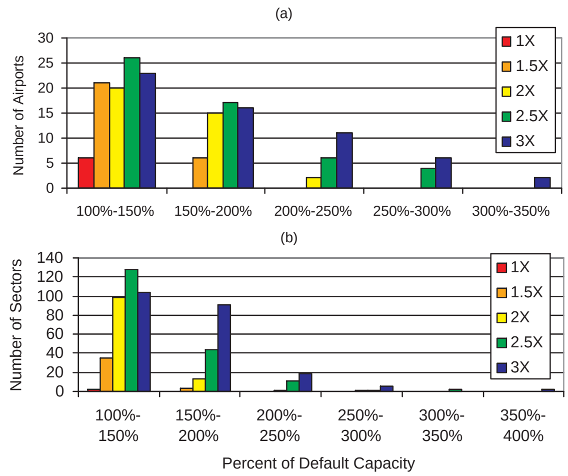

Figure 5: Required capacity comparisons for 1x, 1.5x, 2x, 2.5x, and 3x. (a) Comparison between number of airports in various ranges of default capacity percentage. (b) Comparison between number of sectors in various ranges of default capacity percentage.

the original flight plan.

Figure 6 shows the average total delay per flight for each simulation. For each group of airport and sector capacity options, the average delay per flight for demands 1.5x through 3x are very similar with standard deviations less than 1 minute. 1x delays are lower because minimum required capacities less than the IFR mode default single runway capacity for airports and less than half of the default for sectors were not allowed. The 1x demand does not stress the system with these default capacity values enough to produce the same delays as the higher demands.

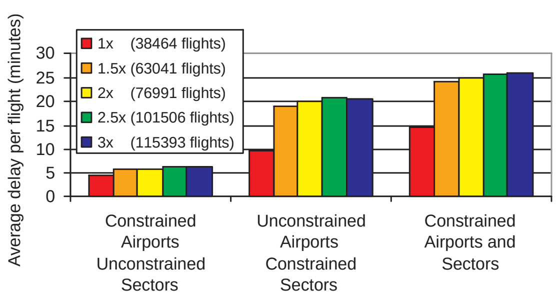

Figure 6: Average total delay per flight for each of the 5 demands with just airport, just sector, and both airport and sector required capacity constraints.

The required capacities were designed according to the delay limits of 15 minutes for any one aircraft (d_f) and 3 minutes average delay (d_a)for an isolated facility. Interactions between facilities produce additional delay. The more facilities a flight passes through, the more opportunities for delay propagation between facilities. The simulations with only airports constrained have the lowest delay because each flight is subject to delays from only two facilities, the origin and destination airport. The simulations where sectors are constrained introduce more facility interactions and therefore, more delay.

Figure 7 shows the average total delay per flight segregated by the number of sectors through which a flight passes for the 3x simulations. For the simulation with unconstrained sectors, the average total delay per flight remains fairly independent of the number of sectors through which a flight passes. The two simulations where sectors are constrained show how as flights pass through more sectors, the average total delay per flight increases.

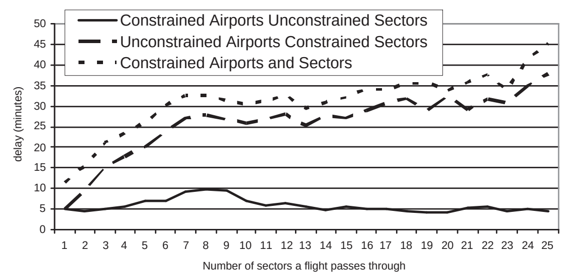

Figure 7: Average total delay per flight segregated by the number of sectors through which a flight passes for the 3x simulations.

6 Application to Future Demand Models

The Required Capacity Estimator has been shown to estimate required capacities that produce consistent delay levels in simulation as demand increases. We now apply the estimator to different types of future demand models and compare the resulting capacity requirements.

6.1 Future Demand Models

There are a wide range of possible demand models for the future. Future demand depends on the proposed growth ratios across the NAS, fleet mix, business strategies, and even route structure. *AvDemand* was used to create just a few of the many possible future demand models. The future demand models discussed in this paper are heterogeneous forecast growth, flight consolidation, and two kinds of point-to-point (PTP) business strategies.

The homogeneous growth of the NAS, demonstrated in the previous sections and used to validate the Estimator, is unrealistic as certain regions are expected to grow faster than others. Terminal Area Forecast (TAF)[10] data projects the number of yearly operations handled at each of 3527 US airports for year 2005 through 2025. This data can be used to create growth ratios from the baseline demand set year

2006 to 2025. *AvDemand* can grow the demand heterogeneously (different growth factor for each airport) according to these ratios to get projected year 2025 demand traffic. Or *AvDemand* can use the normalized ratios as a guide to continue growing the demand until a target NAS-wide growth has been reached. The current traffic demand for 7/7/2006 was used as the baseline in *AvDemand* to create heterogeneously grown 1.5x, 2x, 2.5x, and 3x target traffic demand according to TAF ratios between 2006 and 2025.

AvDemand can also convert operations to enplanements and apply fleet mix changes that support flight consolidation or one of two PTP business models. When a fleet mix change is applied to a 3x operations future demand, the resulting demand no longer represents 3x operations growth, but 3x passenger growth.

Figure 8 illustrates the basic principles of flights consolidation and the PTP business models. Large circles represent hub sized airports and small circles represent smaller satellite airports that may surround a hub sized airport. Arrows represent flights between airports and the line thickness represents the amount of traffic. Flight consolidation merges multiple flights between the same city pairs to fewer flights using larger aircraft. Flights were consolidated when departing within 15 minutes and 1 hour of each other. Figure 9 shows the percent flight reduction from TAF grown demand for each of these cases from 1x to 3x.

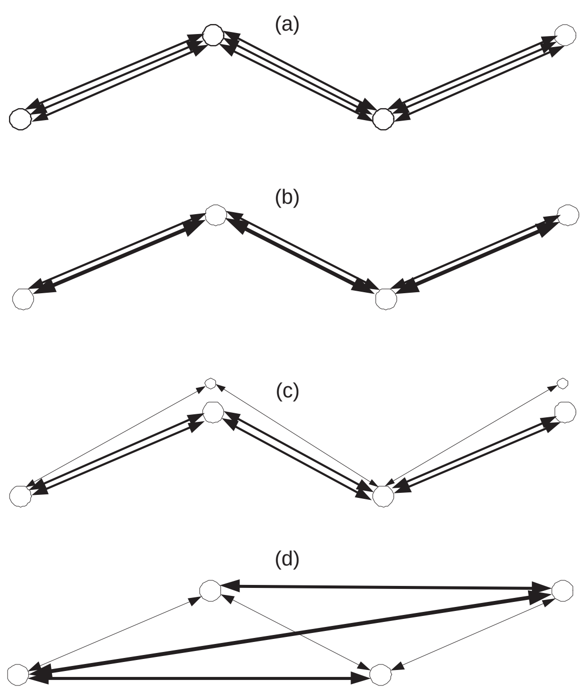

Figure 8: Business model examples. (a) 3x growth of current traffic. (b) Flight consolidation merges several flights into fewer flights using larger aircraft. (c) PTP-A shifts some flights to satellite airports with smaller aircraft. (d) PTP-B uses larger aircraft to shift to some non-stop flights.

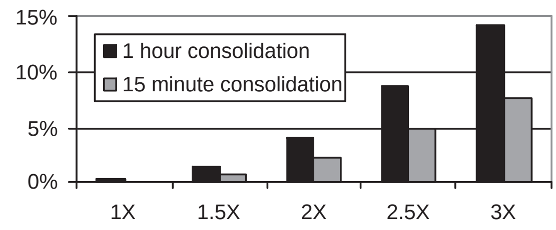

Figure 9: Percent flight reduction from the initial 1x, 1.5x, 2x, 2.5x, and 3x demand sets when flights are consolidated within 15 minutes and 1 hour of each other.

AvDemand models two aspects of PTP called PTP-A and PTP-B. PTP-A directs some traffic from overloaded hubs to local surrounding satellite airports for passengers where the hub area is the final destination. These smaller airports have shorter runways. Hence, a fleet mix shift to lighter weight regional jets is required. PTP-A makes use of a list of suitable airport substitutions within 40 miles of each major airport in order to divert direct flights to these satellite airports. Because these satellite airports handle smaller aircraft, many diverted PTP-A flights are converted to two or more smaller flights. Figure 10 shows the percent of initial hub flights removed and satellite flights added to each demand for a PTP-A conversion. As the demand increases, the percentage of flights that can be replaced with PTP-A flights goes down yet there is a fairly consistent net increase in the number of flights by 5% for the future demands.

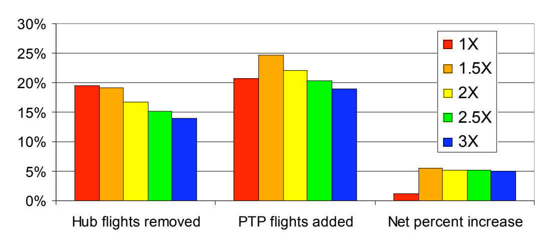

Figure 10: Percent flights removed and added and net increases from the initial 1x, 1.5x, 2x, 2.5x, and 3x demand sets for PTP-A.

PTP-B shifts connecting passengers to direct spoke-to-spoke flights skipping the hub entirely. More direct flights supports a fleet mix shift to more heavy long-haul aircraft. *AvDemand* identifies origin/destination pairs with enough passenger demand to divert passengers from connecting flights to direct flights. Passenger itinerary data are used to determine the ratio of connecting to direct passengers for each origin/destination pair. Then 75% of the connecting passengers are diverted to direct flights. Some connecting flights are removed and either new direct flights are added to the demand, or existing direct flights are upgraded to a larger aircraft.

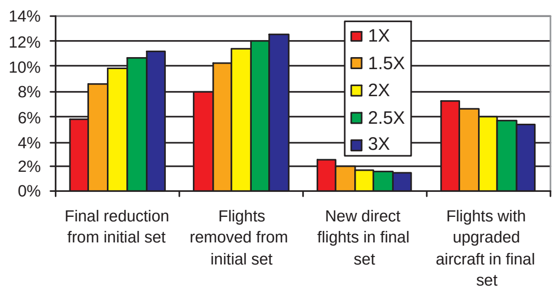

Figure 11: Percent flight removed, added, and upgraded from the initial 1x, 1.5x, 2x, 2.5x, and 3x demand sets for PTP-B.

Figure 11 shows the percentage of flights removed, upgraded, or added to create the final demand. As the demand increases from 1x to 3x, a greater percentage of flights are removed from the original demand. This is because the greater the demand, the greater the number of origin/destination pairs that may be targeted for PTP-B conversion. As the demand increases, a smaller number of flights need to be upgraded or added because larger markets enable larger aircraft to be used.

6.2 Future Demand Required Capacity Results

The increase in the number of facilities that require more capacity and the amount of required capacity is greater for the heterogeneously grown data sets where airports may have different growth rates according to TAF than for the homogeneously grown data sets where all airport have the same growth rate. Although both sets of data are grown to similar numbers of total flights, the fastest growing airports in the heterogeneously grown sets tend to be large airports that are already reaching the limits of their current capacity. Added emphasis on the growth of these airports further escalates future required capacity over current day. There are 16 airports which require more than three times the current capacity to meet 3x demand. Chicago O'Hare (KORD) and Atlanta International (KATL) required the greatest 3x total capacity at 636 and 628 operations per hour, respectively. The greatest percentage increase in required capacity comes from McCarren International (KLAS) in Las Vegas at 4.6 times it's current capacity. ZAU76 and ZAU75 are still the sectors with the greatest required 3x capacities of 79 and 84 flights, and ZAU60 has joined them in requiring over 4 times their current capacities.

When flights with the same origin and destination are consolidated within 15 minutes of one another, the top 10 airports' required 3x capacities are reduced by an average of 16%. Consolidating flights within 1 hour of one another reduces the required 3x capacity another 16%. Overall, flight consolidation is a third less effective for 2.5x than for 3x. At 2x and 1.5x, consolidation of flights within an hour makes little difference over consolidating flights within 15 minutes. Both reduce the required capacity by about 5%. The top enroute sectors' required capacity reductions react similarly. However, consolidating flights within an hour of each other is consistently twice as effective as consolidating only flights within 15 minutes of each other.

Airport required capacity improvements for PTP-A look similar to those of flight consolidation. However, instead of becoming more effective as the demand increases, PTP-A becomes less effective as the demand increases. The 1x demand case is able to take advantage of satellite airports that can handle larger aircraft before turning to smaller aircraft airports. As the demand increases the satellite airports themselves become saturated and a smaller percentage of hub flights can be offloaded from the hub airport. Required sector capacities actually increase for sector ZAU77 due to the 5% extra flights utilizing the same routes as the flights they replace. ZAU77 requires twice its current day capacity of 11 for 1x demand and almost 8 times it's current day capacity for 3x demand.

PTP-B is very effective at reducing required capacity. Only Newark Airport (KEWR) requires an increase in capacity of 1% for all five demand sets . Most other airports have lower required capacities. As the demand goes up, there are more opportunities to divert flights, and required capacities go down. ZAU75 and ZAU76 are the only two sectors requiring a capacity increase. Their respective capacity increase requirements of 13% and 10% for 1x demand reduce to 6% and 0% for 2.5x and 3x demand, respectively.

Figures 12 and 13 show the (a) total number of facilities (airport and sector, respectively) that require some increased capacity and (b) the average increase in capacity required for those facilities for each demand level and demand model discussed. Flight consolidation and PTP-A show similar limited benefits for lower demand levels and start to diverge at 2x. PTP-A does little for reducing required sector capacity and in fact, slightly increases required sector capacity. Flight consolidation performs better when the consolidation window increases from 15 minutes to an hour. PTP-B shows the most extreme improvement in required capacity from the TAF grown demand sets. It fact, PTP-B looks too good to be true. Required capacity estimation is just one aspect of demand analysis. A more detailed analysis of the PTP-B demand model and it's input parameters is needed to establish it's validity. An analysis of the fleet mix and equipment scheduling required to support this demand model is also needed to determine if it is economically viable.

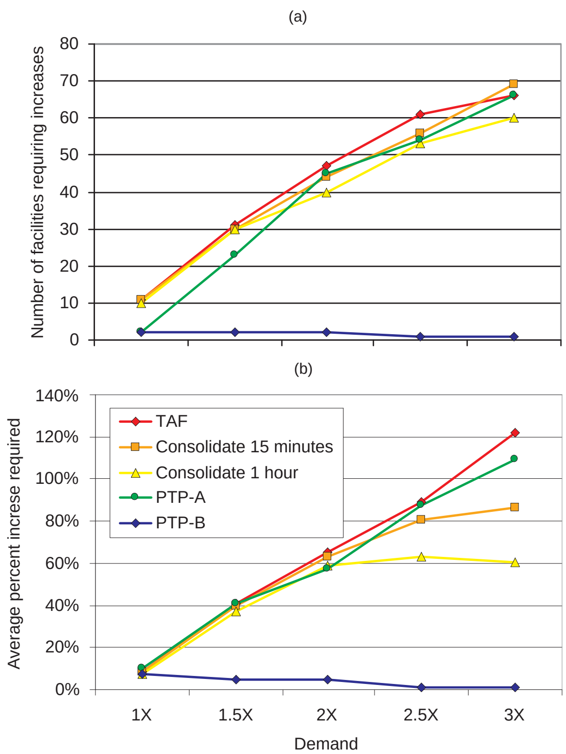

Figure 12: (a) Total number of airports requiring increased capacity over current day. (b) Average percent increase required across the airports shown in (a).

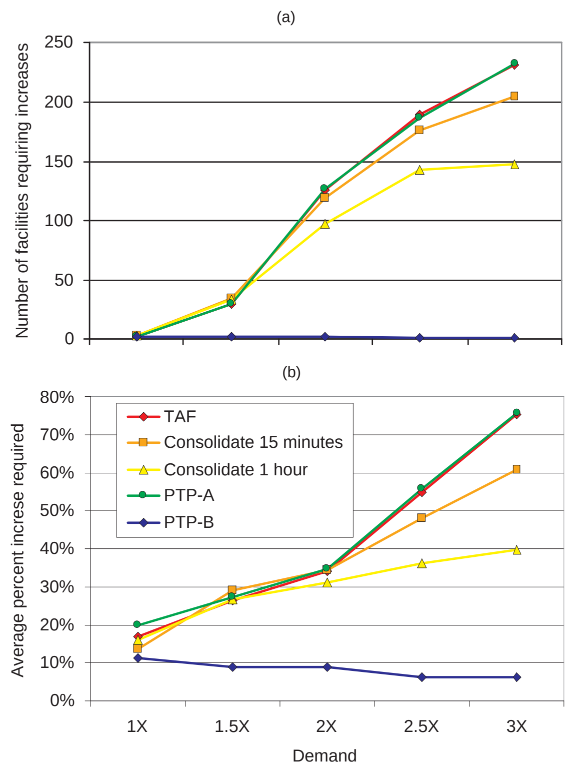

Figure 13: (a) Total number of sectors requiring increased capacity over current day. (b) Average percent increase required across the sectors shown in (a).

7 Conclusions

A process for determining the required capacities that satisfy a proposed demand level has been introduced here. The process was validated using the ACES simulation tool. Consistent delays were produced as demand increased. Several sample future demand models were compared using this process. The demand model showing the greatest improvement in required capacity from the TAF grown demand sets was PTP-B. This demand model shifted connecting passengers to direct spoke-to-spoke flights skipping the hub entirely. PTP-B successfully accommodates 3x more passengers while reducing the number of operations.

Required capacity values combined with other pertinent information can serve as design requirements for operational concept development. This process is one step in an iterative approach to arriving at operational concepts that support a given demand where both are physically, technologically and economically viable.

References

[1] Swenson, H. N., Barhydt, R., and Landis, M., Next Generation Air Transportation System (NGATS) Air Traffic Management Airspace Project. NASA Technical Report. 2006.

[2] Joint Planning and Development Office. Making the NextGen Vision a Reality: 2006 Progress Report to the Next Generation Air Transportation System Integration Plan. http://www.jpdo.aero. May 2007.

[3] VAMS Project Office NASA Ames Research Center. 2006. Virtual Airspace Modeling and Simulation System-Wide Concept Report.

[4] Meyn, L., Windhorst, R., Roth, K., Manikonda, V., Van Drei, D., et. al, Build 4 of the Airspace Concept Evaluation System, AIAA Paper AIAA-2006-6110, AIAA Modeling and Simulation Technologies Conference and Exhibit, Keystone, Colorado, Aug. 21-24, 2006.

[5] Huang, A., Schleicher, D., and Hunter, G. 2004. Future Flight Demand Generation Tool. In *AIAA 4th Aircraft Technology, Integration, and Operations (ATIO) Forum*, September, Chicago, Illinois, AIAA-2004-6400.

[6] Aircraft Situation Display To Industry: Functional Description and Interface Control Document. August 2000. Report no. ASDI-FD-001. Volpe Center Automation Applications Division, Cambridge, MA.

[7] Zelinski, S. 2005. Validating the Airspace Concept Evaluation System Using Real World Data. In *AIAA Mod-*

eling and Simulation Technologies Conference and Exhibit, August, San Francisco, California, AIAA 2005-6491.

[8] Welch, J. 2002. Assessing Capacity Needs Of Congested US Airports. In *AIAA Aircraft Technology, Integration, and Operations (ATIO) Forum*, October, Los Angeles, California, AIAA-2002-5862.

[9] Department Of Transportation and Federal Aviation Administration. Airport Capacity Benchmark Report 2004. http://www.faa.gov/events/benchmarks/. November 2006.

[10] Federal Aviation Administration Terminal Area Forecast (TAF). 2006. http://www.apo.data.faa.gov/main/taf.asp