ACC Capacity, Cost and Overload Avoidance Trade-Offs

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***Abstract* - This report analyses the interrelationships between ACC cost, capacity, and sector overload avoidance. Among our findings is that the cost of capacity provision grows exponentially, that sector occupancy rate-regulated randomness forces ACCs to give up about half of their capacity, and that high sector occupancy distribution is well-behaved and allows to manage ACC sector overload avoidance.**

Keywords – ACC; Cost; Capacity; Safety; Sector; Occupancy; Big Data

I. Introduction

The Single European Sky (SES) performance scheme regulates Air Navigation Service Providers (ANSP) to reach target values in key performance areas safety, capacity, cost-efficiency and environmental impact; this is monitored by the European Commission and its SES Performance Review Body (PRB). Independently, the Performance Review Commission (PRC) of Eurocontrol commissions and publishes yearly factual ANSP performance measurements, the Air-Traffic Management (ATM) Cost-Effectiveness (ACE) benchmarking report [1].

In the recent years it has become obvious that the four SES performance areas are not independent from each other, and that e.g. Functional Airspace Block (FAB) performance plans, often geared to contain ANSP cost, risk to fail to provide capacity matching demand.

In this context the PRU has started a while ago to perform in the ACE report some deeper analysis and benchmarking of ANSP staff and sector productivity on the basis of the high-level operational performance data provided by the ANSPs. However, said analysis is clearly limited by the highly aggregated nature of the data provided.

In this report we are investigating into the relationships between Area Control Centre (ACC) cost, capacity, and Air Traffic Controller (ATCO) sector overload avoidance, using a rich data set from the Maastricht Upper Area Control Centre (MUAC) of Eurocontrol that encompasses, minute-by-minute, the exact configuration pattern of open sectors and the location of all flights within those sectors.

Among our findings is that ACC cost-effectiveness highly depends on keeping all open sectors well occupied, that the cost of capacity provision seems to grow exponentially with the amount of open sectors, that sector occupancy exploits rate-regulated randomness, that ACCs must give up about half of their available sector capacity to situations of sector under-fill, and that sector occupancy distribution is rather well-behaved and allows to (mandate to) manage, monitor and benchmark ACC sector overload avoidance.

II. Current ACC Benchmarking

ANSP achievement on capacity versus cost is analysed by the Performance Review Commission (PRC) and the Performance Review Unit (PRU) of Eurocontrol in application of a performance review framework based on ICAO recommendations, the ACE framework.

In the ACE framework (Fig. 1), PRC and PRU introduce the concept of ANSP economic cost-effectiveness, which takes into account as input ATM/CNS provision costs plus the costs of induced ATM delay, and as output the safe flight hours production service of an ANSP, with ANSP productivity being a key performance driver, with the goal to capture the trade-offs between ACC capacity and costs.

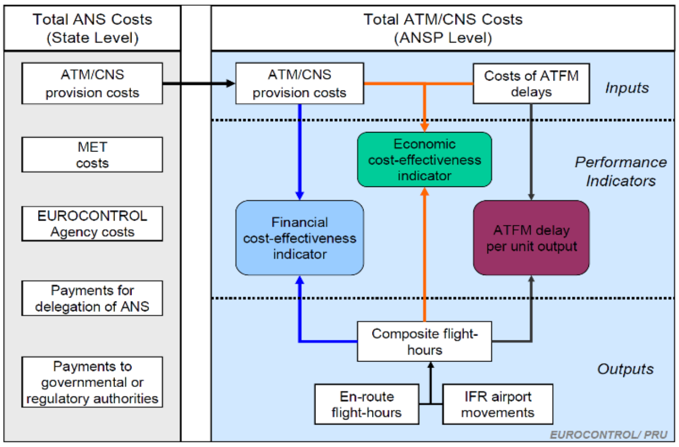


Figure 1. ACE performance review framework

This framework provides significant merit. By costing ATM delay, ANSPs are provided with clear guidelines, on the input side, on the cost benefit of ANSP delay containment investments for the airspace users funding the services, making IATA award the PRC a Special Recognition for its achievements in 2006.

In further breaking down the cost-effectiveness performance indicator, the ACE framework then introduces the notion of ATCO duty hours (number of hours licensed ATCOs spend working in the OPS room, e.g. controlling traffic or supervising operations) and ACC open sector hours, and then, derived from it, ATCO-hour productivity, ACC sector productivity and ACC staffing per sector (Fig. 2).

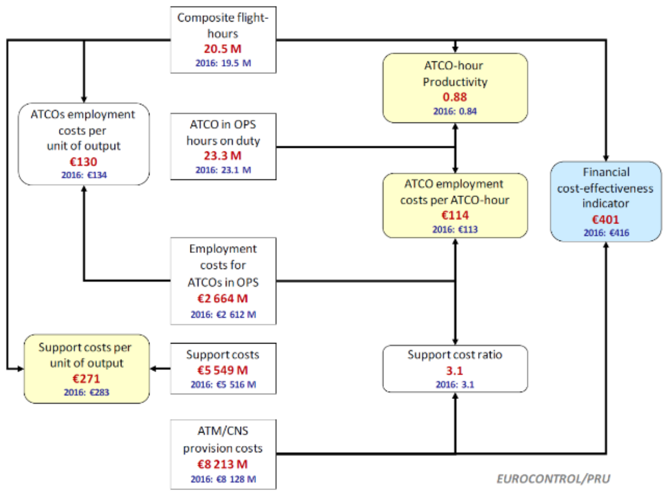


Figure 2. ACE performance framework details

In its 2017 ACE report the PRU concludes for the output side of the framework:

"The greater ATCO-hour productivity in Maastricht is mainly the result of significantly higher sector productivity (more than eight aircraft on average simultaneously present in a sector). It is noteworthy that MUAC sector productivity can be two times the productivity achieved by ACCs with a similar staffing per sector in Cluster 2.

Other factors as yet unidentified (and not measured) such as the impact of different operational concepts and processes, the operational flexibility, could also affect ATCO productivity performance. There may also be cultural and managerial differences. These elements would deserve further analysis in order to provide further insight on the differences in ATCO-productivity and identify best practice."

In this report we de-aggregate MUAC open sector hours and the respective flight hours by the sector opening patterns employed, and then further de-aggregate into quasi-ad-hoc sector occupancy distributions, thereby gaining insight into ACC sector capacity utilisation, sector opening cost-benefit, sector capacity evolution and the management of probability of sector occupancy overshoot. We shall not look at delay, though.

It should be noted that the underlying data for the sector occupancy and occupancy distribution analysis, namely the flown flight trajectories and the actual sector opening patterns timetables, are both available to the Network Manager, the former (in slightly worse quality) from its ETFMS system and the latter as published by ACCs to NM via a respective B2B interface. This would allow the PRU to take the analysis further and extend it to other ACCs than MUAC.

The aim of this report is therefore to suggest specific extensions to the ACE framework and to the SES safety regime. Elaborating the often non-linear interdependencies between cost, capacity, and safety in terms of excessive sector occupancy avoidance will allow the ATM community to improve the maintenance of the delicate balance between safe capacity provision and cost reduction under increasing traffic in the future. Moreover, we would hope that such an extended framework could also help a more detailed cost benefit assessment of ATM investments.

III. Sector Occupancy

The excellent cost-effectiveness of MUAC is achieved by outstanding sector productivity. In the 2017 ACE benchmarking report, MUAC again stands out at an average of 8.4 flights per open sector, which "can be two times the productivity achieved by ACCs with a similar staffing per sector and similar operational characteristics". What are the factors that make MUAC achieve such high sector productivity?

To better understand those factors we analyse data collected from the MUAC Flight Data Processing System on the operational sector openings and all individual flights occupying those operational sectors since 2011.

MUAC is divided into three sector groups (BRU, DEC, HAN) that are configured rather independently. BRU and HAN each feature four basic airspace areas, and DEC three, all in (usually) two layers. This makes eight respectively six basic airspace blocks per sector group that can be combined in certain predefined patterns to operational sectors, which are then manned by two ATCOs each in the OPS room. For instance, in the BRU sector group the pattern B4.5 joins in the western part the basic airspace blocks Koksy High and Nicky High to one ATCO team, and Koksy Low plus Nicky Low to a second team (sandwich configuration), and in the eastern part allocates Olno High and Olno Low to a third ATCO team and Lux High plus Lux Low to a fourth (columnar configuration).

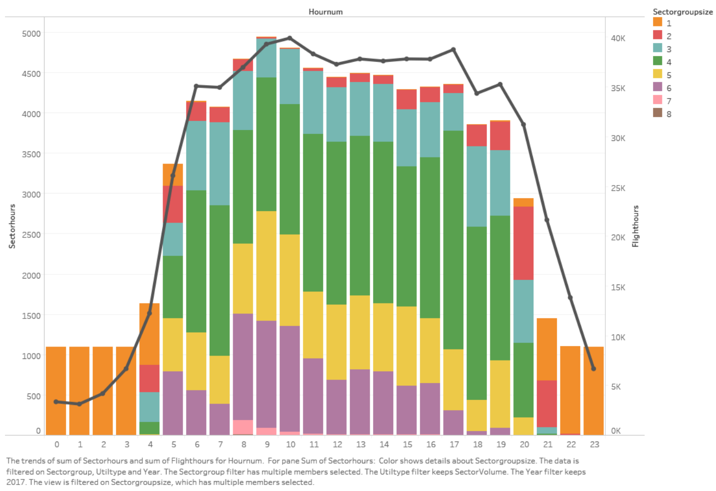


Figure 3. ACC ATCO sector team deployment versus flight demand

Sectorisation patterns are pre-planned and rostered according to predicted traffic and then adapted on the fly to actual traffic demand in the course of the day at a pace of about 30 minutes, resulting in the sector openings as depicted in Fig. 3 which manage to track the amount of traffic rather well, except during the night where more capacity than needed is offered (due to the three sector groups being each allocated to one dedicated ATCO team for ATCO licensing reasons).

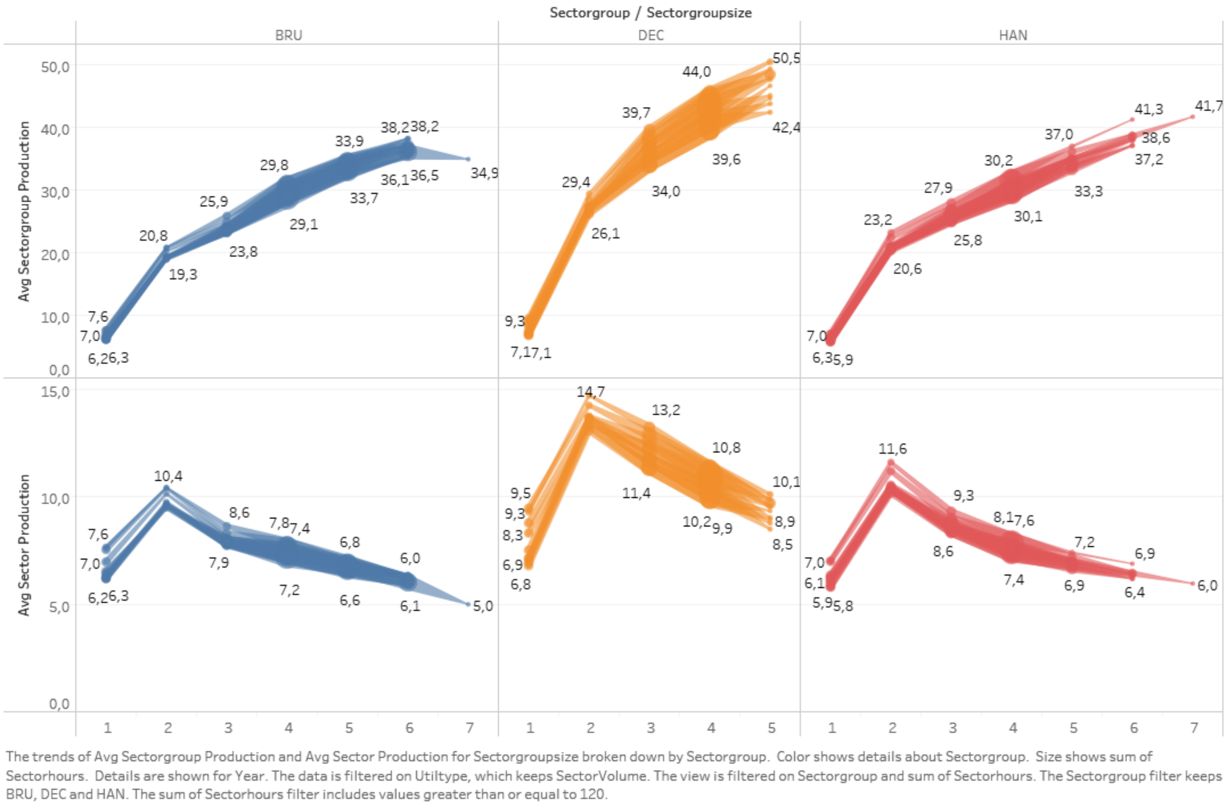


Figure 4. Capacity gained by more sector teams

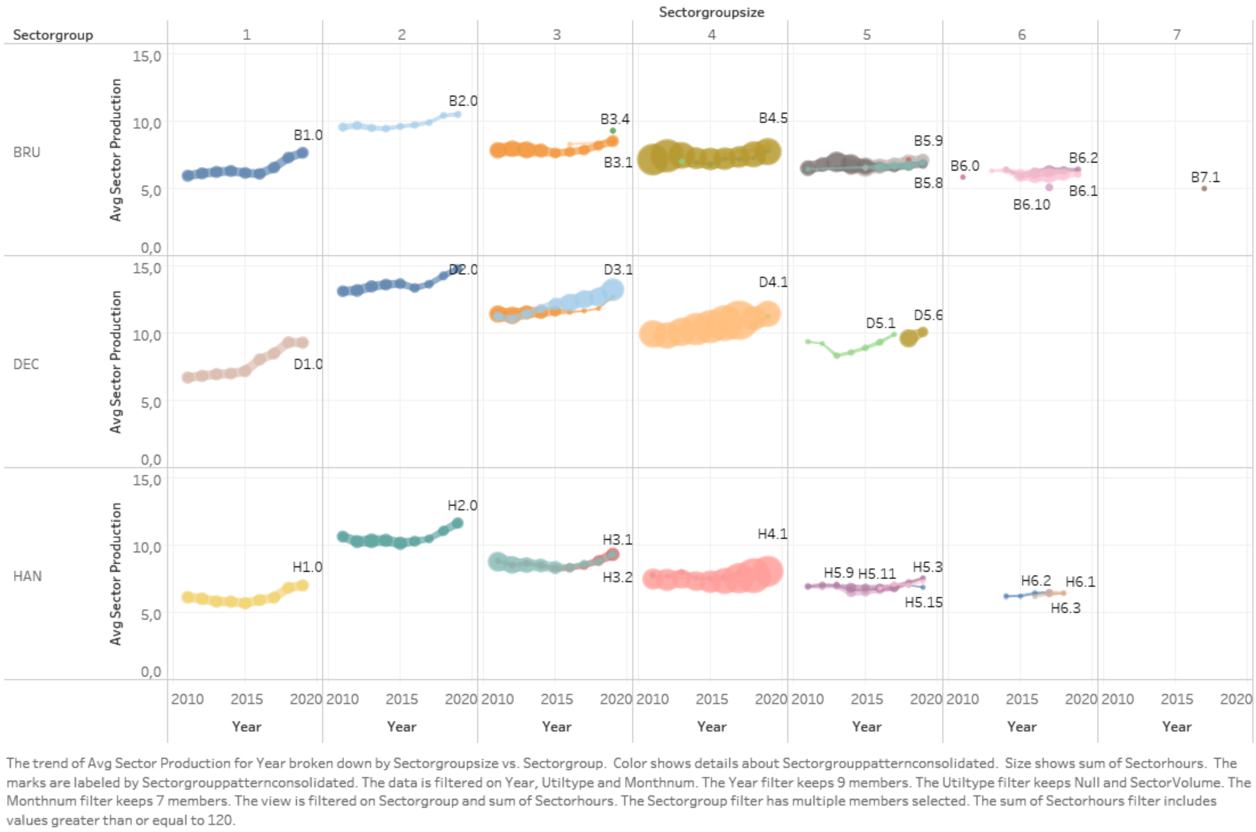


Figure 5. Sector productivity evolution since 2011

TABLE I.. SECTOR PRODUCTION INCREASE FROM 2017 TO 2019 (JAN TO JUL)

Year		Sectorgroupsize 1	2	3	4	5	6	7	Grand Total
2017	Sectorhours	4,921	2,469	6,532	17,135	7,431	6,686	326	45,500
	Avg Sector Production	7,1	11,6	10,3	9,0	6,9	6,1	5,4	8,3
	Difference in Avg Sector Production ..								
2019	Sectorhours	4,996	3,287	9,065	16,750	5,986	1,305		41,390
	Avg Sector Production	8,0	12,5	10,9	8,9	7,8	6,3		9,3
	Difference in Avg Sector Production ..	0,9	0,9	0,6	0,0	0,9	0,2	-5,4	1,0

Sectorhours, Avg Sector Production and Difference in Avg Sector Production from the Previous along Table (Down) broken down by Sectorgroupsize vs. Year. The data is filtered on Utiltype, Sectorgroup BRU/DEC/HAN and Monthnum. The Utiltype filter keeps SectorVolume. The Sectorgroup BRU/DEC/HAN filter keeps True. The Monthnum filter keeps 7 members. The view is filtered on Year, Sectorgroupsize and sum of Sectorhours. The Year filter keeps 2017 and 2019. The Sectorgroupsize filter keeps 8 members. The sum of Sectorhours filter includes values greater than or equal to 120.

Increasing the “size” of a sector group, i.e. deploying more operational ATCO teams each handling lesser amounts of basic airspace blocks, increases cost due to the additional ATCO duty hours required, but would also increase capacity. For more detail refer to e.g. [2]. The two charts of Fig. 4 and Fig. 5 show how sector group size correlates in MUAC with average yearly sector/sector group occupancy, and how sector production of different configuration patterns has evolved since 2011.

There are a couple of noteworthy observations that can be made here:

1. MUAC achieves highest average sector occupancies by high sector capacities and, in addition, by managing sector group configurations and sizes such that at every size all constituent sectors are well filled with traffic.

2. The bulk of the sector hours is spent with the sector groups split and operated by four ATCO teams, in DEC also a lot by three, in BRU by five. This correlates with the previous hourly chart.

3. Average sector production is highest when the sector group airspace is split into two operational sectors. Splitting the sector group further into smaller volumes gains sector group occupancy, but reduces average sector productivity more and more, thereby also reducing the achieved sector group gain.

4. DEC sector group with its relatively bigger airspace is more productive than BRU and HAN, with BRU being most constrained.

5. In particular in recent years, average sector productivities of given configurations have increased somewhat slightly, in BRU and HAN more prominently for smaller sector group sizes.

6. In stark contrast to the introduction of the D5.6 configuration (with a third layer in the western part) which pushed its average DEC sector group occupancy beyond 50 in 2019, the temporary introduction of the B7.1 configuration in BRU (with a third layer in the eastern part) in 2017 had such low average sector production that the overall average sector group occupancy decreased versus configurations with six operational sectors.

The last point is of particular interest as it indicates that in densest airspace the traditional means of increasing ATC capacity by distributing work to more ATCO teams are beginning to reach limits inherent to the current operational concepts. Delays generated in such dense airspaces at moments of highest demand are thus not principally caused anymore by lack of staffing, but would rather require even higher per-sector/per-ATCO capacities through further ATC automation.

As to the effect of such envisaged sector capacity increase Table I is worth noting. How comes that between 2017 and 2019 the average sector occupancy increase within all sector group sizes is below 1.0, and even slightly negative for bread-and-butter sector group size 4, and still the overall MUAC average sector occupancy increases from 8.3 to a marvellous 9.3?

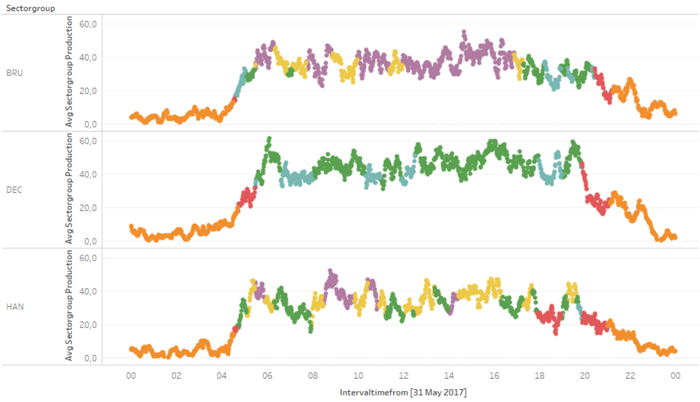
It turns out that the slight increase in particular in size 2 and 3 sector capacities allows those configurations to be used much more often versus the size 4, 5 or even 6 configurations with their worse efficiency, thereby significantly amplifying the cost reduction effect of pure sector capacity increase, an aspect that should be duly considered when estimating ACC benefits (or drawbacks) of future ATM improvements.

IV. SECTOR OCCUPANCY DISTRIBUTION

Now, why is the MUAC average sector occupancy “only” around 9 (recalling that this is easily twice that of other comparable ACCs), whereas the declared sector capacity in terms of Sustainable and Peak Occupancy Monitoring values as used for tactical capacity management (i.e. making the decisions about sector group configuration patterns) are nearly twice as high? Is ATC wasting half of its capacity (refer also [3])?

Answering this question reveals a crucial relationship between ATC cost and capacity on the one hand and ATC safety in terms of sector occupancy overshoot protection on the other hand.

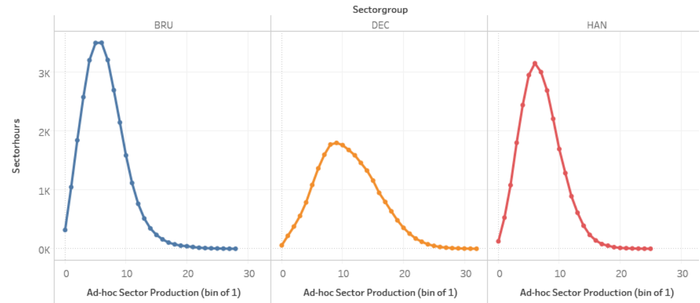
To gain further insight into the matter we shall now investigate in more detail the ad-hoc sector occupancy occurrences and their distribution. The method we chose here defines ad-hoc sector production in a simplified manner as the average sector occupancy (in terms of sum of flight time divided by sector time) within every one-minute respectively five-minute time interval on the clock. Fig. 6 depicts the ad-hoc one-minute sector group production timeline of an arbitrary day in 2017. We observe that sector group occupancy fluctuates a lot, with waves of traffic followed by troughs.



The plot of Avg Sectorgroup Production for Intervaltimefrom broken down by Sectorgroup. Color shows details about Sectorgroupsize. The data is filtered on Sectorgroup BRU/DEC/HAN, Utiltype and DAY (MDY). The Sectorgroup BRU/DEC/HAN filter keeps True. The Utiltype filter keeps SectorVolume. The DAY (MDY) filter keeps May 31, 2017.

Figure 6. Sector group occupancies of an arbitrary day

This results in the distributions of sector (not sector group) occupancies for the complete 2017 given in Fig. 7.



The trend of sum of Sectorhours for Ad-hoc Sector Production (bin of 1) broken down by Sectorgroup. Color shows details about Sectorgroup. The data is filtered on Sectorgroup BRU/DEC/HAN, Year and Utiltype. The Sectorgroup BRU/DEC/HAN filter keeps True. The Year filter keeps 2017. The Utiltype filter keeps SectorVolume. The view is filtered on sum of Sectorhours, which includes values greater than or equal to 1.

Figure 7. Distribution of sector occupancies

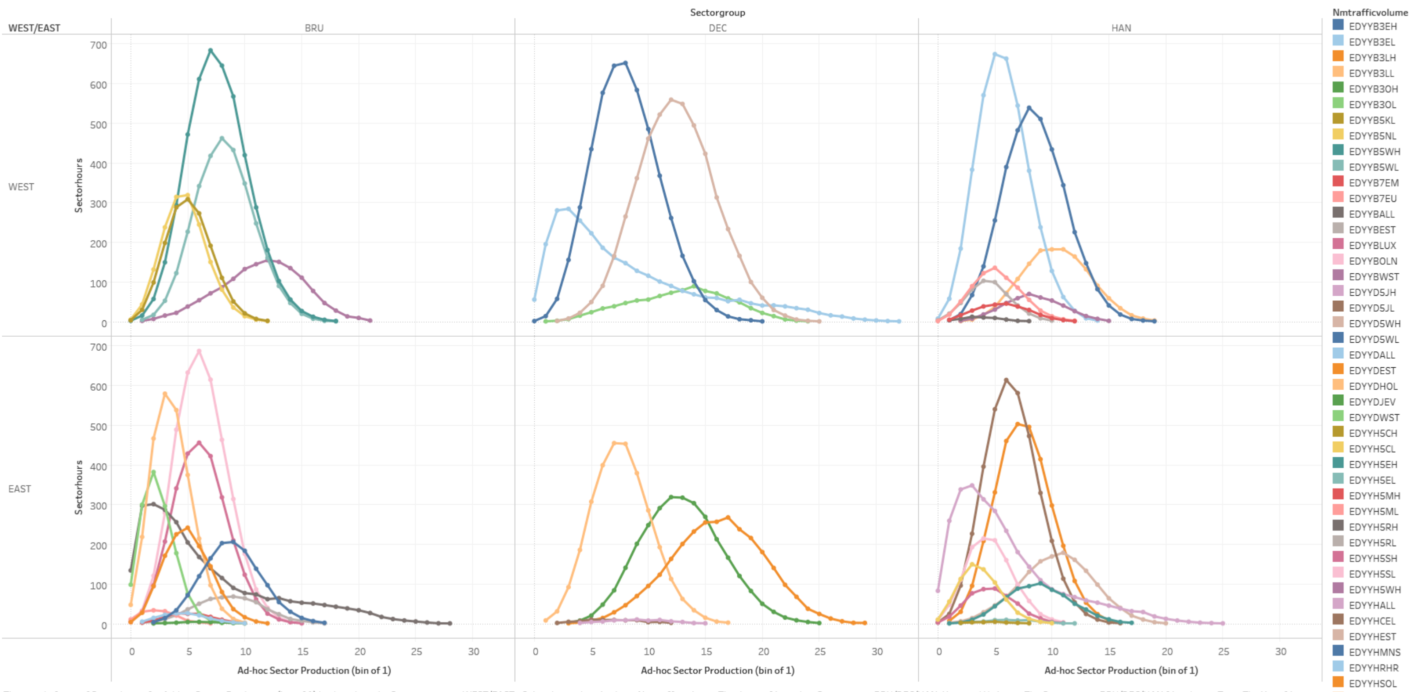
We observe a trace of high sector occupancies (here cut off at one sector hour) extending beyond the highest peak occupancy monitoring values.

However, those distributions are still overlays of individual sector distributions that each have their own defined capacities. In Figure 8 we therefore look at individual operational sector volumes. Now the picture clears somewhat and we can observe the following:

1. Most of the sector occupancy distributions resemble Poisson distributions rather closely [4, 5]. A Poisson distribution indicates rate-regulated randomness within a network of queues feeding queues, as which the ATM airport-and-sector network can be modelled (refer e.g. [6, 7, 8]). This means, however, that despite a controlled entry rate, factual appearance of flights into en-route sector volumes seems rather random, without even considering prediction uncertainty. And indeed, the amount of take-off time noise infused into the departing flows at airports together with climb fluctuations and ad-hoc upstream ATCO interventions lead to a situation in the downstream network sectors that fits the term rate-regulated randomness well.

2. The three night operational sector distributions deviate significantly from the otherwise very regular pictures. This is as expected, given that at night one cannot maintain a rate of traffic matching the night sector capacity.

3. Compared to a perfect Poisson distribution some of the curves lean to the left, with the steep rise to the peak followed by a slower fall, whereas a few others lean to the right, with the rise to the peak followed by a slightly steeper fall. Obviously, the latter is preferential from a cost-effectiveness perspective. These deviations should warrant further analysis



The trend of sum of Sectorhours for Ad-hoc Sector Production (bin of 1) broken down by Sectorgroup vs. WEST/EAST. Color shows details about Nmtrafficvolume. The data is filtered on Sectorgroup BRU/DEC/HAN, Year and Utiltype. The Sectorgroup BRU/DEC/HAN filter keeps True. The Year filter keeps 2017. The Utiltype filter keeps SectorVolume. The view is filtered on sum of Sectorhours, which includes values greater than or equal to 1.0.

Figure 8. Distribution of sector occupancies per operational sector volume

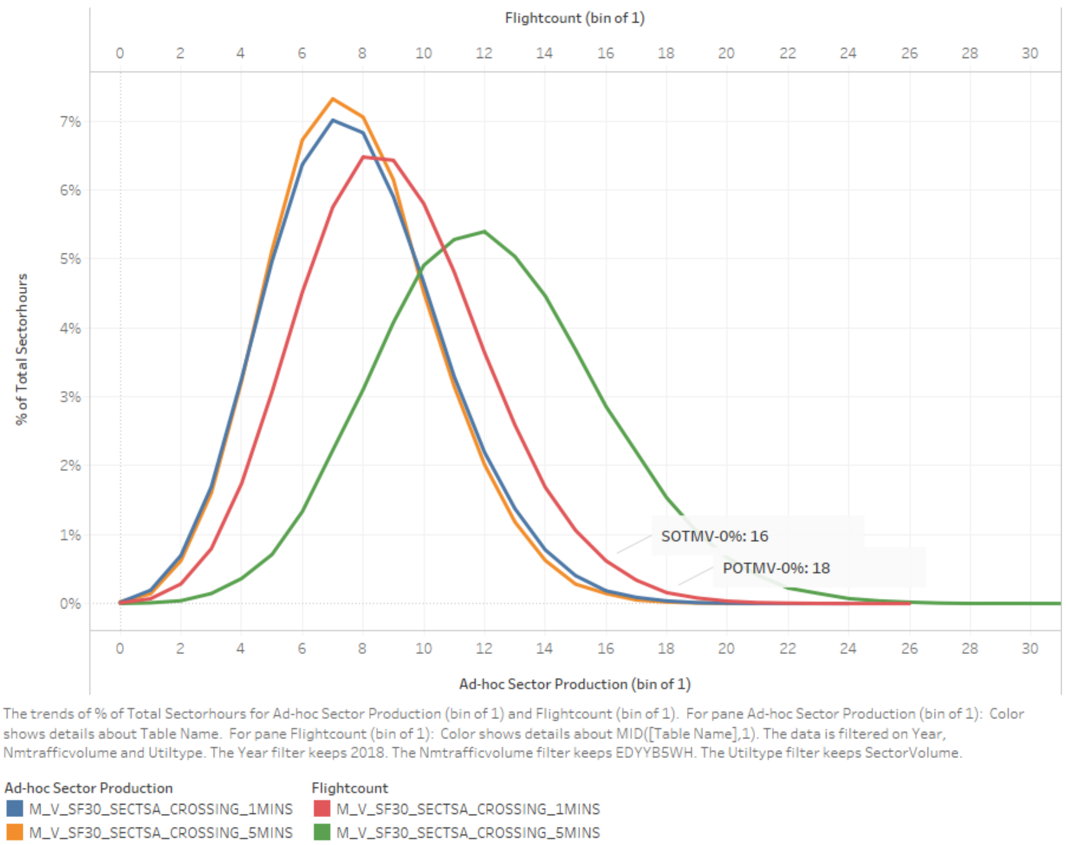


Figure 9. Differences between distributions based on sector production and flight count metrics in a given sector volume (EDYYB5WH)

V. Sector Occupancy Management

High-performance ACCs like MUAC manage optimal sector productivity by basing their pre-tactical and tactical Air-Traffic Flow and Capacity Management (ATFCM) processes on predicted occupancies, comparing those to sustainable and peak occupancy traffic monitoring values (SOTMV, POTVM) defined upfront per sector. In the following we briefly look into the relationship between those monitoring values and the actual occupancies occurring in the sector.

Please not though a) that OTMV values are designed for application in tactical ATFCM, i.e. in the time horizon until about one hour before traffic arrival where late tactical adjustments to the opening and closing of sectors are determined, and therefore encode buffers to address the significant amount of (in particular take-off) uncertainty still involved in this time frame, and b) that OTMV values relate to a slightly different definition of occupancy, namely the counting of distinct flights within one-minute intervals.

Fig. 9 shows, for a given operational sector, the distributions of one-minute-interval truncated sector production, five-minute-interval truncated sector production, one-minute-interval distinct flight count, and five-minute-interval distinct flight counts. Fig. 10 shows on a logarithmic scale the cumulative sector time percentage still exceeding the given sector production.

We observe:

1. The basic shape of all four distributions is very similar. Averaging the flight time over five-minute intervals versus over one-minute intervals reduces the occurrence of higher values only slightly. As one would expect, the one-minute distinct flight count distribution is offset from the truncated sector production distribution by 1-2 flights to the right, and the five-minute district flight count somewhat further.

2. The actual one-minute flight counts in the sector exceed the SOTMV for 1.3% of all sector time, and exceed the POTMV for 0.3% of all sector time; actual one-minute truncated sector production exceeds the SOTMV for 0.30% of all sector time and the POTMV for 0.04% of all sector time; and actual five-minute truncated sector production exceeds the SOTMV for 0.17% and the POTMV for 0.02% of all sector time.

3. In order to protect sectors from the overshooting occupancies on the right side of the distribution curve, and given the random flight occurrence behaviour, the peak of the curve respectively the average occupancy must not be bigger than about half of the safely manageable maximum sector occupancy. This implies that an ACC distributing flight responsibility to ATCO teams on the basis of airspace volume occupation must, for safety reasons, unavoidably give up half of its available sector capacity to systemic situations of sector under-fill.

4. Occurrences of high-occupancy tails to the right with their increased risk of sector overload are rather well-behaved also beyond POTMV and predictably approach rarity.

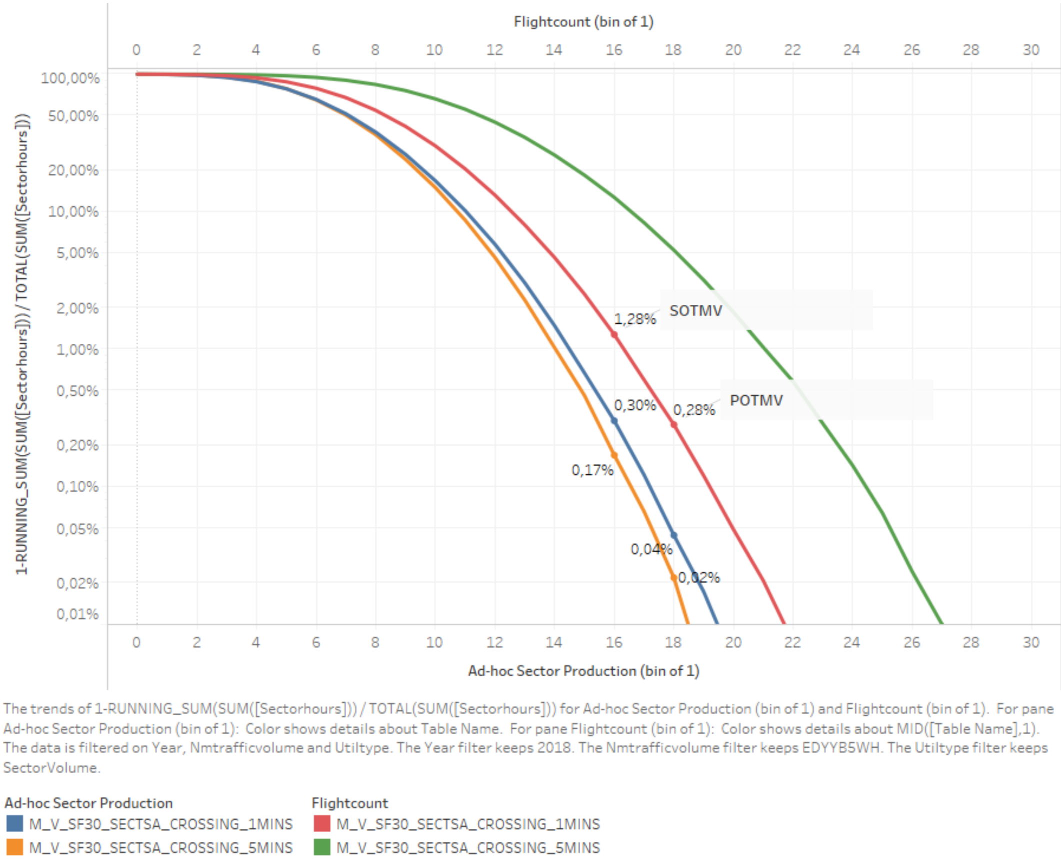


Figure 10. High value tail of cumulative occupancies

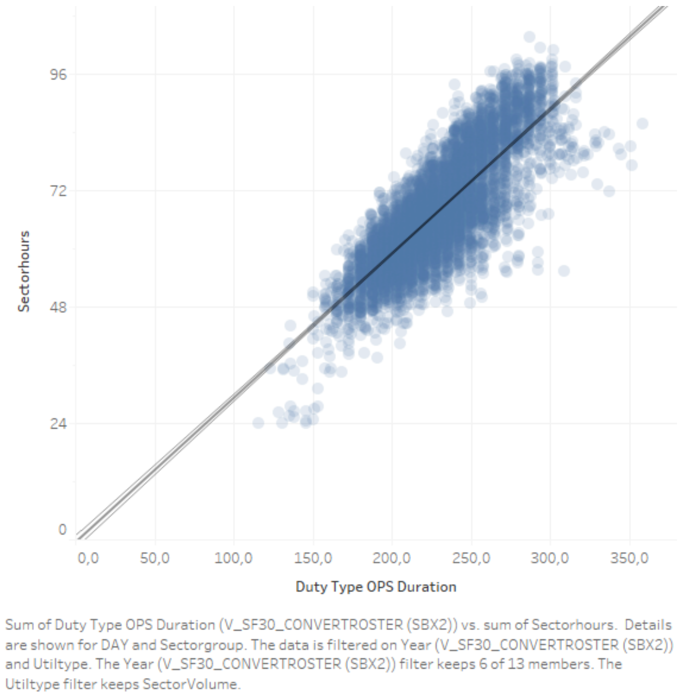


Figure 11. Daily sector hours per ATCO duty hours

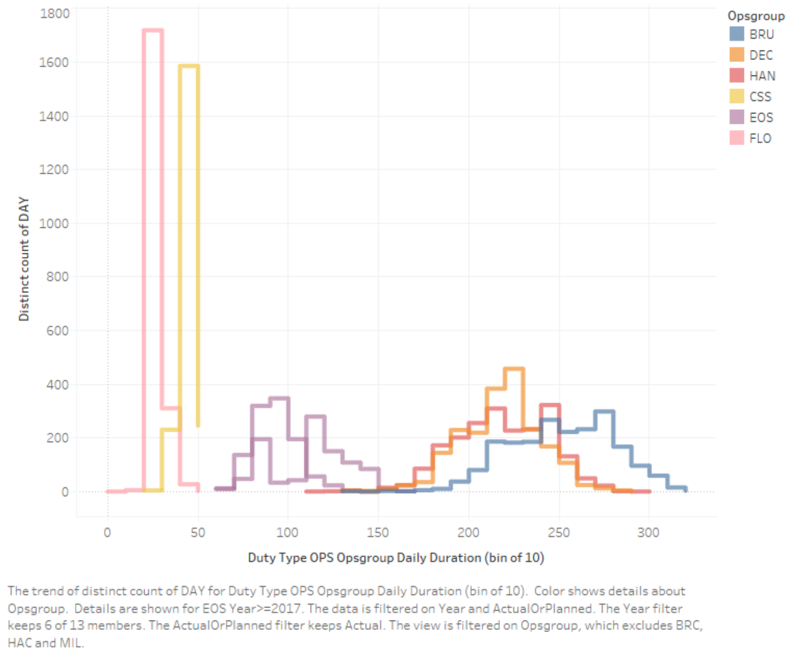


Figure 12. Distribution of daily ATCO duty hours

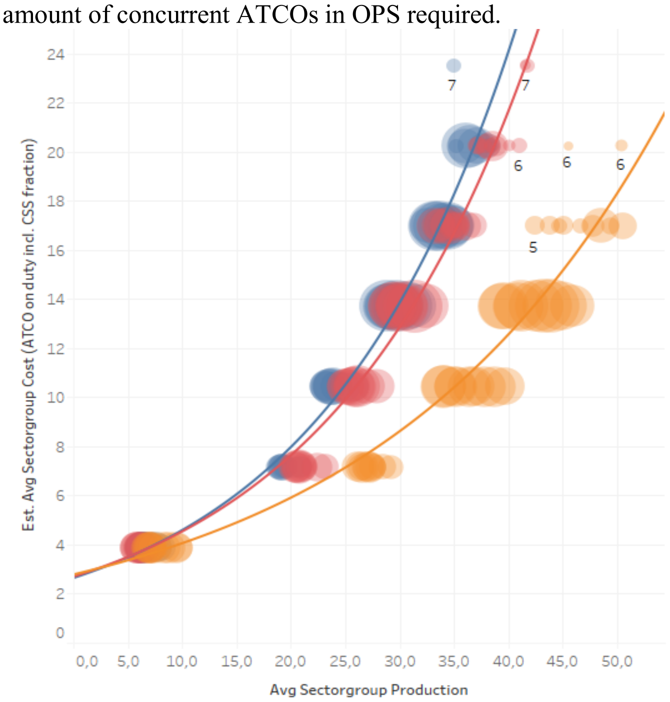
VI. Sector Cost

So far, we have implicitly hinted at the sector hours being a proxy for ANSP ATCO employment cost. However, the actual ATCO employment cost factor are the ATCO shifts. Fig. 11 shows the relationship between the daily amount of sector ATCO shift hours spent versus the open sector hours effected in the sector group that day. Refer also [9].

Fig. 12 shows the distribution of the daily operational duties of the different OPS groups (with BRU, DEC, HAN and CSS counting as ATCO in OPS duties in the sense of the ACE report).

The dot cloud of daily sector hours versus ATCO sector duty hours indicates a somewhat dynamic linear need of the average 3.3 ATCOs per open sector in all three sector groups. On top of this come a good 40 daily ATCO center supervision (CSS) duty hours shared by the three sector groups, or about 2 ATCOs on average, that do not correlate with the daily sector hours.

Fig. 13 summarises those findings and depicts for the three sector groups, using the indicative figures derived above, the seemingly exponential relationship between achievable average sector group occupancy and cost, the latter in terms of average amount of concurrent ATCOs in OPS required.



Avg Sectorgroup Production vs. Est. Avg Sectorgroup Cost (ATCO on duty incl. CSS fraction). Color shows details about Sectorgroup. Size shows sum of Sectorhours. The marks are labeled by Sectorgroupsize. Details are shown for Year. The data is filtered on Utiltype, which keeps SectorVolume. The view is filtered on sum of Sectorhours and Sectorgroup. The sum of Sectorhours filter includes values greater than or equal to 24. The Sectorgroup filter has multiple members selected.

Figure 13. Cost of capacity

The analysis shows quite stable relationship parameters over the last nine years of MUAC operations for HAN and in particular BRU, with DEC still increasing occupancy for the same amount of ATCOs over time. We suspect traffic density as limiting and thereby cost driving factor; this would deserve some further research.

It should be noted that the analysis addresses only the ATCO in OPS duties as in [1], and excludes the office duties performed by ATCOs outside the OPS room (buffering traffic uncertainty somewhat), non-ATCO OPS duties, and all other support cost e.g. for ACC infrastructure; those rather static costs one would assume to scale over the years with total amount of flight hours served and/or the maximum ACC system capacity.

VII. Conclusions and Recommendations

1. Analysis of observed ACC sector opening patterns and sector flight occupancies provides the regulator detailed insight into ACC management of trade-offs between capacity, cost and occupancy overshoot avoidance.

2. The overall capacity gained by an ACC through opening of more sectors diminishes in dense airspace, with the cost of the capacity growing exponentially.

3. Small absolute sector capacity gains by system improvements gains much bigger overall ACC productivity increase due to often allowing to open less sectors than before under the same traffic.

4. In densest airspace, delays generated at moments of highest demand cannot be attributed anymore to lack of staffing, but would rather require even higher per-sector/per-ATCO capacities, e.g. through further ATC automation. This holds true even if some participating sectors causing delay are not fully collapsed into their constituents, as de-collapsing them might well reduce overall capacity.

5. To avoid excessive rates of sector occupancy overshoot, ACCs must limit their average sector occupancies to about half of their sector capacities.

6. Sector occupancy overshoot probabilities are well-behaved and deserve monitoring in the context of ACC safety processes related to the definition of sector capacities and ATFCM monitoring values.

7. It should be considered to amend the SES performance scheme to mandate such safety processes from ACCs.

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