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4D-Trajectory Air Traffic Management: Are There ‘Killer Apps’? – Part 2

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The USA and Europe are developing plans – NextGen and SESAR – to transform the processes of Air Traffic Management (ATM). These will improve safety and efficiency, and match predicted increases in air transportation demand. They use advanced networking technology updated with information from satellite navigation and digital non-voice communication. The strategic goal, envisaged for 15–20 years hence, is a new ATM paradigm. Aircraft would fly on Four-Dimensional (4D) trajectories, incorporating altitude, position, time, and other aircraft positions and vectors. This vision would involve extremely large investments from the airline industry and ATM service providers. Thus, development priorities need to be based on sound business cases. But will these necessarily lead to the strategic vision of a 4D-trajectory system? Will the changes in practice be limited to a series of short and medium term operational improvements rather than strategic improvements? So, are there ‘Killer Apps’ for 4D-trajectory ATM? ‘Killer App(lication)s’ is jargon for innovations so valuable that they prove the core value of some larger technology. Killer Apps generate high degrees of stakeholder technical and financial cooperation. Ironically, most past ATM Killer Apps have improved safety, e.g., modern radar data processing led to collision avoidance systems. The analysis here attempts to identify and then size potential 4D-trajectory ATM Killer Apps. The evidence for Killer Apps has to pass key tests. Killer Apps obviously have to offer enormous benefits to stakeholders in the context of the potential costs. The bulk of these benefits must not be obtainable through technologically ‘cut down’ *non* – 4D-trajectory versions. Part 1 of this paper (Brooker, 2012a) sets out the framework for investigating these questions. Part 2 examines potential Killer Apps derived from improvements in Fuel Efficiency, Capacity and Cost. An abbreviated version of this paper was first presented at the European Navigation Conference (ENC 2011), London in November 2011.

KEY WORDS

1. SESAR. 2. ATM. 3. Killer Apps.

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1. INTRODUCTION. Part 1 of this paper (Brooker, 2012a) sets out the framework for investigating questions about Four-Dimensional (4D) trajectory Air Traffic Management (ATM) ‘Killer Apps’. ‘Killer App(lication)’ started out as jargon

Table 1. Current (2008) estimated benefit pool – minutes per flight – actionable by ANSP. Adapted from (PRC/ATOS&P, 2009 [Table 5]).

		Estimated additional time (average per flight in minutes)		
		Europe	USA	Engines
Holding at gate per departure	en-route-related	1·4	0·1	Off
(only delays >15 minutes included)	airport-related	0·9	1·8	Off
Taxi-out phase (min. per departure)		4·3	6·2	On
Horizontal en-route flight efficiency		2·1–3·9	1·4–2·6	On
Terminal areas (min. per arrival)		2·8	2·9	On
Estimated benefit pool actionable by ANSP		≈ 11·5–13·3	≈ 12·4–13·6	

for a piece of software so valuable that it made people buy the computer system on which it operated: it is now used more widely to cover specific innovations that drive the adoption of a larger technology. 4D-trajectory air traffic management (ATM) is being explored in the USA and Europe as part of their plans – NextGen (Next Generation Air Transportation System) and SESAR (Single European Sky Air traffic Research system) – to transform the processes of ATM. The following text mainly uses SESAR information, but supplements with research and analysis results from NextGen. Three aspects of system performance – Fuel Efficiency, Capacity and Cost – could potentially provide Killer Apps. The analysis here attempts to identify and then size (to no better than the order of a billion euros per annum) potential 4D-trajectory ATM Killer Apps crudely but robustly. The assessments focus on changes to the current situation rather than attempting to estimate the future situation accurately.

2. FUEL EFFICIENCY KILLER APPS.

Currently, aircraft do not normally fly great circle routes because of sector route structures, and they may also be subject to delay – e.g., stacking because of airport capacity limits. The excess distances flown by aircraft have been the subject of considerable research interest, e.g., Magill (1998) and Calderon-Meza and Sherry (2010) for European and USA flights respectively. Fuel's contribution to the total costs incurred obviously varies with the relative price of jet kerosene compared to other operational costs. For simplicity, the present discussion concentrates on fuel costs. The actual price of Jet-A1 fuel has varied considerably over the last decade and is unlikely to stabilise in the future (IATA, 2011). Cook and Tanner (2011) provides a thorough quantitative analysis of the calculation of the fuel cost to European airlines for four flight phases (at-gate, taxi, cruise extension and arrival management) and the other contributions to operational costs.

A very useful concept is that of a 'benefits pool'. Very loosely, this is the maximum possible benefit if all flightpaths were optimized. Thus, the benefits pool represents a theoretical optimum. Tables 1 and 2 are adapted from an up-to-date and authoritative study in this area (PRC/ATOS&P, 2009), which uses precise definitions and assumptions. Table 1 shows the estimated benefit pool for major airports in terms of minutes of delay. A large part of the various holding delays are attributable to

Table 2. Current (2008) estimated benefit pool – kg of fuel per flight – actionable by ANSP. Adapted from (PRC/ATOS&P, 2009 [Table 5]).

	Estimated excess fuel burn (kg)	
	Europe	USA
Holding at gate per departure (only delays >15 minutes included)	≈ 0	≈ 0
Taxi-out phase	65	93
Horizontal en-route flight efficiency	180	118
Terminal areas	115	119
Estimated benefit pool actionable by ANSP	360	330

demand/capacity imbalances rather than route structure issues. There are similar total estimated excess times for the USA and Europe, but with differences in the distribution along the phase of flight because of different ATM practices.

The financial impact of inefficiencies depends on the phase of flight, in particular airborne versus ground costs, highlighted by the 'Fuel Burn' column in Table 1. Table 2 is the equivalent figures in terms of estimated 'Fuel Burn' in kg (kilograms). This shows the dominance of the engine-on phases. An omission from these Tables is the vertical dimension. PRC/ATOS&P (2009) notes that: *"The focus of this section is on horizontal en-route flight efficiency, which is of much higher economic and environmental importance than the vertical component."*

How much does this excess 'Fuel Burn' cost in Europe? From PRC/ATOS&P (2009), there are about 10 million controlled flights in Europe a year. As noted, the dollar price of jet fuel varies considerably and there are currency conversion issues. (Cook and Tanner, 2011 [Table 1]) quotes 0·8 €/kg in a 'High Scenario'. The 360 kg per flight figure from Table 2 gives an annual European cost of 360 × 0·8 × 10 million = about €3 billion: a large figure when compared to typical airline profits. Estimates of future costs would depend on a variety of factors, but most industry bodies indicate that the annual figures would tend to increase markedly as traffic increases, e.g., see CANSO (2008).

There are numerous initiatives aimed at eliminating fuel inefficiencies, in part because they link closely to environmental impacts. A current USA study (Reynolds et al., 2010) analyses 61 purely operational mitigations. CANSO/IATA/Eurocontrol (2008) sets out five action points of the Flight Efficiency Plan, with each point having several components. Table 3 is a simple list of some of the sources of fuel inefficiency and potential solutions in a pre-4D era – abstracted from Reynolds et al. (2010). The core assumption is that the nature of the current ATM concept of Clearance Based Operations (CBO), remains conceptually the same as at present. The solutions to inefficiencies are the product of clever and up-to-date thinking about operations, e.g., requiring some combination of better information systems/controller displays, making use of Mode S position data, or introducing specific computer assistance to optimise a particular operational feature, such as the formation of aircraft queues. In contrast, Trajectory Based Operations (TBO) produce efficiency gains because the *time contracts* for flight operations reduce the need for queueing mechanisms, and hence reduce the need for holding and the frequency of taxi delays.

Table 3. Examples of Fuel Inefficiencies and Typical CBO potential ATM solution.

Fuel Inefficiency category	Typical Pre-4D ATM potential solutions
Taxi-out	Optimise taxi-out procedures
Departure	Optimise take-off and climb profiles
Standard routes etc	Optimise alignment
Congested airspace	More controllers and airspace redesign
Holding and vectoring	Precision navigation and speed control
Arrival	Optimal arrival profiles (CDA, LP/LD)
Taxi-in	Optimise taxi-in procedures

For present purposes, there are three categories of benefits recovery (compare the Interdependencies list (CANSO, 2008):

- 'Developmental': achieved within CBO (i.e., Pre-TBO improvements).
- 'Trajectory': then achieved only through TBO introduction.
- 'Irreducible': inherently constrained and hence unobtainable.

The 'Developmental' category includes the operations mitigations sketched above, plus new technology/procedures that retain CBO.

In contrast, the 'Trajectory' category requires the key features of TBO: highly accurate 4D navigation, time-based operational contracts for airport operations at airports and ATM operational concepts that facilitate these operations.

'Irreducible' is what is left after all the 'Developmental' and then 'Trajectory' gains have been implemented. There would be a variety of reasons for some benefits being irrecoverable. Aircraft need safe separations, so not all flights can have ideal flightpaths. The need to minimise environmental impact means, assuming noise levels are not reduced dramatically, there will be a reluctance to change routes near to airports, particularly straight-in approaches. Military operations will generate some restrictions of civil flights, although Flexible Use of Airspace will mitigate this.

The extent of 'Irreducible' benefits also depends on airport and airspace business and political constraints. If airport movements are over-scheduled then congestion effects will impede flights. Political constraints arise from fragmented airspace and/or ATM operations. Different regions/countries may connect inefficiently through less than optimal routes, with different operating procedures and Air Traffic Control (ATC) hand-over protocols. One of the goals of SESAR is to build on work done by Eurocontrol and others to 'de-fragment' European airspace. As noted, the difference between the USA and European Horizontal en-route flight efficiency figures in Table 1 suggests the extent of potential European de-fragmentation benefits. For TBO to offer 'Fuel Efficiency Killer Apps' it is necessary that the 'Trajectory' category be large. This contribution is squeezed on both sides: by the Pre-TBO developmental gains and the limits placed by the 'Irreducible' constraint.

Very few of the 'Developmental' initiatives are themselves Killer Apps. Most of them should provide a significant benefit, but it is not obvious that there are many novel improvements with a large benefit/cost ratio. Several 'Developmental' initiatives are not new and have been implemented at many major airports already – e.g., Continuous Descent [CDA] and Low Power/Low Drag Approaches [LP/LD]) were introduced at major UK airports from the 1970s. The issue is how to complete implementation at all appropriate airports. Some initiatives have a long history of non-implementation. For example, Knorr et al. (2011) discusses speed control benefits, stating: *"Additional research is also required to evaluate practical implementations of speed control";* although this was in fact the subject of considerable research thirty years ago. Thus, the Attwooll and Benoît (1985) paper on speed control, is aimed at absorbing ATC delays and reducing the amount of fuel burnt: the paper lists some of the earlier Eurocontrol-led work by Benoît, Swierstra and their colleagues. These studies showed the vital importance of larger system issues, e.g., changes to time-based ATC, the level of automation, and co-ordination between en-route and approach. It would be interesting to determine the main causes of non-implementation, given that the Eurocontrol research was of high quality. Was it the cost benefit analyses – in particular, the costs of engineering, software, and display changes? Was it a low oil price era that took the pressure off fuel efficiency? When the oil price is very high then fuel efficiencies become very important, but a very high oil price may link to low Gross Domestic Product (GDP) growth in developed countries, and hence low traffic growth. Were there insurmountable problems with the nature of the potential changes to CBO (Histon and Hansman, 2008)?

To estimate the relative sizes of the three parts ('Developmental, Trajectory and Irreducible') for Europe is extremely difficult. Single European Sky (SES) 'Developmental' initiatives will reduce lateral inefficiencies through better navigational processes and nearer-optimal route structures. In contrast, 'Trajectory' gains are most effective in removing the need for air queueing effects by varying speeds and flight profiles, with fewer taxi operation queues reducing the likelihood of flights being impeded on the airport. CANSO (2008) provides some help. CANSO's figures are compatible with rough estimates of about €3 billion, in the following proportions:

- 'Developmental': one third.
- 'Trajectory': one third.
- 'Irreducible': one third.

i.e., about a billion euro each.

How could these proportions be made more precise? There are several public estimates of SESAR's fuel saving benefits in the literature: a key question in each case is what is being assumed about the relative sizes of the three components above. Does this imply that fuel efficiency is an immediate Killer App for TBO? It does not. The reason is that the industry views 'Developmental' improvements as 'low hanging fruit'. Some of them may be significantly beneficial without needing major changes to subsystem ATC concepts. Thus, they will be priority projects, especially because airlines will tend to view them as having a quick financial payback. The 'Trajectory' improvements would only become a Killer App if and when the benefits from 'Developmental' changes are exhausted or shown to be impracticable or requiring too many subsystem/conceptual changes to CBO.

It is essential to monitor actual fuel efficiency achievements regularly and on a like-for-like basis (PRC/ATOS&P, 2009). The expenditure to obtain a billion euro benefit from 'Developmental' improvements, perhaps from ten or so dominant projects, is allocated over a large number of Air Navigation Service Providers (ANSP) facilities. One survey (Eurocontrol, 2008) covered 138 airport development plans for 2030,

Table 4. Scenario Growth Rates for IFR Movements (Eurocontrol, 2010). Number of years in final two columns are rounded.

	Annual Growth Rate %	% Increase by 2030	Years to x1·5 traffic	Years to x3 traffic
A: Global Growth	3·9	122	11	29
C: Regulated Growth	2·8	79	15	40
D: Fragmenting World	2·2	58	19	50
E: Resource Limits	1·6	40	26	69

while another report (PRU, 2011) covered 37 ANSPs, with 65 Area Control Centres, 249 Approach Units and 451 Towers.

3. CAPACITY KILLER APPS.

Many authors have discussed European ATM demand and capacity issues over many years, e.g., see Brooker (1990, 2009a). The focus here is on strategic, long-term capacity (i.e., assured day after day) rather than the kinds of tactical gains made on a short-term basis – e.g., using visual procedures in very good weather to sequence aircraft closer together. The general argument is that planners assess the need for future extra capacity by looking at the timing of the projected capacity gap. They then compare this with the time required to improve the CBO system sufficiently and/or the time to implement a TBO system that delivers very large capacity increases. The nagging problem is that if decision-makers wait for the gap to pose significant operational penalties, then such penalties could get much more serious before a new paradigm could be introduced.

The SESAR Capacity performance targets are to make *available* 73% more ATM capacity and to *enable* three-times as much in the longer term. Here, the italicising of the words *available* and *enabled* suggests the need to be clear about the intent of the targets. What matters to users is the capacity of the ATM *system,* which needs to include airport capacity as well as airspace capacity. The former mainly depends on the effective use of runways, keeping aircraft safely separated. The latter mainly depends on the workload of controllers in safely handling traffic through volumes of airspace. Omitting any kind of philosophical debate, the 73% figure supposes a future airport configuration that delivers that much more of traffic than currently. The target is then that the whole ATM system has the capacity *available* to manage this throughput. In contrast, to *enable* three times as much traffic is more specifically an ATM target because the aim is to be able to move three times as much traffic – i.e., typically three times the traffic density – through an unspecified block of en route/terminal airspace.

Current traffic projections put these targets into context. The first two columns of Table 4 are from forecasts (Eurocontrol, 2010 [Figure 29]). They show very clearly the large differences in (average annual) growth rates, and hence the very different cumulative estimates for 2030 traffic, with the increase ranging from 40% to 122%. These forecasts rest on a number of assumptions and summarise a complicated geographical picture of traffic growth over time. One key assumption is that further developments at a number of airports add runway capacity – i.e., the forecast is not the 'unconstrained demand'. Thus, the forecast would be further constrained if (to quote), "*projects currently foreseen may be delayed, reduced in scope or even cancelled*" (Eurocontrol, 2010). The growth percentages do not represent the same level of growth at peak times or in the currently busiest airspace sectors. Growth at airports generally reflects peak spreading of traffic over more and more hours. Thus, forty years ago, Heathrow airport operated at peak hourly throughput for two or three hours, but now its busy period is usually most of the day and evening. Growth does not take place to the same degree for all European countries, which cover a wide variety of stages of economic growth, business activity and tourism development. For example, Scenario E (Resource Limits) shows average annual growth for the UK at 1·1% but the figure for Turkey is 4·3%, corresponding respectively to cumulative growth by 2030 of 25% and 143% (Eurocontrol, 2010 [Figure 31]).

The final two columns of Table 4 are approximate estimates of the date for achieving x1·5 and x3 traffic respectively, assuming that the scenario growth rates would persist indefinitely. Of the x3 traffic estimates, only the highest growth scenario takes less (just) than a typical human generation of thirty years. Would airlines consider that a x3 demand occurring several decades hence could require a Killer App now? This seems improbable. The need for the ATM system to be able to handle a x1·5 current demand is obviously more likely to be a feature in current airline planning considerations. The first question that airline decision-makers would ask is whether TBO is necessary to handle that level of traffic. Alternatively, could a further developed CBO system provide an acceptable solution?

There is some evidence that further CBO developments could generate at least 50% extra European airspace capacity. (Brooker, 2009a) presents some quantitative estimates of *potential* airspace capacity gains from some current projects: "DMEAN, air traffic flow measures, CPDLC and FASTI". These estimates all derive directly from official State and Eurocontrol Cost Benefit Analyses (CBA), and in combination, increase sector capacity by 63%–73%. It should be noted that much of the increased demand in European traffic forecasts tends to be associated with countries currently with spare ATM capacity (Eurocontrol, 2010). Thus the implication is that, if current projects were implemented *and* then delivered the anticipated capacity gains, then a developed CBO-based ATM could successfully handle x1·5 current traffic.

Although the airspace capacity gains from TBO do not yet appear to offer a Killer App, is there a *system* capacity feature of TBO that might be attractive to airlines? Could it offer major gains in runway capacity at some existing airports, rather than going to the large expense and potentially long implementation of adding runways and/or building wholly new airports? This would be achievable because of the much better time-keeping navigation of TBO flights. The gains are significant for single runway operations, where runway occupancy is alternately an Arrival (A) and a Departure (D): i.e., a sequence ADA(DADA…). Brooker (2009b) describes the nature of a safe ADA operation in some detail. The key navigational features in determining the ATC planned timings, which determine the hourly runway capacity, are a 'safety buffer time' of some seconds between a departure taking-off and the next arrival crossing the threshold, and the need to allow for statistical variations in inter-arrival times (Brooker, 2009b [Figure 1]). Aircraft operational timings could be much more accurate than at present, thus much reducing both these factors. The standard ADA cycle time could be markedly reduced and hence produce a large increase in hourly runway capacity.

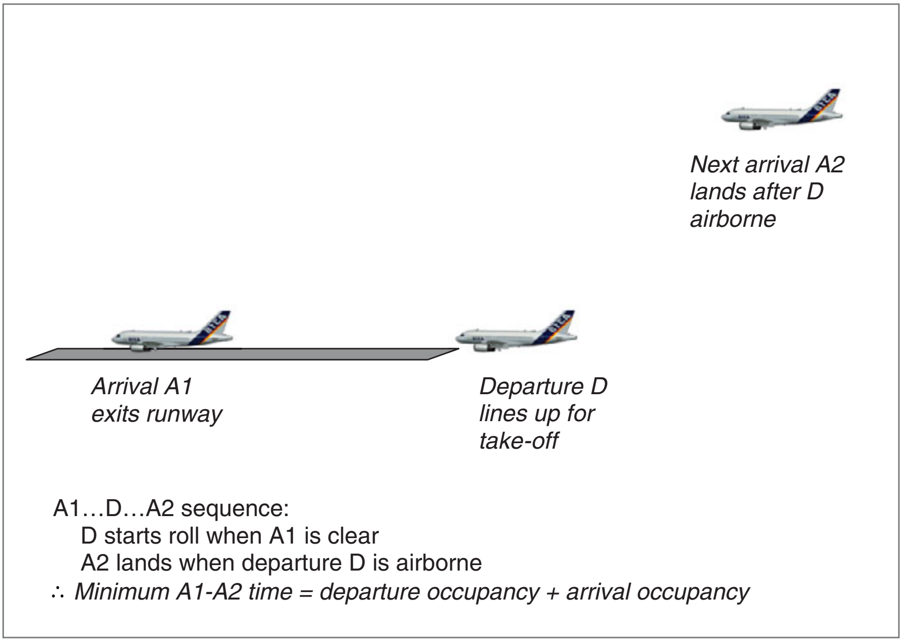

Figure 1. Idealised operational cycle for single runway.

Brooker (2009b) examines a transitional system of CBO and TBO flights, using a very simple queueing model, and cautiously assumes a 15% reduction in inter-arrival times. A 100% TBO operation might deliver an even larger capacity, as the ADA operation could be tailored to the individual aircraft sequence. Figure 1 illustrates an ideal situation in which the minimum time between two arrivals is the sum of the departure occupancy and arrival occupancy. Wichman et al. (2003) suggest that the theoretical TBO runway usage under IFR would be 80 movements (i.e., ~90 seconds between arrivals), to be compared with a CDO rate around 50 movements an hour (i.e., ~140 seconds between arrivals). There are problems with attaining such a limiting rate. Wake turbulence restrictions affect some categories of inter-arrival pairs: these generally have small effects when the inter-arrival spacing is 140 seconds, but much more so if it were 90 seconds. Runway occupancy times will tend to increase with the proportion of larger aircraft. There might still be significant variations in achieved departure occupancy time. It would be necessary to ensure that the higher movement operation would be resilient against rare navigational/human errors and aircraft FMS problems.

Suppose around half the theoretical timing improvement was *in practice* routinely achievable (i.e., an inter-arrival time of ~115 seconds, equivalent to runway usage of ~63 movements per hour). (How could this kind of figure be made more precise?) This would increase runway capacity by ~25+%. Eurocontrol (2004. Table 2) examined in some detail the operations of airports across Europe. From a survey, more than 60% of the airports had a single runway or parallel independent runways, and so could benefit from the TBO operation. About another 15% use crossing runways, which again would be good candidates for potential TBO operational

Table 5. Some estimated Premiums, BA Heathrow versus Gatwick, on Profit per Flight, in approximate 2011 prices, inflated by 54% from 1996 data, and £/€ = 1·15 (CAA, 2001).

Route	Premium (€ 1000)
Daily short-haul service	4·3
Dubai	18·3
JFK New York	52·7

benefits. Thus, 75+% of airports could potentially add ~25+% of their current capacity – an increase of ~20% in total. Some environmentally-restricted airports could not benefit, e.g., Heathrow, which operates under a segregated operation on its two runways, with its capacity largely determined by wake vortex regulations rather than aircraft navigation. [NB: in spite of extensive research, there are major problems with the validation of vortex wake models, with hazardous aircraft encounters either not being monitored at all or access to data now being commercially restricted, e.g., see Holzäpfel et al. (2009).]

How worthwhile would this TBO airport capacity be to airlines? Conceptually, a simple way of estimating the benefit is to use the '*Value of a flight*', which could be taken to be (at least) 'the average profit per flight'. Eurocontrol (2009) quotes a value of €700, based on work by the IATA Cost Benefit Task Force. However, airline profitability has varied considerably from year to year, and there are wide variations depending on the nature of the flight. There are very good reasons for believing that the €700 figure is a significant under-estimate for flights at congested hub airports and there are likely to be an increasing proportion of such airports. CAA (2001) analysed in some detail the extent to which runway slots at Heathrow have a premium value over those at other London airports. The key factors are the proportions of business passengers and the use of connecting services. Table 5 shows some examples of the CAA estimates (based on 1996 data, so indicative at best), uprated to current prices and converted to euro. Note that these estimates are premiums on the comparable Gatwick figures – reasonably assumed to have positive values.

What would the extra TBO-based airport capacity be worth for European airline traffic? Assume (cautiously) that the future baseline traffic is 10 million flights. Assume that about half of these flights would be at capacity-limited runways, hence the availability of extra flight slots would indeed be very beneficial to the airlines. The 'Challenges to Growth' report (Eurocontrol, 2004), included a detailed analysis of current and future capacity at European airports. Eurocontrol (2008) noted plans for five major new airports and 27 new runways by 2030, out of 138 airports surveyed. Assume that TBO operations would add the ~20% figure to this number. Suppose that the average *Value of a flight*, taking into consideration the much larger premium values for congested hub airports, is €2000. Multiplying the factors together gives an annual value of €2000 × 0·20 x ½ x 10 million = €2 billion. In contrast, the standard Eurocontrol €700 figure and a quarter of airports at capacity limits would produce €0·35 billion. This wide range of rough estimates suggests that this would be a productive area for joint operational and economic modelling by stakeholders. As sketched in Brooker (2009b), such gains would progressively become available in a transition period from CBO to TBO systems.

Table 6. UK NATS forecast and planned en route (Eurocontrol) costbase [Simplified: source material is NATS (2010. B3·2)].

£M 2008/09 Prices	2011/12 Forecast	2020/21 Planned
Staff and Direct Costs	299	281
Pension Contributions	85	44
Regulatory Return	97	77
Depreciation	146	142
Other	– 33	– 46
TOTAL cost base	594	498

4. COST KILLER APPS. Airlines view the costs of ATM as a major problem. Airline critics have often expressed concerns about a variety of cost-related issues, e.g., the lack of competitive pressures in ATM providers, excessive salaries paid in some states, poor project management in implementing new facilities, the slow uptake of cost-saving technology, etc. This is why the SESAR *Cost* target appears to be a tough one: "50% less [direct] ATM cost/flight". The European ATM/CNS provision costs are given as €7·6 billion (PRU, 2011), out of a total Gate-to-Gate ANSP cost (e.g., including meteorological charges) of €8·6 billion, to be compared with about 9·4 million IFR (Instrument Flight Rules) movements (=flights within the context of airport pairs) in 2009.

First, it is necessary to repeat the same kind of exercise discussed in the previous sections, i.e., to ask what gains would be achieved by developmental improvements to CBO operations. NATS' 10-year Business Plan (NATS, 2010) provides an illustration. NATS is a good example to use for three reasons: it has very complex and busy airspace, it is part owned by an airline consortium, and its charges are externally regulated by appropriate UK bodies. Together these mean that it publishes a considerable amount of financial and planning information. Table 6 shows the plans to change important cost components, at an average rate per decade of 17·8%. Controller numbers remain about the same, but there are large reductions in Operational Support Staff and Engineers, in part enabled by outputs from the current investment programme. Note the large change in pension costs. If achieved across Europe, this would produce provision costs of €6·2 billion (i.e., a €1·4 billion reduction). Changes to the ANSP cost base are only part of the cost target because the metric is *cost per flight*. Focusing on 2020, the *lowest* scenario projection (Eurocontrol, 2010) is a traffic increase of about 32%. Coupled with the 17·8% cost base reduction, this delivers about a 38% reduction in total over a decade, in comparison to the SESAR target of 50%.

In recent years, the work of Eurocontrol and others has made apparent the large differences in ATC service costs across European states. Some of these differences are simply the result of employment costs. For example, PRU (2011 [Figure 4·10]) shows that for controller employment costs per controller-hour the highest cost figure is about twice the European median. The concern that ANSPs do not make sufficient efforts to achieve efficiencies and economies of scale in provision and system procurement led, in part, to the introduction of Functional Airspace Blocks (FABs). In essence, groups of States get together and create an airspace block based on ATM operational requirements and established regardless of State boundaries, thus optimizing and aligning procedures and services within the FAB, and consolidating facilities. Originally, FABs were proposed as a means of improving airspace design, but the Single European Sky (SES) regulations signalled an intent that FABs should help deliver consolidation within the industry. These regulations require all European Union members to be part of a FAB by 2012. As of December 2011, nine FABs exist/are being developed – e.g., the South West FAB is Portugal and Spain.

A survey of aviation professionals (Helios Technology, 2011) posed the question: *"How many en-route ATC centres does Europe really need?"* The respondents had very mixed views: 16% stated *'at least the current number'* (~ 60), 35% stated *'about one per state'* (~ 30) and 49% stated *'about one per FAB'* (~ 10). There are good business reasons for these concerns, as the European ATM system is fragmented compared with the USA's system. A report for Eurocontrol by Helios EPS (2006) notes that the typical size of a European en route centre was much smaller than in the USA, the average centre operating 9 sectors at maximum configuration, whereas the average USA centre has 37 sectors. Helios EPS (2006) reported substantial evidence for economies of scale for centre operation:

- Arising from the low utilisation that will inevitably occur at times of low demand in very small centres.
- Through economies of scale from sharing the fixed costs of a centre over more activity, which substantially affects both capital costs and operating costs.

These factors lead to operating costs per flight-hour controlled in the selected European centres being markedly higher than those in USA centres. In the long term, there might be two centres per FAB (which allows for catastrophic contingency arrangements within each FAB).

The conclusion from this brief examination of planned and potential developments is that the SESAR Cost target could well be achievable through 'Developmental' improvements, i.e., while maintaining the current CBO operational concept. The open questions are about the extent that current plans for 'internal efficiencies' (e.g., those of NATS listed above) will be implemented successfully and if the FAB facilities consolidation will be achieved and deliver the potential economies of scale. Only time will provide concrete answers to these questions.

What would be the Cost Killer Apps? Such a Killer App would have to make substantial inroads into the operational cost base, far beyond the kind of efficiency and consolidation savings noted above. The key would be substantial reductions in the number of controllers (and consequent reductions in other staff) arising from the TBO concept. The evidence for potentially very large improvements in controller productivity through SESAR and NextGen TBO concepts comes mainly from research by the USA's National Aeronautics and Space Administration (NASA). Official NextGen and SESAR documents (JPDO, 2011; SESAR Consortium, 2007) discuss controller productivity in general terms, but do not go into detail about the long-term *function allocation* of tasks between controllers, pilots, automation or the estimation of output gains. The NASA work, mainly using real-time simulations, has attempted to make such estimates.

As an example, the (Erzberger, 2004) review quotes capacity gains compared to current standards of 100% – 200%. Simulation of controllers using trajectory-based automation and data link communication of control clearances to aircraft in en route sectors provided the following key conclusions in the present context:

> *"Under laboratory conditions, the controller was performing the separation assurance functions that are performed by 4–10 people under today's operations… The controller maintained legal separation and issued conflict-free direct route amendments while working the combined traffic in five Fort Worth Center high-altitude sectors at traffic levels nearly equivalent to that of today's traffic"* (McNally and Gong, 2007).

A variety of function allocations have been investigated (Wing et al., 2010). Investigations of operational viability and capacity gains achievable through mixed CBO/TBO flights have also been carried out (Lee et al., 2005). Some researchers judge that some form of supervisory control of separation by controllers is the most viable concept (Dwyer and Landry, 2009). However, there are major human-automation operational and implementation issues – e.g., see the discussion in Sheridan (2006).

However, it would cost a great deal of money to implement these kinds of changes. A simple way of estimating the implications is to examine projected depreciation contributions. In loose accounting jargon, depreciation is a way of spreading the costs of a capital asset over its useful lifetime to a business. A fraction of the value of the asset is an expense in any year of its use, i.e., it appears in the profit and loss account [= income statement] and is in essence the annual cost base of an ANSP. Asset lifetimes vary considerably, but are typically 8–15 years for ATC systems (NATS, 2011). Software implemented in operational aviation systems would be a capital asset with a long lifetime. If ANSP capital spend on SESAR were to be capitalized over (say) 15 years then, depending on the depreciation method, roughly one fifteenth would be charged in any year of use. Thus a billion euros of capital would appear as 67 million euro in the yearly depreciation. If airlines have to buy ATM-related kit then they also incur depreciation costs, but might depreciate over the typical life of an aircraft, say 20 years. There are also finance costs, e.g., interest on loans to finance asset purchase, but these are not estimated here.

Given these kinds of numbers, what kind of reasonable cost scenario could be constructed for a European TBO system? Table 7 illustrates some 'TBO potential' figures. The first numerical column is simply the 2009 data (PRU, 2011). The next column is a simple adjustment to the 2009 data to estimate 'Potential 2020/21' figures. The aim is to get the numbers in line with the NATS planned improvements in Table 6. This is simply done by multiplying the 'Other staff employment costs' and 'Non-staff operating costs' by two thirds. This gives a 16% reduction in Total Costs. To estimate the 'TBO Potential' in the last column, the 2020/21 costs for 'ATCOs (controllers) in OPS employment costs' and 'Other staff employment costs' are multiplied by two thirds. There are additional ANSP depreciation costs of €209 million euro, obtained by depreciating a capital cost of €6·22 billion discounted over 15 years and halving. The *arbitrary* depreciation cut of a half is because ANSPs already have large capital spending programmes, so that some of the new depreciation will replace depreciation that has 'dropped out' of the accounts (PRU, 2011 [Section 6.3]). The 'Total' figures show an order of a billion euros saving in each of the two calculations.

Table 7. Illustrative breakdown of European Gate-to-gate ATM/CNS provision costs.

€ million – constant prices	2009#	Potential 2020/21*	TBO Potential**
ATCOs in OPS employment costs	2360	2360	1573
Other staff employment costs	2406	1604	1069
Non-staff operating costs	1340	893	893
ANSP Depreciation	885	885	1094
Cost of capital	470	470	470
Exceptional Items	118	118	118
Total (rounded)	7580	6330	5218
		Airline Depreciation	577

Actuals from (PRU, 2011 [Figure 2·4]).

* 'Other staff employment costs' and 'Non-staff operating costs' times two thirds.

** 'ATCOs in OPS employment costs' and 'Other staff employment costs' times two thirds; assumed additional ANSP capital cost of €6·22 billion discounted over 15 years and halved, and airline capital cost of €11·53 billion discounted over 20 years. Civil costs only.

The immediately obvious problem with this calculation is the assumption of a one-third reduction in controller etc costs. Note that this covers controllers in both en route and terminal airspace for which there is financial recovery via en route charges. The key decision-making question is: *"At what point will there be sufficient agreement about the TBO operational concept for confidence about the most-probable productivity increases?"*

The source of the €6·22 billion ANSP capital spend figure is the European Commission (European Commission, 2009 [Table 3]), which lists a SESAR spend of €29·6 billion, of which €6·2 billion is for civil ANSP services. However this is only part of the total SESAR spend to achieve TBO (it does not cover Capability levels 4 and 5). The NextGen situation is even more uncertain:

> *"A recent NextGen portfolio analysis, commissioned by the JPDO, already shows that some NextGen automated air and ground capabilities originally planned for 2025 may not be implemented until 2035 or later and could cost the Government and airspace users significantly more than the projected cost estimate of $40 billion"* (Dixon, 2010).

There is always uncertainty about long-term cost estimates of technological systems development, especially if the portfolio of projects involve multiple systems, software and safety criticality. Brooker (2009a) notes:

> *"UK government guidance on 'optimism bias' in IT system development projects note overruns by 10% to 54% and overspends from 10%–200%."*

But there is a large 'below the line' problem with Table 7. The focus of airlines would in fact be on the additional outlays they would have to incur for investment in ATM-related – *and for no other purpose* – aircraft equipment. A figure of €11·53 billion for SESAR Capability levels 1–3 has been presented (European Commission, 2009 [Table 3]). The cost to full TBO capability might be markedly larger. Simply taking €11·53 billion and depreciating over 20 years, the annual depreciation figure would be of the order of €577 million. This would take about half out of the postulated €1 billion saving in the charges cost base.

5. CONCLUSIONS.

Part 1 of this paper (Brooker, 2012a) examined the kinds of decision criteria that need to be used in assessing potential 'Killer Apps' for Air Traffic Management (ATM) using Trajectory Based Operations (TBO) concepts. Inter alia, it concluded that Safety and Environmental features of ATM are unlikely to generate Killer Apps. The three remaining Killer App candidates are 'Fuel Efficiency, Capacity and Cost'.

Fuel Efficiency needs little explanation. Ideally, the ATM system's design would enable flights as a whole to use minimum fuel in going from origin to destination. This would include direct horizontal routeing, minimum cost vertical profiles and infrequent need for queue management devices such as stacking in terminal areas. A very useful phrase is the 'benefits pool', which measures the potential gains from fuel efficiency improvements. Currently, it appears that about a third of the benefits pool is irreducible, in that inherent constraints on flights – e.g., safety minima between aircraft – mean that Four-Dimensional (4D) TBO would not secure them. About a third of the pool might be achievable by developmental improvements – e.g., restructured routeings – but these gains would require the implementation of a variety of projects. The remaining third would be obtainable through TBO, but not otherwise. The TBO gains are not yet a Killer App because the current developmental improvements are 'low hanging fruit'. When it is certain which of these projects are going to be successful, TBO does offer large financial gains, of the order of a billion euro per annum and possibly more.

Capacity generally refers to airspace capacity. It is obvious that capacity is only a problem if it prevents demand from being satisfied. The two key issues are growth rates and geographical factors. European demand is very difficult to forecast. If growth rates are low, because of poor Gross Domestic Product (GDP) growth and/or very high jet kerosene prices, then it will be decades before Clearance Based Operations (CBO), given some developmental improvements, would fail to match growth. Geographically, much of the European growth is likely to be in countries that have considerable potential for CBO system development rather than the currently more Air Traffic Control (ATC)-developed states, which are of course improvising their operations. For TBO to provide an early airspace Killer App, growth would need to be very high in developed states.

However, there is a potential *airport* Killer App. Many of Europe's airports are near capacity. Eurocontrol strategists have identified the need for many extra runways and new airports if demand is to be met. Airlines' preferences are generally for extra capacity at existing airports, to make best use of their facilities and to benefit from the premiums attached to long-haul business traffic and hub operations. TBO could provide a large amount of extra capacity at existing airports/runways. This is because its very accurate, time-contracted, method of operation would enable much closer separations between sequences of departures and arrivals on mixed operation runways. On present knowledge, there would be no increase in segregated mode runways – i.e., arrivals or departures only – because of the major gaps in safety modelling of vortex wake hazards. However, over Europe as a whole, the TBO gains might be worth of the order of €0·35 billion to €2 billion per annum. This depends on how many runways are likely to reach chronic capacity limits. The wide range of estimates suggests that this would be a productive area for joint operational and economic modelling by stakeholders.

Cost is primarily about the charges made to airlines for the provision of Air Navigation Services (ANS). The annual charges are simply related to the ANS Providers (ANSP) cost base, which is similar to the manual Profit and Loss (= Income) accounting statement. This comprises staff and running costs plus interest and depreciation allocated to the year. Depreciation is a slice of previous capital expenditure according to the assumed life of the capital asset. CBO improvements are likely to reduce the cost base significantly through lower overheads, new pension restructures and facility consolidation through Functional Airspace Blocks (FABs). Trajectory Based Operations (TBO) would affect the *effective* cost base in three ways:

- Reduced controller etc staff and related costs.
- Increased depreciation etc costs for the ANSP's capital costs.
- Increased depreciation etc costs for the airline capital costs.

The third of these is not included in the charges made by the ANSP, but it is directly incurred by the airlines to fit kit etc on aircraft. The first two might produce a gain of a billion euro per annum, but the third could cut that back by half.

Would these produce a *Cost* Killer App? The first necessary assumption is that TBO would improve controller productivity considerably, and hence reduce controller numbers and related costs. The evidence for a factor of two or greater improvement in controller productivity is mainly work by USA's National Aeronautics and Space Administration (NASA) research establishments carrying out real-time simulations. The second necessary assumption is that the total increase in depreciation for ANSPs and airlines is markedly less that the controller productivity gains. Present estimates are consistent with such an assumption *if* the later stages of SESAR do not add large extra costs, and *if* SESAR costs generally do not increase markedly beyond current estimates.

The general conclusion from simple crude calculations is that potential 4D TBO Killer Apps *do* exist. The main issues are the degree of knowledge about CBO developmental improvements, the right estimates for traffic growth and airport capacity, demonstrations that very accurate flight time-keeping is routinely achievable, and good estimates of TBO controller productivity gains. As Part 1 of this paper (Brooker, 2012a) notes, this is in the context of projected large positive impacts on GDP and employment.

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