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Dynamic Cost Indexing

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Aircraft maintenance – marginal delay costs

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1 Introduction and overview of status

Assigning delay costs attributable to the mechanical attrition of aircraft waiting at gates, subjected to arrival management, or accepting longer re-routes in order to obtain a better departure slot, is an important component of the Dynamic Cost Indexing framework. These costs are substantial and cannot be neglected in assigning proper costings to delay recovery trade-offs. This document represents the first occasion this has been addressed within this study, such that the derivation of costs is presented from first principles, with a supporting introduction to this research area.

2 Introduction to aircraft maintenance

Before describing the contribution of maintenance costs within the Dynamic Cost Indexing context, this section provides an overview of aircraft maintenance: what it comprises, when it is scheduled and the costs involved.

2.1 Maintenance composition

Regular maintenance is necessary in order to maintain (or restore) the aircraft structure, systems and components in an airworthy condition. These can be grouped as:

- airframe
- engine and APU
- components and 'rotables'[1]

Aircraft and engine manufacturers publish documentation for maintenance planning purposes for their aircraft and engine families. These contain the minimum required maintenance tasks and how and when they should be carried out, for example: Airbus – Maintenance Planning Document (MPD); Boeing – Maintenance Planning Data (MPD) document (Kinnison, 2004). Traditionally, these maintenance tasks are divided into categories – 'line'/'transit', 'A', 'B', 'C' and 'D' (from lightest to heaviest) – enabling aircraft operators to plan regular inspections. Although the required maintenance tasks and the number of engineers assigned will vary between aircraft type and maintenance, repair and overhaul (MRO) company, Table 1 summarises typical checks. Additional or revised tasks are notified by regular Advisory Circulars (AC) and Airworthiness Directives (AD) issued by civil aviation regulatory authorities, such as the European Aviation Safety Agency (EASA) and the FAA.

For modern aircraft types (e.g. B737NG family and B777), the 'letter check' distinctions are less important, since Maintenance Steering Group (MSG) 3 task-orientated maintenance programmes are employed. MSG-3 (replacing the earlier MSG-1 and MSG-2 philosophies) allows maintenance tasks to be grouped into packages in a way that is more efficient for the operator – matching work against operational requirement – rather than carrying out checks that are pre-defined by the MPD. Although MSG-3 based checks arrange tasks into multiples

[1] Parts that are repaired/re-conditioned and returned to service

of phase intervals (e.g. 48 times the 'Phase 1' interval), the industry generally still refers to maintenance checks as 'A', 'C' and so on.

Table 1 Typical maintenance checks

Check	Location	Description	Duration [(a)]
'Line' / 'transit'	At gate	Daily (before first flight or at each stop when in transit). Visual inspection; fluid levels; tyres and brakes; emergency equipment	≈1 hour
'A'	At gate	Routine light maintenance; engine inspection	≈10 hours (whole shift) / overnight
'B'	At gate	If carried out, similar to 'A' check but with different tasks (may occur between consecutive 'A' checks)	≈10 hours to ≈1 day
'C'	Hangar	Structural inspection of airframe, opening access panels; routine and non-routine maintenance; run-in tests	≈3 days to ≈1 week
'D'	Hangar	Major structural inspection of airframe after paint removal; engines, landing gear and flaps removed; instruments, electronic and electrical equipment removed; interior fittings (seats and panels) removed; hydraulic and pneumatic components removed	≈1 month

(a) Duration will depend on whether defects are found that require remedy

2.2 Maintenance scheduling

Having briefly mentioned MSG-3 task-based maintenance, the summary in Table 2 of maintenance scheduling is in terms of the traditional letter checks. To help illustrate the cycle of checks, Table 2 lists typical[2] maintenance check intervals for the twelve aircraft types included in earlier reporting in this area by the University of Westminster for EUROCONTROL's Performance Review Commission (Cook et al., 2004 – henceforth the 'Cost of Delay' study). The listed check intervals have been assembled through an extensive literature search of aircraft maintenance planning articles. The compiled data of Table 2 are not otherwise available as an up-to-date (public) source.

Intervals between checks are specified by a combination of flight cycles (FC), flight (not block) hours (FH) and calendar months. Taking the B757-200 as an example, each 'C' check is scheduled to occur every 18 months, or every 6000 flight hours, or every 3000 flight cycles – whichever comes first. This means that a heavily utilised short-haul aircraft will most likely require a 'C' check due to its number of LTO cycles, whereas an aircraft operating longer haul will be due a 'C' check as a result of hours flown (reaching 6000 FH before 3000 FC is reached). A less intensively utilised aircraft would require a 'C' check at 18 months, regardless of the number of hours flown or cycles completed. 'B' checks can be discounted as they are becoming less common, being associated with older aircraft types.

'A' and 'C' checks are of particular interest to this study, between them accounting for around 40 - 50% of the overall maintenance cost to airlines (including overheads, plus

[2] Maintenance check intervals can vary considerably depending upon factors such as utilisation and the operating conditions (e.g. operating predominantly in a sandy environment compared with an icy one). Phase intervals have been converted to letter check intervals.

engine and component maintenance that takes place during these checks). This is the case even when considering the multi-million dollar cost per aircraft 'D' check.

Not all 'A' and 'C' checks include the same maintenance tasks, as some tasks are only required every second or third check. To distinguish these differences, checks are numbered so that a '3A' is carried out every third 'A' check and a '2C' every second 'C' check[3].

Table 2 Typical maintenance check intervals

Aircraft	'A' Check	'B' Check	'C' Check	'D' Check
B737-300	275 FH	825 FH	18 months	48 months
B737-400	275 FH	825 FH	18 months	48 months
B737-500	275 FH	825 FH	18 months	48 months
B737-800	500 FH	n/a	4000-6000 FH	96-144 months
B757-200	500-600 FH	n/a	18 months / 6000 FH / 3000 FC	72 months
B767-300ER	600 FH	n/a	18 months / 6000 FH	72 months
B747-400	600 FH	n/a	18 months / 7500 FH	72 months
A319	600 FH	n/a	18-20 months / 6000 FH / 3000 FC	72 months
A320	600 FH	n/a	18-20 months / 6000 FH / 3000 FC	72 months
A321	600 FH	n/a	18-20 months / 6000 FH / 3000 FC	72 months
ATR42-300	300-500 FH	n/a	3000-4000 FH	96 months
ATR72-200	300-500 FH	n/a	3000-4000 FH	96 months

Multiple sources, including: *Aircraft Technology Engineering & Maintenance*, *Aircraft Commerce* and *Boeing AERO*.

When checks overlap they are combined into one event, with the higher check including the lower check's tasks. Taking the B757-200 as an example again, assuming each 'A' check is scheduled to take place every 600 FH, the tenth check is likely to coincide with a 'C' check (i.e. 600 FH × 10 = 6000 FH, also a 'C' check interval) – in this case the tenth 'A' check would become part of the more substantial 'C' check.

There are other factors to be taken into consideration by airlines when planning their fleet maintenance schedules. For example, if a major overhaul is expected to coincide with an airline's peak season (if the check was based on calendar interval), it may be brought forward so that the aircraft is not unavailable at a critical time. Similarly, when arranging a heavy maintenance ('D') check for an aircraft, hangar capacity can be a limiting factor. For example, B747-400 'D' checks are expected to peak in 2016 with 143 required in that year – operators of this aircraft type may be constrained by hangar availability, pushing up maintenance costs, or causing the check to be brought forward in order to secure a slot (Goold, 2008).

[3] Checks that are split up (phased) are numbered differently: an 'A1' check is the first half with 'A2' the second half (e.g. the maintenance work has been divided over two nights, 'A1' and 'A2' completing the 'A' check). A 'C' check might be split into twelve equal parts: 'C1', 'C2', 'C3' … 'C12' completing the full 'C' check cycle (Kinnison, 2004).

2.3 Maintenance costing

According to AeroStrategy/OAGback, the MRO market was worth USD 45 billion in 2007. Engine overhaul accounts for around 35% of the cost. Typically, around 80% of the total cost can be attributed to staff costs, not just the engineers and technicians working with the aircraft but also the managers and administrators scheduling the programme, and thus contributing towards the maintenance 'burden' (overhead), as explained by Friend (1992):

> ***Direct maintenance cost represents work done on the aircraft or its components (maintenance burden is an overhead allowance to reflect allocated charges for the fleet in technical support, facilities, etc.).***

In addition, for outsourced maintenance and for operators participating in power-by-the-hour (PBTH) contracts, these overheads are built into the unit cost.

The maintenance costs for an aircraft and its engines vary with age. When new, the costs associated with the airframe are relatively low and rise steadily, whilst still under manufacturer's warranty, levelling off as maturity is reached (after around five years). A mature aircraft has a steady, predictable maintenance cost, which begins to rise again after around 15 years, as airframe and components age.

Older aircraft require considerably more non-routine maintenance and remedial work due to Airworthiness Directives and corrosion prevention tasks. The expensive cost of 'D' checks cause large peaks to occur during the life of an aircraft.

Maintenance agreements offer a method of smoothing these large peaks over a longer period, allowing more predictable and effective budgeting. Power-by-the-hour (PBTH) or cost-per-flying-hour (CPFH) maintenance agreements offered by the manufacturers and MRO companies, now account for the majority of airline maintenance contracts[4]. Examples include the Rolls Royce 'TotalCare' and General Electric 'OnPoint' engine packages, plus the recently launched Boeing 'GoldCare' air-transport-by-the-hour package for the new B787. In essence, PBTH contracts specify an agreed per-flight hour price to maintain the airframe/engines for the predicted usage, based on the ratio of flight hours to cycles. The operator would pay more if the agreed usage threshold was exceeded (though this might be absorbed across the fleet by another slightly under-used aircraft), whereas the maintenance provider would absorb the risk of an unexpected additional cost due to abnormal wear and tear.

3 Previous research addressing marginal maintenance costs

Notwithstanding on-going literature reviews, the only previous work known to the authors which has attempted to allocate detailed marginal costings to airline maintenance activities, is that reported by the University of Westminster for EUROCONTROL's Performance Review Commission, in the 'Cost of Delay' study (ibid.).

What exactly is meant by a 'marginal' minute? When calculating costs associated with delay, we cannot assume that all costs are unit costs. A minute of tactical delay usually generates

[4] This reflects a wider trend to outsource heavier maintenance tasks.

a 'marginal' cost, i.e. the cost of doing something, such as an aircraft waiting at-gate, for a minute later than planned, and usually a minute longer than planned. Some of the associated costs are the same as the unit cost, an example being an en-route ATC charge. Marginal maintenance costs are clearly not like this, as large proportions of them are sunk costs, in terms of overheads, or fixed on a per-cycle basis, due to the high aircraft workload during take off and landing.

In the 'Cost of Delay' study, block-hour direct operating costs (BHDOCs) were derived for a range of twelve aircraft (chosen to represent a cross-section of European air traffic movements and flight-hours) based on 'low', 'base' and 'high' cost scenarios. These BHDOC values were derived from primary airline interview data, a literature search, and comparisons with two independent sources of BHDOC data ('ICAO Digest of Statistics' and Airline Monitor). Based on the primary airline data, and supported by the literature findings, it was found that using 15% of the BHDOC values gave good estimates of the corresponding *unit* maintenance costs (which included both the direct maintenance cost *and* maintenance burden). These results are summarised in Table 3.

Table 3 BHDOC and maintenance costs per block-hour (2002)

Aircraft	**BHDOC**			**Maintenance proportion**	**Unit maintenance cost**
	Low	**Base**	**High**		**Base**
B737-300	2 540	**4 950**	6 250	x15% =	**743**
B737-400	2 950	**5 280**	6 530		**792**
B737-500	2 540	**4 550**	5 630		**683**
B737-800	2 130	**4 040**	5 950		**606**
B757-200	3 330	**5 960**	7 380		**894**
B767-300ER(a)	4 090	**7 590**	11 080		**1 139**
B747-400(a)	8 430	**10 730**	11 970		**1 610**
A319	2 670	**5 240**	6 630		**786**
A320	2 720	**4 790**	6 860		**719**
A321	3 180	**5 690**	7 040		**854**
ATR42-300	1 400	**2 510**	3 100		**377**
ATR72-200	1 730	**3 100**	3 830		**465**

(a) Widebodies

All costs are Euros per block-hour (2002) and include burden

To convert these unit costs to *marginal* costs, Annex H of the 'Cost of Delay' study developed a gate-to-gate model whereby the total maintenance cost (including burden) was apportioned between the airframe/components (65%) and powerplant (35%), then distributed across thirteen phases of flight, as illustrated in Figure 1. Over half of these costs (50% of the airframe/components', 60% of the powerplants' - making 53.5% in all) were allocated as fixed, per-cycle costs, and thus frozen out from the marginal delay cost allocation. These per-cycle costs are incurred during the highest intensity phase, i.e. from take-off roll to top of climb, and from top of descent to landing roll. In these phases, a high share of the total wear and tear is experienced and no delays were assumed (a separate airborne phase was allocated for arrival management). The remaining proportion (46.5%) of

the (unit) maintenance costs were allocated approximately equally for the airframe and components costs, across the remaining phases of flight, and using fuel burn as a proxy for workload to apportion the powerplant costs across the phases (fuel burn ratios were found to be very similar by phase for each of the aircraft studied).

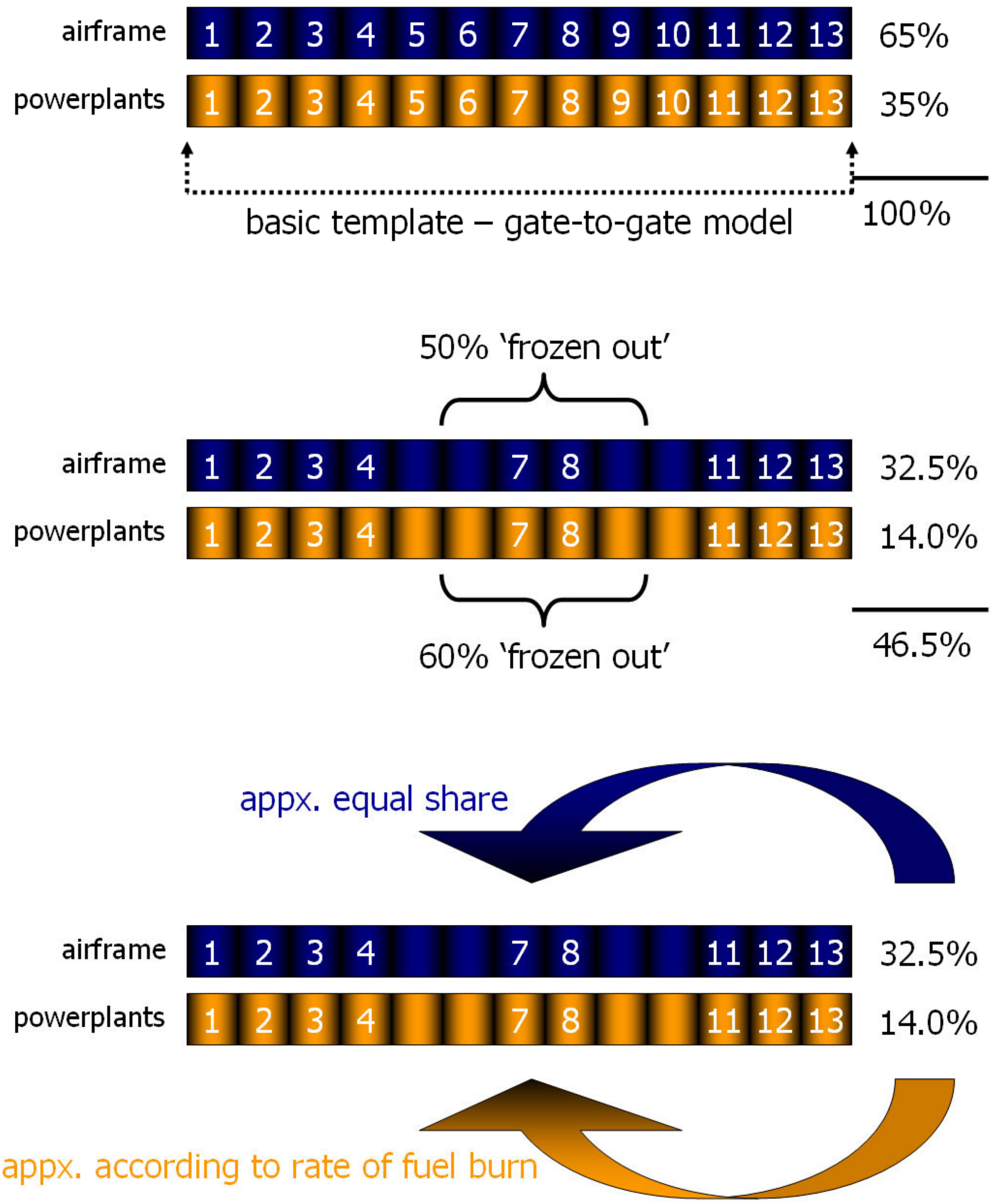

Figure 1 Summary of how Annex H allocates the maintenance cost by minute of delay

4 Calculating unit maintenance costs for 2008

Although the 'Annex H' approach described in the previous section is a fairly crude method for deriving marginal minute costs, it was derived partly in consultation with industry experts, has been presented at several maintenance conferences, and undergone airline peer review. It was decided that a similar approach would be taken within the context of the Dynamic Cost Indexing study. The new costs were derived in two basic steps: first, updating the 2002 values to 2006, then from 2006 to 2008.

However, some of the assumptions demonstrated to be valid in 2002[5] are no longer applicable in 2008, and two enhancements to the method have been developed. The enhancements will be referred to later in the discussion. Regarding the assumptions, through a literature review and consultation with industry experts, two key trends have been identified:

- The cost of fuel has greatly increased since 2002 and continues to do so (the USD[6] price per gallon has risen by approximately 250% to April 2008). This means that BHDOC values are now disproportionately affected by mounting fuel prices, such that the 15% relationship between BHDOC and unit maintenance costs, valid in 2002, could no longer be assumed to hold.

- The cost of maintenance has changed in a highly variable way for a number of airlines. To 2006[7], some have risen sharply since 2002, whilst others have had periods of very large falls, not all of which can be explained by change in the age or composition of aircraft fleets.

In the 'Cost of Delay' study, eight airlines were interviewed and provided detailed operational data for the selected aircraft types. To update the derived 2002 unit maintenance costs (given in Table 3) recent data were sought for the same airlines or their successors/suitable alternatives. The revised eight airlines consist of: Air France, ThomsonFly, CSA, easyJet, Iberia, KLM, Lufthansa and First Choice. Financial and fleet utilisation data were obtained from ICAO for these eight from 2002 to the most recently available year, 2006[8].

BHDOC data to 2006 were also obtained from Airline Monitor to offer a comparison with US airlines (compiled from US DOT Form 41 returns). Whilst relating to US data, Airline Monitor has a useful advantage over ICAO reporting in that data are also given by specific aircraft types (as we shall discuss later). The total cost of maintenance (including burden) calculated

[5] The 'Cost of Delay' study calculations were carried out with data primarily from 2002 and 2003. To ensure consistency with the publicly available EUROCONTROL model (Excel spreadsheet downloadable from: http://www.eurocontrol.int/ecosoc/public/standard_page/documents.html) the 'Cost of Delay' BHDOC values are referenced in this document to 2002.

[6] The strength of the Euro against the US Dollar has offset this somewhat in Europe. EUR/USD exchange rates: 1:1 ('Cost of Delay', 2002) ; 1:1.36 (average for 2007); 1:1.5 (2008 January-May average).

[7] 2006 is the most recent full year of airline financial returns.

[8] 2005 financial and 2003-2006 fleet utilisation data are missing for KLM.

from the ICAO data for each airline, is shown in Table 4. A crude, proportional reduction was made, based on utilisation, for freighters (and also for Concorde in the case of Air France).

Table 5 shows the average maintenance cost per block-hour, and the changes between 2002 and 2006. Two of the three charter and low cost airlines have reported a decrease. Overall, the average increase in maintenance cost per block-hour was only 0.2%. The median increase was 15% (Lufthansa). These values are reported in USD.

Table 4 ICAO total maintenance costs, by airline

Airline	2002 (USD 000s)	2006 (USD 000s)	% increase
Air France	1 139 123	1 380 133	21%
ThomsonFly	99 161	117 585	19%
CSA	40 546	88 815	119%
easyJet	77 281	197 245	155%
Iberia	285 188	464 587	63%
KLM	576 361	988 813	72%
Lufthansa	939 782	1 285 945	37%
First Choice	80 914	81 738	1%
Total	**3 240 358**	**4 606 867**	**42.2%**

(Adjusted for freighters and Concorde, where appropriate; includes burden)

Table 5 ICAO maintenance costs per block-hour, by airline

Airline	2002 (USD)	2006 (USD)	% change
Air France	1 307	1 539	+18%
ThomsonFly	904	675	-25%
CSA	447	581	+30%
easyJet	632	486	-23%
Iberia	617	915	+48%
KLM	1 262	-	-
Lufthansa	869	996	+15%
First Choice	702	722	+3%
Average	**843**	**845**	**+0.2%**

(Adjusted for freighters and Concorde, where appropriate; includes burden)

Some of the total maintenance cost increases (Table 4) can be explained by large-scale fleet composition changes – for example, by 2006, easyJet had replaced a large number of their older B737-300s with new A319s, with the responsibility for their maintenance and spares

contracted out to 'easyTech' (a ten year joint venture between easyJet and SR Technics). Airline takeovers and maintenance centralisation within an airline group have also had an effect. The following three graphs, with costs indexed to 2002 and plotted for the intervening years, show the maintenance cost fluctuations that have occurred over the four years, and demonstrates the lack of clear overall trends.

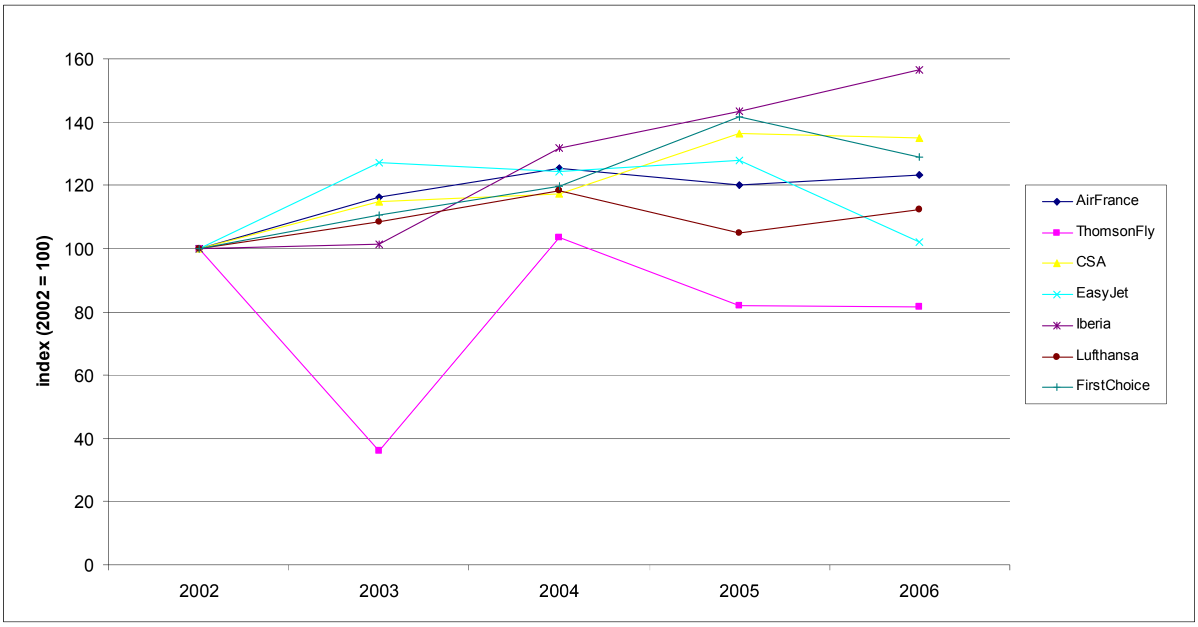

Figure 2 ICAO maintenance cost by aircraft
(Adjusted for freighters and Concorde, where appropriate; includes burden)

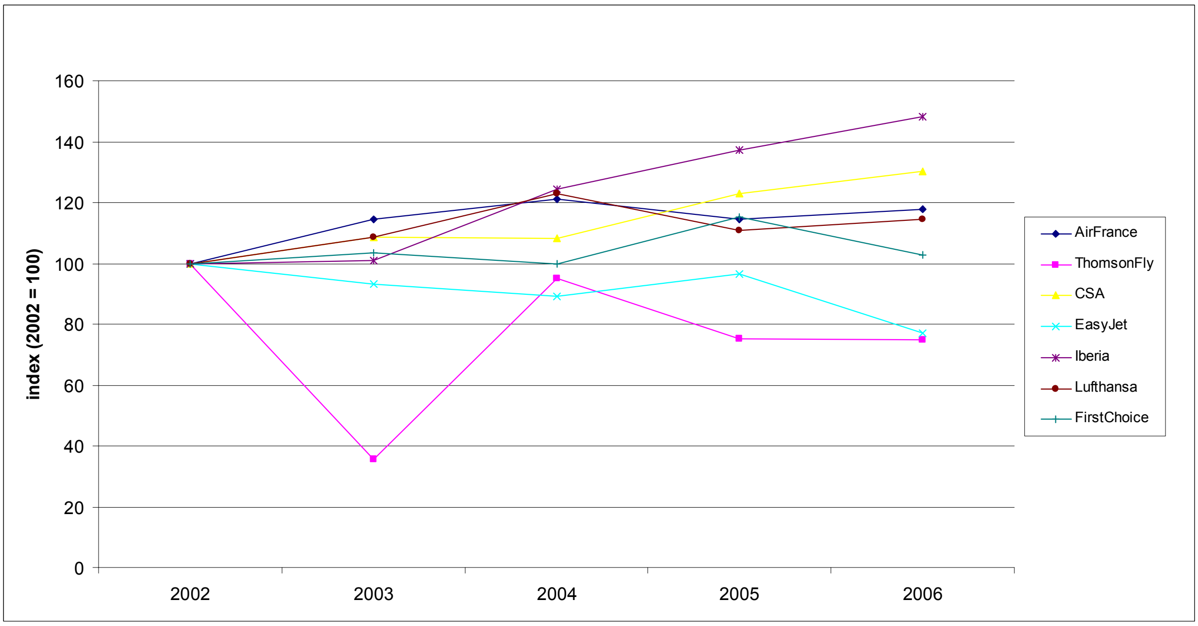

Figure 3 ICAO maintenance cost by block-hour
(Adjusted for freighters and Concorde, where appropriate; includes burden)

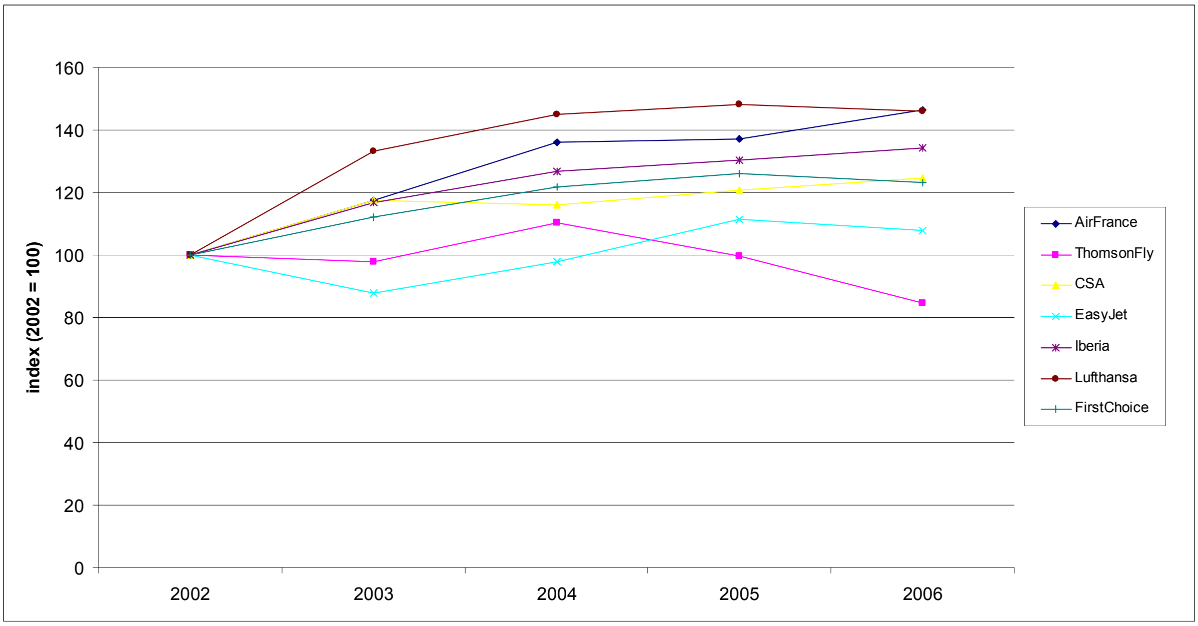

Figure 4 ICAO non-fuel/non-maintenance BHDOC
(Adjusted for freighters and Concorde, where appropriate; includes burden)

Figure 4 demonstrates that the troughs in maintenance costs (e.g. reported by ThomsonFly) do not appear to be offset by other direct operating cost increases. As mentioned, Airline Monitor publishes US BHDOC data compiled from DOT Form 41 returns, which allows a comparison to be made between 'new single aisle'[9] and 'twin aisle' aircraft, as shown in Table 6. Although the data may include freighters (which cannot be corrected for), the average maintenance cost per block-hour for both aircraft categories is reported to have decreased in the US for the period 2002-2006.

Table 6 Airline Monitor average maintenance cost per block-hour, by aircraft size

Aircraft type	2002 (USD)	2006 (USD)	% change
Narrowbody	597	564	-6%
Widebody	1 065	1 031	-3%

A similar, direct comparison was not possible with the ICAO data, due to its aggregated form. However, a series of simultaneous equations were solved to estimate the average narrowbody and widebody maintenance costs per block-hour, for each airline in Table 5. This method used seat-hours as a proxy for unit costs, as justified by the good fit (R^2 = 0.96) demonstrated in Figure 5. The results across the airlines, used to estimate unit cost changes from 2002 to 2006, for narrowbodies and widebodies, ranged from decreases of 30% and 12%, respectively, to increases of 40% and 50%, respectively.

[9] 'Old single aisle' and 'all single aisle' data were not used in this comparison.

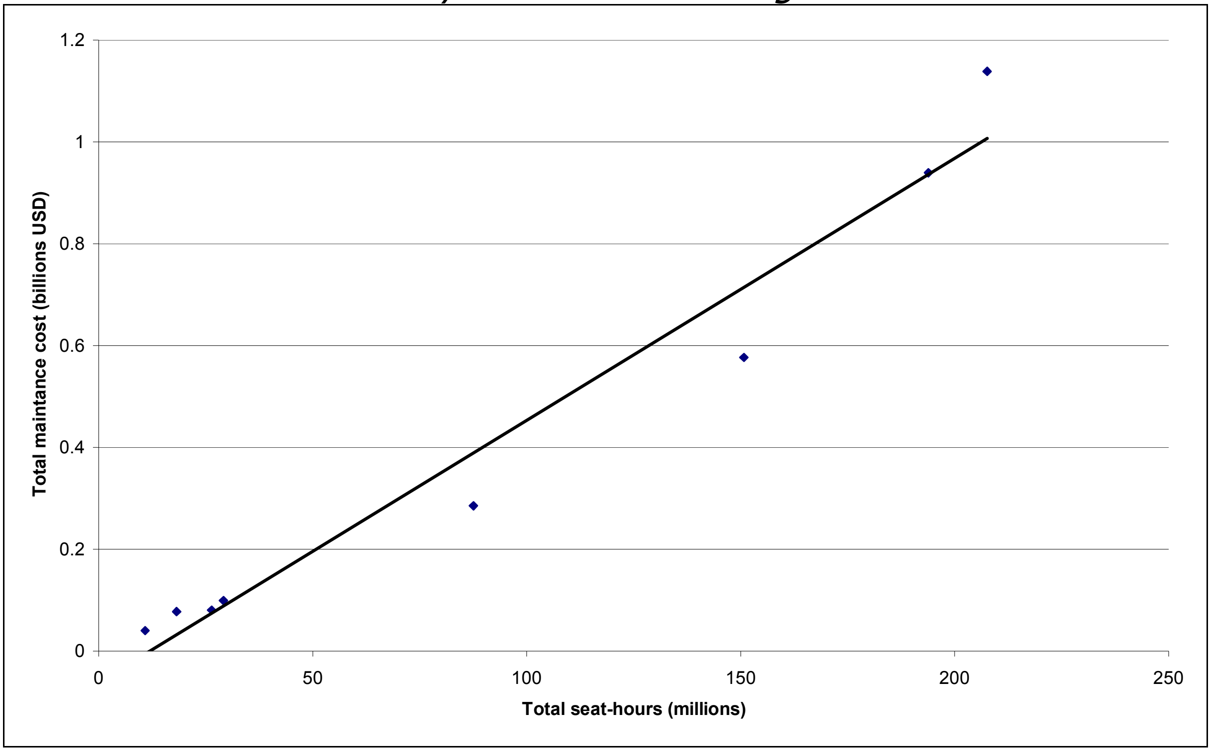

Figure 5 ICAO total maintenance cost by total seat-hours, 2002
(Adjusted for freighters and Concorde, where appropriate; includes burden)

These increases (narrowbodies, 40%; widebodies, 50%) were adopted as the 'high' cost scenario adjustments (see Table 7) to derive 2006 values from the 2002 costs (of Table 3). The 'low' cost scenario adjustments adopted in Table 7 are twice the decreases described in Table 6, and (very close to) half the decreases derived from the ICAO simultaneous equation solutions, thus being nearer to the more limited (but European) data and taking account of the explicit (but US-based) data. Whereas it is relatively more straightforward to reflect these *extreme* cases, it is more difficult to assign representative base change values in the absence of more European data. With reference to both ICAO and Airline Monitor changes, 2002-2006 adjustment values of 0% have been judgementally assigned to the base case, noting that this value is very close to the average described in Table 5.

Table 7 Adjustments to 2002 maintenance costs per block-hour, to derive 2006 values

Aircraft type	Low	Base	High
Narrowbody	-12%	0%	40%
Widebody	-6%	0%	50%

Finally, in the process of obtaining the 2006 maintenance unit costs for each of the twelve aircraft, the ratios of each 2006 aircraft value derived from tables 3 and 7, were compared against the aircraft-specific ratios in the 2006 Airline Monitor data to make a final, *a posteriori* smoothing of the data, to take account of any differential 'creep' in costs between the specific aircraft types, from 2002 to 2006 (i.e. at a finer level of detail than the broad widebody and narrowbody adjustments). It was preferred to do this *a posteriori* to allow the generic widebody/narrowbody method to determine the fundamental, primary changes,

since these could be made with significant reference to European data, even if only at this coarser, aggregated level. The 2006 values were thus proportionately reduced to produce aircraft-specific cost ratios half-way between the raw 2006 values derived, and the values which would be obtained by full adjustment to the Airline Monitor ratios. The major effect here was disproportionately trimming the widebody and A319/A320/A321 values. Airline Monitor does not report ATR data, so these were adjusted in the same way as the B737-300 (they were trimmed by around 10%)[10].

The last step towards estimating 2008 unit maintenance costs, was to inflate the final 2006 values. It is worth noting that by 2006, most of the eight ICAO airlines analysed were paying more for maintenance per block-hour than in 2002 (Figure 3) and none had managed to reduce this cost in each of the four years. It is therefore proposed that most of the potential savings to be made by outsourcing maintenance work and signing PBTH contracts, for example, in addition to improved utilisations, have now been made. A flat-rate increase was therefore applied across all the aircraft, and all scenarios, to inflate the 2006 values to estimated 2008 values. The rate taken was an average of the cost of *supplying* maintenance services (i.e. the increase experienced within the MRO industry, though not necessarily paid by the airlines) and the median increase per block-hour among the study airlines (15%, for Lufthansa, Table 5). The cost of supplying maintenance has risen by 5.5% p/a[11] for these two years (i.e. 11.3% compounded) and the airline median rate (15%) is the equivalent of 3.55% p/a (i.e. 3.55% compounded between 2002 and 2006 gives 15%) – 7.2% compounded over two years. This suggests a compounded increase of 9.25% between 2006 and 2008 (i.e. {11.3% + 7.2%} ÷ 2), across all the aircraft, and all scenarios. The final unit costs are presented in Table 8.

[10] Incidentally, this final set of twelve 2006 values gave ratios very similar to another (unpublished) partial data source available to the authors, which was based on European costs.

[11] Consultation with maintenance managers revealed that between 2002 and 2004 the annual growth in the cost of maintenance supply had been driven down by the terrorist attacks of 9/11, and was 2-3% p/a (a value of 2.5% was used). However, from 2005 onwards, the annual increase has been 5-6% p/a (5.5% used).

Table 8 Maintenance costs per block-hour (2008)

Aircraft	Unit maintenance costs		
	Low	Base	High
B737-300	690	740	900
B737-400	710	760	930
B737-500	570	620	770
B737-800	500	540	670
B757-200	840	900	1 090
B767-300ER [(a)]	930	970	1 280
B747-400 [(a)]	1 440	1 500	1 930
A319	580	630	800
A320	570	620	770
A321	660	720	910
ATR42-300	350	370	380
ATR72-200	430	460	460

(a) Widebody

All costs are Euros per block-hour (2008) and include burden

5 Maintenance cost component of the marginal minute

Having now derived the unit maintenance costs of Table 8, we are in a position to calculate the costs of central interest in the context of Dynamic Cost Indexing – the marginal minute costs.

A similar approach is adopted to that of Annex H, as described in Section 3. A key difference here, however, is that it has been possible to identify maintenance burdens as a typical proportion of unit costs for both widebody and narrowbody aircraft, using Airline Monitor (2006) data. For both types, the burden is approximately 40%, and this has been subtracted from the Table 8 values, before 65% of the remaining variable unit cost was assigned to the airframe/components, and 35% to the powerplants (as before). The same proportions of these (50% and 60%, respectively) were then removed from the marginal minute cost allocation, on the basis that these are per-cycle costs.

To calculate the at-gate marginal minute costs, 20% of the remaining airframe/components-only costs are used, i.e. these at-gate costs assume the engines are not running. The 20% value essentially reflects an assumption that the airframe and components attract maintenance costs at 20% of the typical (marginal), *low-intensity*, off-block cost (for example during taxi and cruise). This value was chosen judgementally, in consideration of the fact that the APU may be running, most electrics and buses will be powered, as will the cabin climate control and avionics, with the airframe and components also exposed to the corroding influences of terrestrial weather.

The marginal minute cruise cost comprises the sum of both the marginal airframe/components costs (off-block, low intensity) and, of course, the marginal

powerplant costs. The marginal powerplants cost for cruise were derived from the low-intensity, averaged off-block airborne phase costs (essentially cruise and holding), adjusted for typical cruise fuel burn ratios, as per the earlier Annex H method, and further adjusted for the typical ratios of time spent in each phase for each of the twelve aircraft types (estimated from published utilisations). If, instead of thus trying to reflect true powerplant wear and tear, flat-rate (by-the-hour) costings are assumed, this will reduce the values shown by between 2% (B747-400) and 10% (B737-800).

From Table 9, it is evident that the airborne marginal costs are seven to eight times higher than the corresponding at-gate costs. The values for cruise could also be used as a good approximation for arrival management, the latter being estimated to be less than 10% lower.

It is to be noted that if the cruise marginal minutes are used in cost assumptions as consistently and significantly extending block-hours, this will itself lower the corresponding unit costs of Table 8, from which these values are derived. When used in this way, this means that the marginal cruise estimates will be higher than the true 'elastic' values. This may be considered as a refinement in future research (see Section 6).

Table 9 2008 maintenance marginal minute costs

Aircraft	At-gate			Cruise (/arrival management)		
	Low	Base	High	Low	Base	High
B737-300	0.4	0.5	0.6	3.6	3.8	4.6
B737-400	0.5	0.5	0.6	3.7	3.9	4.8
B737-500	0.4	0.4	0.5	2.9	3.2	4.0
B737-800	0.3	0.4	0.4	2.6	2.8	3.5
B757-200	0.5	0.6	0.7	4.3	4.6	5.6
B767-300ER	0.6	0.6	0.8	4.4	4.6	6.1
B747-400	0.9	1.0	1.3	6.8	7.1	9.1
A319	0.4	0.4	0.5	3.0	3.3	4.1
A320	0.4	0.4	0.5	2.9	3.2	4.0
A321	0.4	0.5	0.6	3.4	3.7	4.7
ATR42-300	0.2	0.2	0.2	1.8	1.9	2.0
ATR72-200	0.3	0.3	0.3	2.2	2.4	2.4

All costs are Euros per marginal minute (2008) and exclude burden

Figure 6 summarises the work presented in this document on costing the unit (per block-hour, with burden) and marginal (at-gate and cruise, without burden) maintenance costs. It is now possible to compare some of the costs derived with individual values which have been sourced from the literature. Comparing the maintenance costs per block-hour in

published sources[12], with the base scenario values of Table 8, gives ratios in the range of 0.6 (worst case; B747-400) to 1.1 (B757-200), with the other values (B737-300, A320, A321) being 0.8 – 1.0.

This means that our values tend to give slightly high estimates, although in the absence of any officially consolidated and cross-type reconciled European source, such as those of Table 8, it is somewhat difficult to justify further adjustments based on isolated reports. In essence, the unit values produced appear to be rather robust, and objections raised that they are slightly high would doubtless be challenged by carriers such as CSA and Iberia, with four-year increases running at 30% and 48%, respectively (see Table 5).

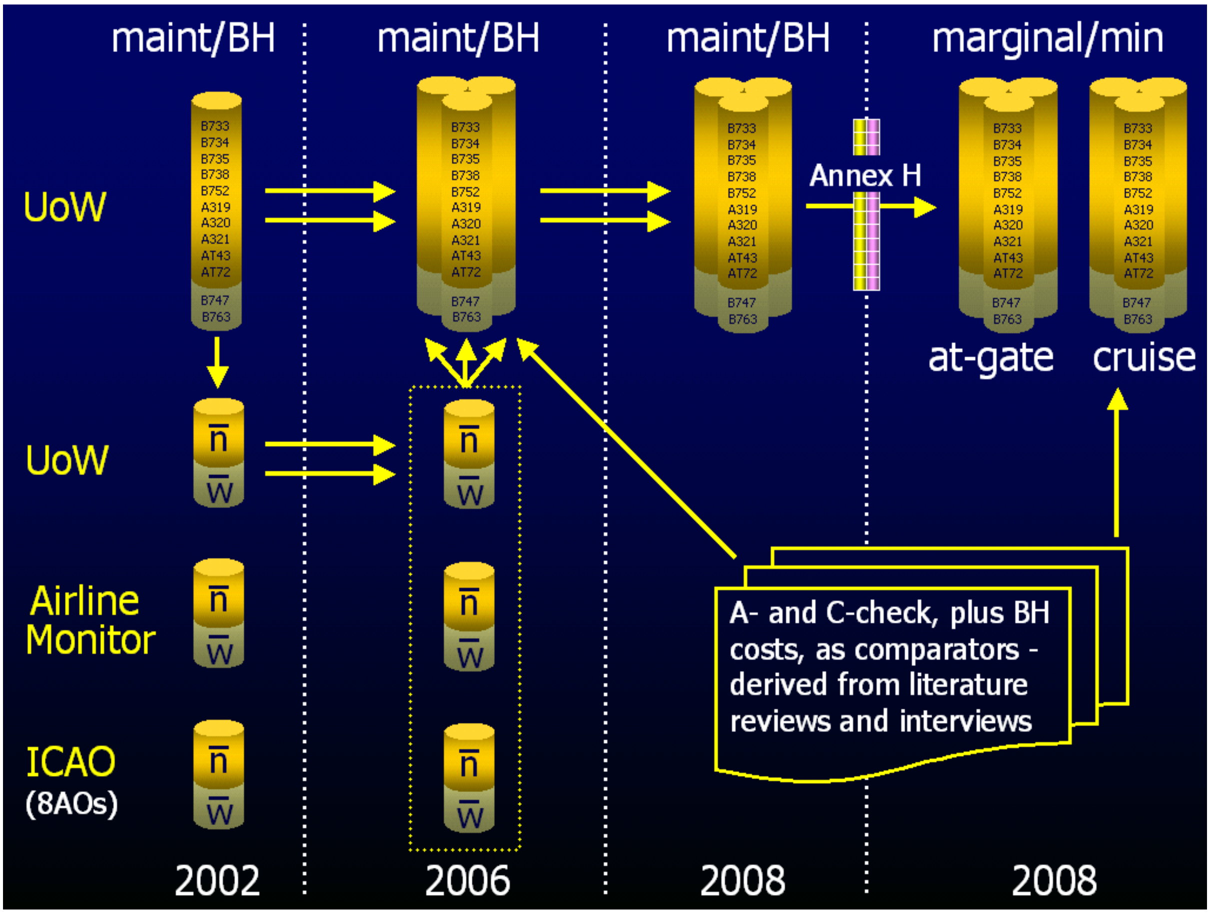

Figure 6 From maintenance cost per block-hour to marginal maintenance costs

Of interest from the Dynamic Cost Indexing perspective, is that the marginal cruise minutes of Table 9 are similar to the literature-sourced values for combined 'A' plus 'C' checks, per block-minute (see Table 10). The literature sources do not consistently report whether burden was included or not, although it is suspected that they all do, except for the B737-800. Crudely correcting for 40% burden, the ratios average out at 0.89. The implication for airlines is that using 'A' plus 'C' check estimates for marginal minute costings probably gives reasonable estimates of the true marginal cost of maintenance.

[12] Corrected to 2008 values in the same manner as our values and using an exchange rate of EUR 1.0: USD 1.5.

Table 10 2008 marginal cruise minute maintenance cost c.f. average 'A' + 'C' check

Aircraft	DCI marginal cruise minute (from Table 9)	Literature average 'A' + 'C' checks	Ratio: DCI base / literature average
B737-300	3.8	5.9	*1.55*
B737-800	2.8	1.9	*0.68*
B757-200	4.6	7.9	*1.70*
A320	3.2	4.4	*1.38*
A321	3.7	4.4	*1.18*

All costs are Euros per marginal minute (2008). Table 9 values exclude burden; see text.
Costs shown for aircraft where literature values were available.

6 Review of status, next steps and priorities

The two major enhancements already made to previous research in this area both relate to the derivation of the marginal minute costs. Firstly, the data used has allowed the maintenance burden to be excluded from the estimations. Secondly, more refined methods have been employed to allocate the at-gate and cruise marginal costs from the averaged off-block costs.

If time permits, we may broaden the ICAO data reference base beyond the airline sample carefully selected for the purposes of the current calculations, and review the issue identified in Section 5 whereby the marginal cruise minute cost estimates (Table 9) may be slightly high. However, both of these enhancements are likely to require significant additional researcher input and are not expected to produce substantial changes in the final output values.

As far as the Dynamic Cost Indexing tool is concerned, the values derived here will allow airlines to use updated, generic 2008 values for marginal maintenance cost estimations, in the typical cases where operators are not in possession of aircraft-specific (or even tail-specific) costs. These generic costs seem to produce similar estimates to those based on 'A' plus 'C' checks, which are currently only used by / available to, a small number of airlines.

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