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Flexibility Metrics and Their Application to Departure Queue Management

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***Abstract*— Flexibility for operators is a Key Performance Area (KPA) for Air Traffic Management (ATM). This paper presents a framework for development of operator flexibility metrics, with a first test-case application to management of departure queues. Through the use of virtual queuing (VQ) in departure operations, operators are provided with additional flexibility in prioritizing flights for departure. VQ allows flights whose delays are more expensive to skip ahead in the departure queue, while other flights with less expensive delays move back. Operators are expected to benefit significantly from the additional flexibility of VQ because the cost of departure queuing delays can vary widely among different flights due to differences in delay already accumulated, different number and types of passengers, and considerations such as crew time limits. Flexibility metrics derived from delay recovered with VQ relative to physical queuing (PQ) are compared under a variety of operational scenarios. These scenarios include: non-linear delay costs, variable costs by aircraft type, flexibility across all flights and flexibility constrained to intra-operator exchanges, as well as small physical queues at the departure runway end. Flexibility measures have been defined that are not dependent on the specifics of the operator business case (i.e., cost structure or decision criteria). This is accomplished through a comparative assessment of flexibility metrics derived from fast-time simulations assuming a variety of operator cost functions and optimization objectives. Results show that metrics can be normalized to allow operators, based upon their cost-structure and optimization objectives, to infer a value of improved flexibility. Results also indicate that constraining exchanges to intra-operator and including small physical queues at the departure runway end substantially reduce the flexibility performance of VQ, which implies that operational mechanisms to permit inter-operator exchanges and to reduce the size of small physical queues could substantially improve operator flexibility performance.**

***Keywords-** flexibility, key performance area; investment; performance measurement; benefits; metrics; departure queues, departure queue management; virtual queuing*

I. Introduction

For decades operators have argued for the provision of greater flexibility on the part of Air Traffic Management (ATM) [1]. The desire for flexibility benefits is re-iterated in the International Civil Aviation Organization (ICAO) Global ATM Operational Concept [2] as one of the performance expectations of the ATM system. Thus, flexibility is a Key Performance Area (KPA) for the ATM system. The RTCA Task Force 5 report [3] emphasizes flexibility as an area of benefits. Both Single European Sky ATM Research (SESAR) [4] and Next Generation Air Transportation System (NextGen) [5, 6] have qualitatively described flexibility shortfalls and benefits. With both NextGen and SESAR relying on capabilities requiring investment on the part of the user community, it is imperative that these qualitative benefit stories be developed into quantitative measures to help operators and the Air Navigation Service Provider (ANSP) develop their business cases.

Literature relevant to flexibility in ATM operations includes work by the U.S. Joint Planning and Development Office (JPDO) to develop NextGen performance metrics, which calls out flexibility as a "fundamental attribute" that remains a challenge for metrics development [7]. Other papers [8-13] describe trajectory flexibility metrics, with focus on strategically-planned flexible aircraft trajectories for mitigation of traffic complexity in the airspace. The literature also describes modeling of operator decision-making behavior in schedule disruptions with ground delay programs (GDPs), using simple non-linear costs as a function of delay time [14-16] to drive decision-making, an approach that is applied in this paper as well. Bayesian network analysis [17] suggests that actual operator decision-making behavior in schedule disruptions varies widely in ways that depend on operators' business models. Thus, individual operators ultimately need to analyze the flexibility benefits to their own operations.

Flexibility metrics measure the range of potentially useful options available to operators. Increased flexibility provides benefit to operators because they can use flexibility to make their own choices based on their own valuations of outcomes. For example, in today's U.S. ATM system, Collaborative Decision Making (CDM) increases operator flexibility (relative to no CDM) by allowing each operator to exchange the positions of its flights in a GDP for an arrival airport with reduced capacity because of bad weather. With the increased flexibility provided by CDM, an operator can reduce arrival delays for higher-priority flights at the expense of relatively low-priority flights, and in this way reduce the impact of the schedule disruption to the operator. CDM is a successful and widely-used flexibility-increasing feature of the U.S. ATM system. The CDM principles have been applied to departure queue management on the surface to provide operators

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flexibility to reorder flights within the departure sequence to reflect their business needs [18].

Flexibility interacts with another KPA, predictability. Over a long period of time, predictability can be measured with long-term statistics of how well the originally intended schedules of flights were met in actual operations. In the example of a GDP, bad weather at the arrival airport disrupts schedules, thereby contributing negatively to predictability, and CDM is a way for operators to mitigate disruption costs. Thus, increased flexibility may be used to limit the costs of unpredictability.

For the purpose of developing flexibility metrics for new flexibility-increasing systems, the focus is on quantitative measures indicating how much a system increases the set of potentially useful options available to operators. Useful options are those that are expected to reduce costs, at least for some operators at some times. Whether or not the options are actually exercised by a specific operator in a particular operational scenario depends on the priorities of the operator, which depend on a variety of factors including the operator's business model. Because priorities and valuations of different alternatives are operator-dependent, the use and benefit of increased flexibility may differ widely among different operators.

A fundamental question regarding flexibility metrics is that of whether it is possible to define operator-valuation-independent measures of flexibility that can be applied by both the ANSP and operators to facilitate common understanding regarding performance of flexibility-enhancing systems. Valuation-independent flexibility metrics would be somewhat analogous to value-independent maximum service-rate metrics, like the number of operations that can be handled in a given time period, for the capacity KPA.

II. FLEXIBILITY METRICS FOR DEPARTURE QUEUE MANAGEMENT

Today, at congested U.S. airports, long queues of departing aircraft develop when departure demand exceeds the departure capacity of a runway or the surrounding airspace. Once aircraft are in the queue, at many airports operators have little opportunity to exchange positions among the flights, so the queuing discipline with such physical queuing (PQ) can be characterized as first-come first-served (FCFS). Each operator is motivated to enter each of its flights into the queue as soon as possible, lest another operator take its place.

Virtual queuing (VQ) is defined generally to encompass any number of processes or mechanisms that are an alternative to PQ, in which flights that become ready to depart are considered for the departure sequence without (or before) having to leave the vicinity of the gate to enter a physical queue at the runway. A software system or other collaborative process, similar to those defined in [18] is involved in managing the flights in the "virtual queue" and their planned order of departure or entry into a small physical queue. Benefits of VQ relative to PQ in terms of reduced fuel burn already have been studied [19], and are not addressed here. This paper focuses on the additional flexibility provided by VQ, which can be used by operators to move flights with higher delay costs ahead in the queue (at the expense of flights with lower delay costs), thus allowing operators to reduce overall delay costs.

There are multiple reasons why the cost of delays to some flights may be more than other flights. For example, if flight A already has accumulated significant delay prior to departure and flight B has not, then the cost of additional departure queuing delay to flight A may be higher, because flight A's departure queuing delays propagate to subsequent legs of the airframe's itinerary, whereas most of flight B's departure queuing delays can be absorbed in the margins provided by operators in the aircraft's itinerary schedule. Other factors influencing relative cost of delays among different flights include the number and types of passengers on the flights, direct operating costs while on the ground, and crew time limits. Also, operators might want to move a flight ahead in the departure queue if, for example, the airframe is needed at another airport more quickly than would be possible with PQ. And, with confidence that flexibility can be used on a daily basis to reduce queuing delays for select flights, operators may be able to re-schedule these flights to reduce their block times.

In this paper, fast-time simulation is used to investigate and develop metrics to quantify the improvement in flexibility provided by VQ relative to PQ. Many operational details of departure management are omitted deliberately, to maintain focus on the aspects pertinent to development of flexibility metrics. The analysis is not intended to be a benefits assessment of VQ.

Operational constraints typically are expected to reduce the flexibility performance of VQ relative to PQ. One such constraint considered in this paper is the restriction of exchanges among flights to intra-operator-only exchanges, rather than permitting exchanges between different operators' flights. Another operational constraint considered in this paper is the provision of small physical queues at the runway end to ensure full utilization of runway departure capacity. Small physical queues reduce flexibility because flights in these queues cannot be exchanged with other flights. In this paper, fast-time simulation is used to develop flexibility metrics for relatively-simple cases without these operational constraints, and then the operational constraints are added to the simulation to show their effect on the flexibility metrics.

A. Fast-time simulation of departure delay recovery

To begin the analysis, PQ and VQ cases were simulated in fast-time in a set of multi-hour operational scenarios, based on departure demand data taken from actual multi-hour PQ scenarios at Newark Liberty International Airport (EWR) departure runway 04L during year 2009. The demand data includes actual pushback time plus scheduled pushback time for each flight, as obtained from the Aviation System Performance Metrics (ASPM) database. It is assumed that actual pushback time is the earliest the flight could have pushed back, in accord with the fact that operators are motivated to push back as soon as possible. (It is recognized that traffic flow management delays can constrain pushback and departure times for some flights, and the simulation does not account for these constraints. However, in the specific scenarios described in this paper, the number of such flights was small, comprising less than 2% of the total number of flights.) Thus, in corresponding simulated PQ and VQ cases, the PQ actual pushback time corresponds to the VQ pushback-ready time. The order of flights in the virtual queue without exchanges is assumed to be identical to the order of departures in the PQ case. Taxi times were assumed to be identical in corresponding PQ and VQ cases. VQ flights are assumed to leave the gate and taxi with perfect timing to meet departure capacity rate limits. Since perfect timing is unlikely in practice, the effect on flexibility performance of introducing small physical queues to compensate for uncertainty is considered. In actual operations, the order of departures may affect the maximum departure rate of the runway. However, as a first approximation, corresponding VQ and PQ cases are assumed to have identical, constant runway maximum departure rates, so total delay across all flights is identical in the simulated VQ and PQ cases.

"Recovered delay" for a flight is defined as the reduction in delay in the VQ case relative to the PQ case. A flight's recovered delay can be positive, negative or zero. With VQ, it is expected that operators will have positive recovered delay for flights where delay cost is relatively high and negative recovered delay for flights where delay cost is relatively low, during times when the virtual queue is not empty. Some flights with high delay cost may have zero recovered delay because the virtual queue happens to be empty when they become ready to push back.

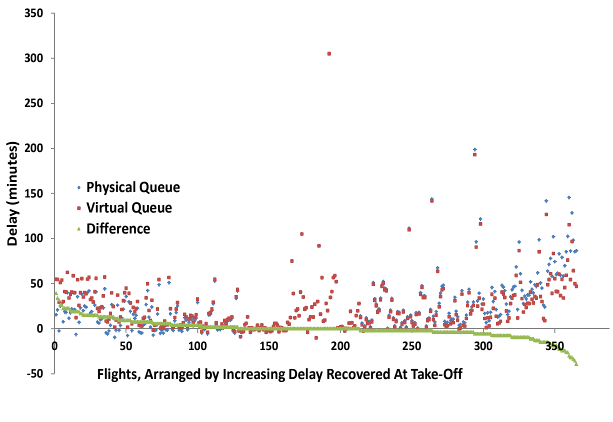

Figure 1. Simulated Delay Recovery with Virtual Queuing

The pattern of flight exchanges depends upon the operator's valuation of the departure times, which may depend upon the delay already accumulated by the flight at pushback-ready time as well as various other factors such as number and types of passengers and considerations related to crew time limits. An operator's flight-exchange behavior in a VQ scenario is modeled by assuming the operator attempts to minimize total cost of delays. For the purpose of developing flexibility metrics, very rough non-linear operator costs as a function of departure delay are adequate, and a quadratic cost function originally developed for arrival delays [20] is used in this paper. Other non-linear cost function estimates from the literature [21] could be used as well.

Fig. 1 depicts the results of PQ and VQ simulations based on data from 17 December 2009 for the 04L departure runway at EWR. The 365 flights in the scenario are arranged along the horizontal axis in order of increasing recovered delay. Also shown is the difference between VQ and PQ delay for each flight. All 365 flights in this scenario were allowed to exchange with each other in the VQ case, even though the flights are those of different operators. There are no small physical queues in the VQ case. Departure delay cost is assumed to be quadratic as a function of total departure delay [20], and no other factors (including aircraft size) influence delay cost. Here, total departure delay is defined as the excess time at the gate beyond schedule (i.e., pushback delay) plus time in queue. Operators are assumed to re-order departures by sending the flight at every departure time with highest marginal delay cost (i.e., with the largest first derivative of cost as a function of delay), which for a cost function quadratic in delay is just the most-delayed flight. A departure capacity of 0.533 per minute resulted in a simulated maximum departure queue size of 21, which is well within maximum departure queue lengths estimated for major U.S. airports with departure congestion issues [22, 23].

Flights on the right-hand side of Fig. 1 are those with positive recovered delay and those on the left-hand side have negative recovered delay. Flights on the right-hand side of Fig. 1 have, on average, larger PQ delays than flights on the left-hand side, so with cost a quadratic function of delay, their delays are more expensive per unit time. Thus, with VQ, delay is reduced for flights with more expensive delay and increased for flights with less expensive delay, and overall cost is reduced.

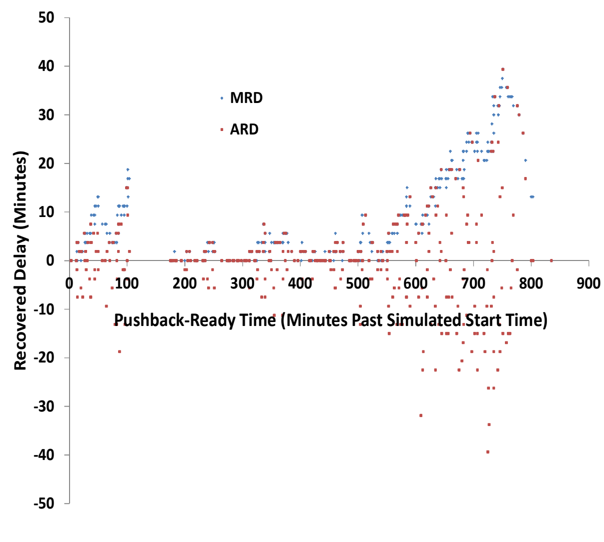

Figure 2. Maximum Recoverable Delay (MRD) and Actual Recovered Delay (ARD) for Each Flight in a Scenario

B. *Flexibility metrics at the individual-flight and scenario levels*

Recovered delay in a specific scenario expresses the increase in scope of the potentially useful outcome space to operators from VQ, but recovered delay is operator valuation-dependent. A valuation-independent metric for an individual flight in a specific scenario is maximum recoverable delay (MRD), defined as the delay a flight could recover if the flight is moved to the head of the virtual queue and departs as soon as possible. MRD is not necessarily actual recovered delay (ARD); rather it is an upper limit to a flight's ARD. For a constant departure rate, MRD is the quotient of the queue length at the time the flight first becomes able to depart and the departure rate. Fig. 2 shows MRD and ARD for each flight in the 17 December 2009 EWR 04L departure scenario described above, plotted as a function of the pushback-ready time for the flights. At the peak queue length in this scenario, MRD is about 39 minutes, and the flight able to depart at this time actually recovered the full MRD. However, since total delay recovered across all flights is zero in the simulation, if some flights get positive ARD, then other flights must get negative ARD. Thus, while MRD is valuation-independent, it is limited in its utility for expressing flexibility, because MRD fails to account for delay-recovery interactions among flights in a scenario.

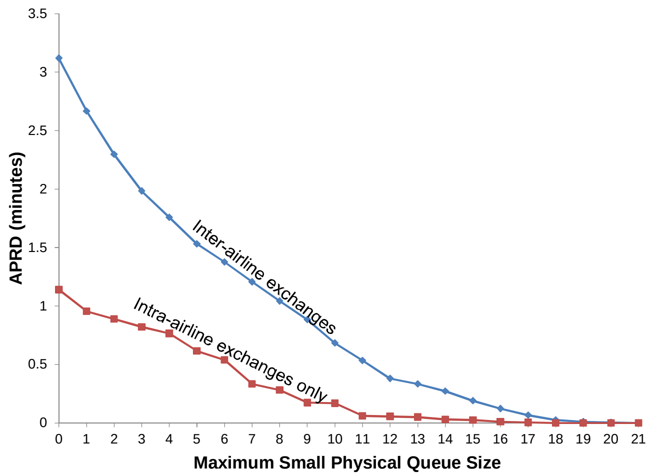

Figure 3. APRD Dependence on Flight-Exchange Assumptions and Maximum Small Physical Queue Size

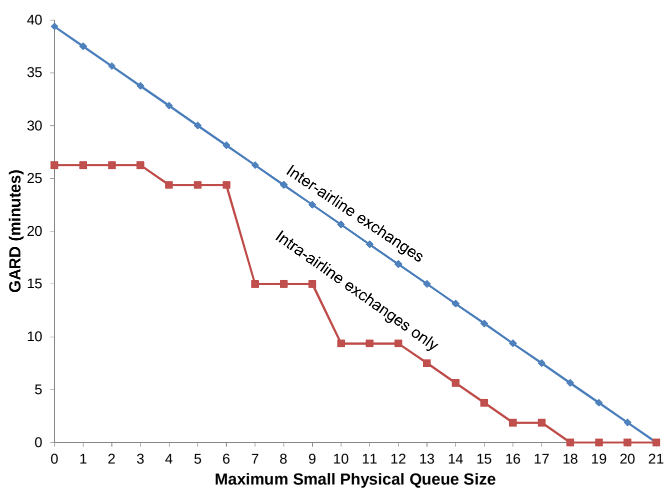

Figure 4. GARD Dependence on Flight-Exchange Assumptions and Maximum Small Physical Queue Size

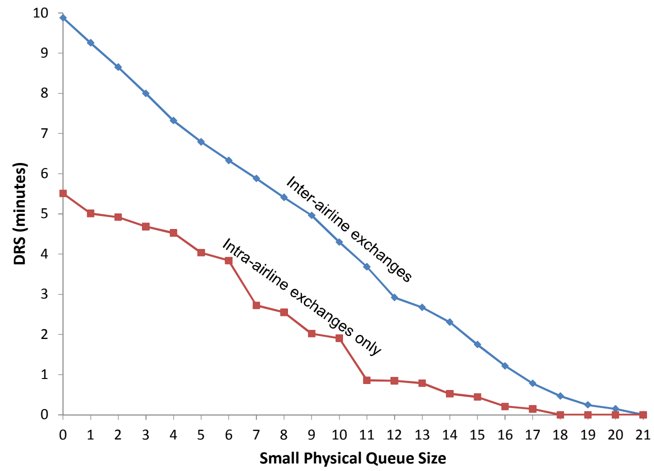

Figure 5. DRS Dependence on Flight-Exchange Assumptions and Maximum Small Physical Queue Size

The existence of interactions between recovered delays among flights implies that scenario-level flexibility metrics need to be considered. To begin, three scenario-level metrics are defined, all of which are valuation-dependent and are computed by comparing PQ and VQ simulation results for a particular scenario day with an assumed flight valuation. Average positive recovered delay (APRD) is the average delay recovered per flight in the scenario, where negative delays do not contribute to the measure. Greatest actual recovered delay (GARD) is the largest value of ARD among all the flights in the scenario. Delay recovery spread (DRS) is defined as the standard deviation of both positive and negative PQ-versus-VQ delay differences across all flights in the scenario, as suggested by the difference curve in Fig. 1. The value of DRS is affected by delay recovery of each flight in the scenario, but weights large differences more than smaller differences. Together, APRD, GARD and DRS quantify key aspects of the distribution of recovered delay among flights in a departure scenario, assuming a particular flight valuation scheme.

Figs. 3, 4 and 5 plot APRD, GARD and DRS for the December 17, 2009 EWR 04L scenario as a function of assumed maximum small physical queue (sPQ) size, for both intra- and inter-operator exchange assumptions, with each metric computed across all flights in the scenario. Flight valuation is assumed to be based on marginal delay cost, as in the results depicted in Figs. 1 and 2. Operator codes in ASPM were used to distinguish different operators in the intra-operator exchange simulation, ignoring potential business relationships that could permit exchanges between flights with different codes. A maximum sPQ size of zero in Figs. 3, 4 and 5 corresponds to no small physical queues. Restricting exchanges to intra-operator-only reduces APRD by more than a factor of two, with somewhat smaller reductions in DRS and even less change in GARD. There is a sharp drop-off in APRD as a function of maximum sPQ size, and a linear decrease in GARD for inter-operator exchanges. GARD shows more of a step-function behavior for intra-operator-only exchanges, reflecting the disappearance of exchange opportunities at specific levels of sPQ size. DRS behavior is intermediate between APRD and GARD, as expected.

C. Valuation-independent, scenario-level flexibility metrics

Among all possible flight valuations for a particular departure scenario, there must be a valuation-independent upper limit to the values of APRD, GARD and DRS. The sheer number of possible departure re-orderings (which exceeds 10^{120} in the 17 December 2009 EWR 04L scenario) makes exhaustive search for the upper limit a practical impossibility. Instead, the observation is made that the last-come first-served (LCFS) queuing discipline maximizes recovered delay at each departure time relative to FCFS, hence LCFS maximizes all three metrics, APRD, GARD and DRS. The upper bounds of the metrics can be computed easily by simulating delay recovery in a VQ scenario with LCFS queuing discipline. These upper bounds for flexibility metrics are somewhat analogous to maximum service rate (operations per unit time) metrics for the capacity KPA in the sense that maximum service rate is an upper limit to operations per unit time that can be handled in a given scenario. Also, flexibility is multi-dimensional, as suggested by the three different flexibility metrics, just as capacity is multi-dimensional. However, the upper bounds for flexibility metrics are unlike maximum service rates for capacity metrics in that they are very unlikely to ever be approached in actual operations involving significant departure queues.

The "consumption" of a flexibility metric (APRD, GARD, or DRS) for a given flight valuation scheme in a scenario is defined as the fraction of the LCFS upper bound actually used. Thus, flexibility consumption is analogous to "throughput" for capacity. A flexibility metric's "stability" indicates how little the consumption of the metric varies across different scenarios, for a fixed valuation scheme. A stable, valuation-independent metric is most likely to be useful to operators and the ANSP, since the metric can be computed across a set of scenarios under PQ and VQ conditions, and each operator, knowing its own valuation scheme, can readily make rough estimates of valuation-dependent flexibility metrics for its own operations.

D. Metric stability analysis

To assess flexibility metric stability, VQ simulations were run across the following set of operator valuation schemes:

In the "delay only" valuation scheme, the operator always sends the most-delayed flight in queue at every departure time.

In the "weighted delay" valuation scheme, delays are multiplied by a weight proportional to the number of seats on the aircraft. The operator always sends the flight in queue with the largest weighted delay at every departure time.

The "weighted delay (shuffled)" valuation scheme is the same as weighted delay, except that, prior to simulation, weights among all flights in the scenario are randomly shuffled. During simulation, weights are kept fixed. Shuffling the weights prior to running the scenario is for sensitivity analysis of how the values of flexibility metrics vary with the specific characteristics of the departure demand. Multiple simulations are run, each with a different weight shuffle. (In the results reported below, 100 simulations were run.)

In the "weighted cost" valuation scheme, the operator always sends the flight with the largest marginal cost at the departure time. Cost as a function of delay time is assumed to be quadratic [19], multiplied by a factor proportional to number of passenger seats on the aircraft.

The "weighted cost (shuffled)" valuation scheme is the same as weighted cost, except that, prior to simulation, weights among all flights in the scenario are randomly shuffled. During simulation, weights are kept fixed. Shuffling the weights prior to running the scenario is for sensitivity analysis with respect to how the values of flexibility metrics vary with the specific characteristics of the departure demand. Multiple simulations are run, each with a different weight shuffle. (In the results reported below, 100 simulations were run.)

In the "random valuation" scheme, prior to simulation, weights between 0 and 1 are assigned at random to each flight in the scenario. During simulation, weights are kept fixed. Random valuation thus assigns different weights to flights that are completely independent of delay. This valuation scheme provides a limiting case where factors unrelated to accumulated departure delay drive the prioritization. Multiple simulations are run, each with a different random assignment of weights. (In the results reported below, 100 simulations were run.)

In the "upper bound" valuation scheme, prior to simulation, weights are assigned to flights that correspond to the reverse order of departures in the FCFS scenario. This valuation scheme implements the LCFS queuing discipline, which yields an upper bound to the flexibility metrics.

Each of the valuations described above were run with four different EWR 04L runway scenario days (November 6, November 12, November 17, December 17, all 2009) and for several different departure capacities. For the three November scenario days, a calibrated departure capacity was determined by finding the simulated departure capacity that resulted in the same maximum departure queue size as the actual day [22]. Other capacities were chosen that were lower and higher than each of the calibrated departure capacities.

Fig. 6 plots APRD, GARD and DRS consumption for the December 17 scenario day described previously. The plot on the left includes the operational constraints of intra-operator-only exchanges and small physical queues (maximum size 5) in the VQ cases, and the plot on the right excludes these operational limitations. In both plots, the flexibility metrics are assessed across all flights in the scenario. Upper bounds to APRD and DRS are much less when operational constraints are introduced, but flexibility consumption is fairly stable, except that there is some spreading with operational constraints. Fig. 7 shows the same type of plot for the November 6, 2009 EWR 04L scenario, also at a departure capacity of 0.533 departures per minute. In this scenario, the main demand pulse is concentrated into a shorter time than in the December 17 scenario, so queues are larger and the upper bounds of APRD, GARD and DRS are larger. In this, as well as other relatively high-demand scenarios that were simulated, consumption stability is observed across intra-operator and

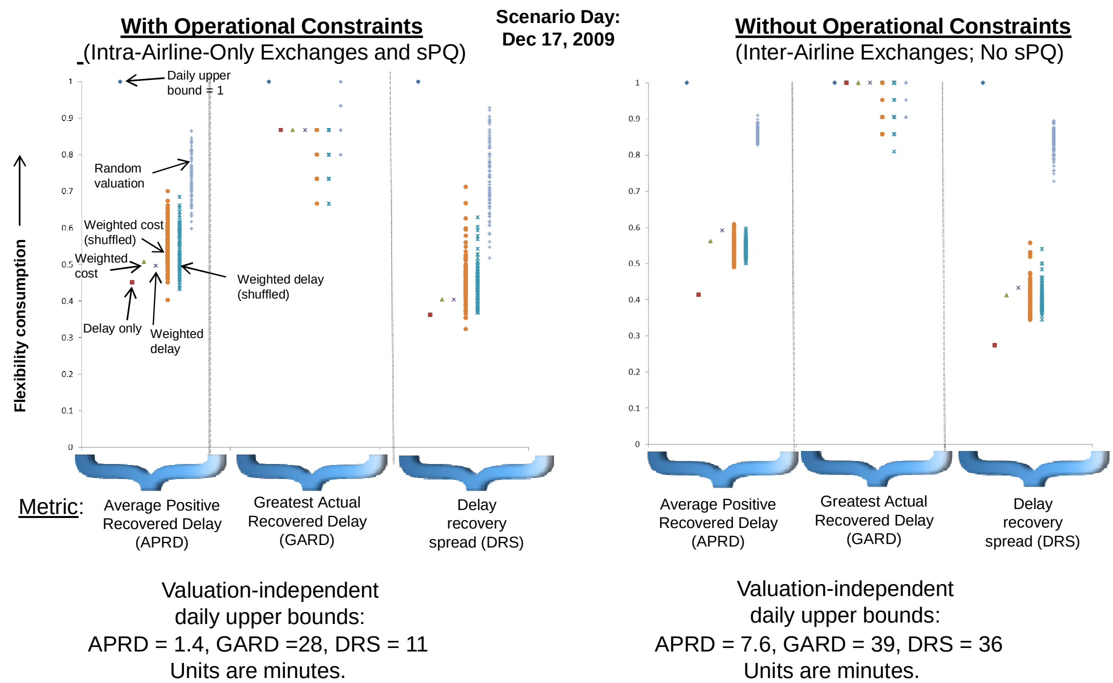

Figure 6. Flexibility Consumption for December 17 2009 Scenario Day

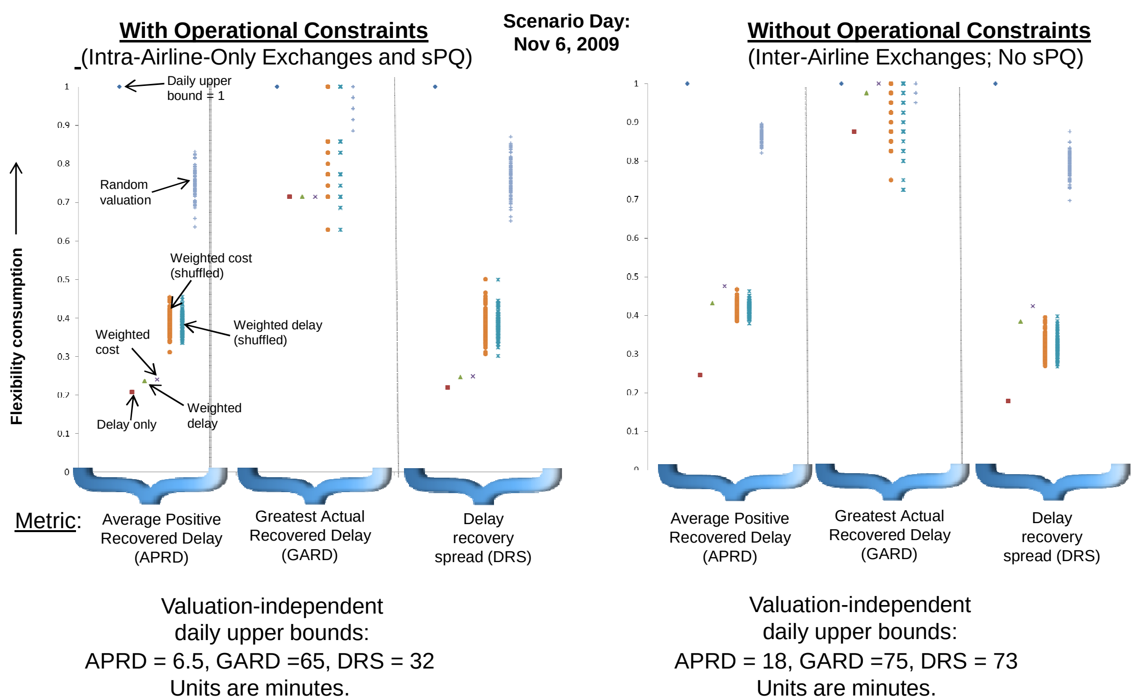

Figure 7. Flexibility Consumption for November 6, 2009 Scenario Day

inter-operator exchange scenarios. In lower-demand scenarios, stability breaks down because fewer flights contribute to the metrics, and therefore the metrics show more spreading across shuffles. Comparing Figs.6 and 7, flexibility consumption is fairly stable across different scenario days, despite large differences in the upper bounds.

III. CONCLUSION

This paper identifies APRD, GARD and DRS as scenario-level, valuation-dependent flexibility metrics that indicate the average and distribution in delay recovery among flights in departure scenarios with VQ. Upper bounds to these metrics, computed by simulating a LCFS queuing discipline, are valuation-independent flexibility metrics that potentially could be used by ANSPs and operators to facilitate a common understanding of flexibility performance of VQ relative to PQ in specific departure scenarios. Introduction of two realistic operational constraints, namely intra-operator-only flight exchanges and small physical queues, significantly reduces delay recovery, with a steep fall-off in APRD at low values of maximum small physical queue size. Thus, measures to facilitate inter-operator exchanges and reduce physical queuing could substantially improve operator flexibility performance. Flexibility consumption, for a given flight valuation scheme, is fairly stable when flexibility metrics have relatively high values (hence the potential operator benefit of flexibility is relatively high). In scenarios where flexibility metrics have relatively low values (hence flexibility is less important), stability breaks down.

Further work is needed to bring the flexibility metrics for departure operations presented in this paper into practical application by ANSPs and operators for use in development of pre-implementation business cases and post-implementation verification of flexibility performance improvements from VQ. In addition, the flexibility concepts presented here need to be extended to other flexibility-increasing ATM improvements, such as those to increase routing flexibility.

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