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Costing Complex Products, Operations, and Support

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14. ABSTRACT

Complex products and systems (CoPS), such as large defense equipment programs are major capital goods in which customers play a central role from design through disposal (Davies & Hobday, 2005). A central idea of the research that this paper reports on is that the degree of complexity in CoPS may have a significant effect on the range of possible variance of their operations and support (O&S) costs. However operational use and other factors also have an important part to play in the complexity of CoPS, which simple ?parts count? approaches may miss. The research design presented is one of a pair of detailed case studies, based on the U.S./UK Harrier combat aircraft. In this work paper, the intention is to explore how different approaches in the U.S. and UK to O&S on the Harrier aircraft have impacted some of the key drivers of costs. In addition, initial comparisons are made with more complex (in parts count terms) aircraft.

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Preface & Acknowledgements

During his internship with the Graduate School of Business & Public Policy in June 2010, U.S. Air Force Academy Cadet Chase Lane surveyed the activities of the Naval Postgraduate School's Acquisition Research Program in its first seven years. The sheer volume of research products—almost 600 published papers (e.g., technical reports, journal articles, theses)—indicates the extent to which the depth and breadth of acquisition research has increased during these years. Over 300 authors contributed to these works, which means that the pool of those who have had significant intellectual engagement with acquisition issues has increased substantially. The broad range of research topics includes acquisition reform, defense industry, fielding, contracting, interoperability, organizational behavior, risk management, cost estimating, and many others. Approaches range from conceptual and exploratory studies to develop propositions about various aspects of acquisition, to applied and statistical analyses to test specific hypotheses. Methodologies include case studies, modeling, surveys, and experiments. On the whole, such findings make us both grateful for the ARP's progress to date, and hopeful that this progress in research will lead to substantive improvements in the DoD's acquisition outcomes.

As pragmatists, we of course recognize that such change can only occur to the extent that the potential knowledge wrapped up in these products is put to use and tested to determine its value. We take seriously the pernicious effects of the so-called "theory–practice" gap, which would separate the acquisition scholar from the acquisition practitioner, and relegate the scholar's work to mere academic "shelfware." Some design features of our program that we believe help avoid these effects include the following: connecting researchers with practitioners on specific projects; requiring researchers to brief sponsors on project findings as a condition of funding award; "pushing" potentially high-impact research reports (e.g., via overnight shipping) to selected practitioners and policy-makers; and most notably, sponsoring this symposium, which we craft intentionally as an opportunity for fruitful, lasting connections between scholars and practitioners.

A former Defense Acquisition Executive, responding to a comment that academic research was not generally useful in acquisition practice, opined, "That's not their [the academics'] problem—it's ours [the practitioners']. They can only perform research; it's up to us to use it." While we certainly agree with this sentiment, we also recognize that any research, however theoretical, must point to some termination in action; academics have a responsibility to make their work intelligible to practitioners. Thus we continue to seek projects that both comport with solid standards of scholarship, and address relevant acquisition issues. These years of experience have shown us the difficulty in attempting to balance these two objectives, but we are convinced that the attempt is absolutely essential if any real improvement is to be realized.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the Acquisition Research Program:

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- Office of Procurement and Assistance Management Headquarters, Department of Energy

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James B. Greene, Jr. Rear Admiral, U.S. Navy (Ret.)	Keith F. Snider, PhD Associate Professor

Panel 18 – Advances in Acquisition Cost Analysis and Estimation

Thursday, May 12, 2011	
11:15 a.m. – 12:45 p.m.	**Chair: Dr. Daniel Nussbaum,** NPS, former Director, Naval Center for Cost Analysis ***Costing Complex Products, Operations, and Support*** Michael Pryce, Manchester Business School ***A Better Basis for Ship Acquisition Decisions*** Dan Billingsley, Grey Ghost LLC/Siemens ***Back to the Future: The Department of Defense Looks Back at the Should Cost Review to Save Buying Power in the Future*** Martin Sherman, DAU

Dr. Daniel Nussbaum—Professor, Operations Research, NPS. Dr. Nussbaum's expertise is in cost/benefit analyses, life cycle cost estimating and modeling, budget preparation and justification, performance measurement and earned value management (EVM), activity based costing (ABC) and Total Cost of Ownership (TCO) analyses. From December 1999 through June 2004 he was a Principal with Booz Allen Hamilton, providing estimating and analysis services to senior levels of the U.S. federal government. He has been the chief advisor to the Secretary of Navy on all aspects of cost estimating and analysis throughout the Navy, and has held other management and analysis positions with the U.S. Army and Navy, in this country and in Europe. In a prior life, he was a tenured university faculty member.

Dr. Nussbaum has a BA in Mathematics and Economics from Columbia University and a PhD in Mathematics from Michigan State University. He has held postdoctoral positions in Econometrics and Operations Research and in National Security Studies at Washington State University and Harvard University. He is active in professional societies, currently serving as the Past President of the Society of Cost Estimating and Analysis. He has previously been the VP of the Washington chapter of INFORMS, and he has served on the Board of the Military Operations Research Society. He publishes and speaks regularly before professional audiences.

Costing Complex Products, Operations, and Support

Michael Pryce—Research Fellow, Manchester Institute of Innovation Research at Manchester Business School. Mr. Pryce's current research project, *Costing Complex Products, Operations and Support*, is looking at innovative methods of costing future defense equipment. He was previously part of the 10 university Network Enabled Capability Through Innovative Systems Engineering (NECTISE) research teams, exploring organisational aspects of Through Life Systems Management. Mr. Pryce's part of the project looked at availability contracting on the Royal Air Force's Harrier and Typhoon aircraft programmes, and the design of the UK's new CVF aircraft carriers. [Michael.Pryce@mbs.ac.uk]

Abstract

Complex products and systems (CoPS), such as large defense equipment programs, are major capital goods in which customers play a central role from design through disposal (Davies & Hobday, 2005). A central idea of the research that this paper reports on is that the degree of complexity in CoPS may have a significant effect on the range of possible variance of their operations and support (O&S) costs. However, operational use and other factors also have an important part to play in the complexity of CoPS, which simple "parts count" approaches may miss.

The research design presented is one of a pair of detailed case studies, based on the U.S./UK Harrier combat aircraft. In this work paper, the intention is to explore how different approaches in the U.S. and UK to O&S on the Harrier aircraft have impacted some of the key drivers of costs. In addition, initial comparisons are made with more complex (in parts count terms) aircraft.

Introduction

Life cycle costing of defense equipment for long-term operations and support (O&S) is extremely challenging. The estimating of system update costs, changes in the roles and missions that systems are used for, and shifts in the commercial and customer organisations that use and support equipment provide major uncertainties and make predictions of costs highly problematic.

The research that this paper is based on seeks to address these issues by exploring complementary methods to existing costing approaches to help identify the range of variance in O&S costs. It does this through a number of comparative case studies. These are intended to illustrate the feasibility of comparative case studies in identifying the nature and scope of cost variance.

The full report on this research will cover the cases, and other O&S related issues, in greater detail than this paper. However, the introduction of some of the cases in this work is intended to allow discussion of the state of the research at the present time and to guide its future development.

Background

The costing of major defense projects is an area of perennial difficulty. With ever-rising program costs, and constant pressure on budgets, decision-makers are faced with a need for the highest-quality, robust cost estimates at the start of programs in order to allow the best informed decisions to be made.

While much work, over many decades, has been focused on estimating the costs of research and development (R&D), this activity still poses problems, as evinced by recent escalations in the Joint Strike Fighter program's R&D cost estimates. However, an area of even greater challenge is operations and support (O&S), which is frequently where the largest part of overall weapon system life cycle costs reside. The unpredictability of the scope and role for the future use of major weapon systems, the multi-decade duration of their use, the increasing gaps between programs rendering analogous data "stale," the extent and timing of major platform upgrades, etc., add up to a series of major challenges for cost estimators looking at O&S (Kirkpatrick, 1993).

The need to make decisions that ensure that force levels and structures can be sustained over program lifetimes, while still at the early stages in a program, shows how understanding the degree of possible variance in O&S cost estimates matter—they can form the greater part of overall life cycle costs (LCCs). If they turn out greater than their estimated baseline then military force structures and capabilities may suffer, while legislators need to be aware of any potential for Nunn-McCurdy-type breaches that can lead to major re-planning of programs, with attendant delays, etc. All of these factors mean that continued efforts should be made to ensure that the factors affecting O&S costs are understood and captured in estimates.

Currently, the approach used by the U.S. Department of Defense (DoD) is mandated through DoD Directive 5000.4 (USD[AT&L], 2006) and implemented by the Cost Analysis Improvement Group (CAIG). The approach taken is one of analytical cost estimates, using analogies from similar, older programs (where possible) to provide proxy data. A major problem in this is that new technologies (e.g., the move from aluminium to carbon fiber structures) may make it very difficult to "read across" old cost data. For some programs, it is also possible to provide "bottom up" estimates using the composition of more detailed cost estimates for components, sub-systems, etc., to build up an overall system cost (Arena et al., 2008; OSD-CAIG, 2007). However, this approach is often not practical in the early stages of programs, where detailed design data is not available.

The research that this paper reports on seeks to explore a complementary approach to current analytical methodologies in early program stages, in order to add to the robustness of cost estimates. It aims to enable better estimates of overall costs to be made by exploring ways of understanding of the degree of possible cost variance from the baseline provided by analytical techniques.

Research Approach

In the acquisition of complex products and systems (CoPS), such as large defense equipment programs, customers play a central role, from design through disposal. As part of the work undertaken in the CoPS Innovation Centre at the University of Sussex in the United Kingdom, an exploration was undertaken of how civilian firms that create CoPS in fields such as communication and transportation move through the value chain by shifting their "centre of gravity" (Davies & Hobday, 2005). This is typically done to allow them to modify their business model to profit from O&S activities and to ensure that the customer gets a better product and/or better value for his or her money. Implicit in this idea is the ability of organisations undertaking O&S for CoPS to change the way that the activities in O&S are carried out to reduce costs for a given capability, with support for this coming from Gregory (1989) and Hurcombe (1989).

This provides a counter to the notion put forward by Reed (1978) that the O&S costs are effectively "locked in" by fundamental design decisions taken early in a program. Reed suggests that this holds true for all combat aircraft, based on extensive empirical case studies, and that the chances to change maintenance costs are limited by this.

Both of these views have problems. The first is that Davies and Hobday are looking at CoPS that are far more predictable and relatively “static” in their use (e.g., telecoms, construction, railways) compared to the more “dynamic” nature of use that many defense equipment programs face. Second, Reed notes that the O&S lock in of costs may only apply to equipment where system repair is undertaken by replacement (rather than repair) of components.

These two issues mean that there is a need to explore further whether the type of equipment affects O&S costs, as well as whether the nature of O&S activities affects the degree of cost lock in. Is it the case that what can be termed “Dynamic CoPS” —such as combat aircraft, with major issues around operations in many changing situations, with variable levels of use/damage over many years—cannot be predictable enough in use to benefit from different solutions to their O&S needs? Is it also the case that by exploring the way Dynamic CoPS are supported, beyond repair by replacement, lock in of costs can be avoided? If this is the case, how does one design new equipment, or modify old equipment, to benefit from such an approach (for current approaches to such design, see Woodford, 1999)?

The research design to explore these questions is one of a set of detailed case studies, based on the U.S./UK Harrier combat aircraft. This aircraft currently serves with the United States Marine Corps and served with the UK Royal Air Force and Royal Navy until the end of 2010.

The main comparisons in this paper are between UK and U.S. Harrier costs, with the U.S. F/A-18 program and the UK Tornado also featured. The data used has been made available by UK sources. This work will be further extended by using U.S.-originated data and the concepts of other researchers in the field, such as Raman et al. (2003) on the F/A-18, to assist in the findings to be reported at the end of the program of research.

The main idea explored in the cases is that the degree of complexity in a project may have a significant effect on the range of possible variance in O&S costs. An initial assumption, that will be tested using the cases, is that the greater the degree of complexity, the narrower the “room for manoeuvre” in reducing O&S costs. Essentially, the idea tested is that greater complexity brings greater cost lock in. Figure 1 shows an overview of the case studies.

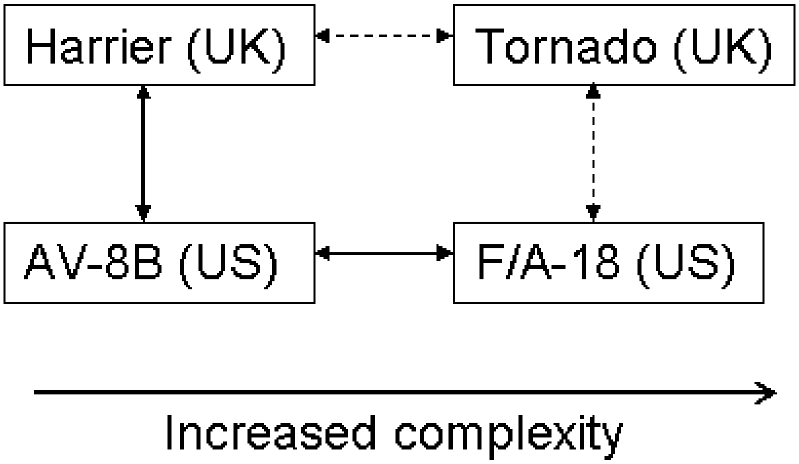


Figure 1. Aircraft Program Comparison Framework

The cases explore the following aspects of O&S:

1. The degrees of variance in O&S requirements between Harriers in the UK and U.S. and other aircraft (F/A-18 and Tornado), to establish how the degree of "designed in" complexity, patterns of operational use, etc., may vary.
2. The UK's Harrier GR.9 upgrade, to explore how design lock in issues were tackled in a system update never imagined by its original designers or users.

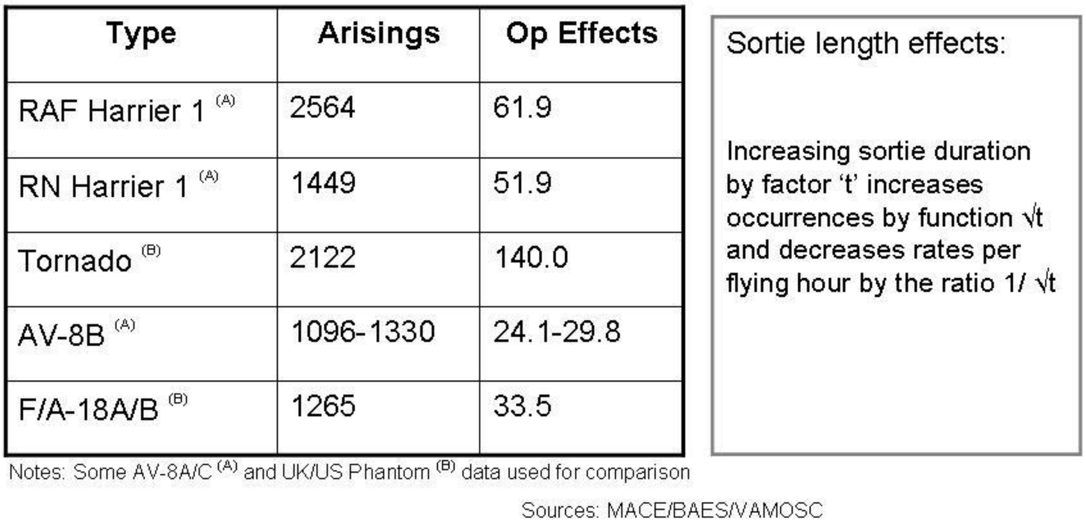
It should be noted that it is an assumption in this paper, and in the ongoing research, that factors such as "arisings" and "operational effects," discussed in the next section, have a rough equivalence in cost terms across all users. This is assumed in terms of the idea that they result in rectification actions that lead to maintenance man hours that are charged at nationally equivalent rates, as well as the consumption of spare parts that have similar costs. On this basis, the factors explored are taken to be good proxies for actual costs incurred over time.

Case Study 1: Aircraft O&S, Design, and Use

The approach to estimating the degree of complexity put forward in this research is based on the idea that it is not component count or lines of code that matter, but rather the number of interactions, both between engineered components, the way an aircraft is used, and the organisations undertaking the O&S activities on the aircraft. The assumption is that the overall effect of these interactions would be revealed by comparisons between arisings (e.g., defects) and their related operational effects (e.g., "failures"). An aircraft can still continue to fly a mission with an arising, but an operational effect will mean that a mission cannot continue as planned.

Figure 2 provides an overview of the level of arisings and operational effects on a number of aircraft platforms. The data presented are relatively old (mid-1980s) but have the great value of being for a similar period of use for each platform. Finding data that are comparative on such a basis is essential to allow meaningful comparisons to be made.

Three main points should be noted in relation to the data in Figure 2. First, the selection of three variants of the Harrier family, from two “generations” used by the Royal Air Force (RAF), Royal Navy, and United States Marine Corps (USMC), allows the effects of issues such as different levels of technology, operational use patterns, etc., to be compared. Second, for the AV-8B, F/A-18A/B, and Tornado, the data presented are for early production batches during a period where they were still being introduced into service. Third, and of great significance for this research, is the difficulty in comparing U.S. and UK data, which use different accounting practices.



Type	Arisings	Op Effects
RAF Harrier 1 (A)	2564	61.9
RN Harrier 1 (A)	1449	51.9
Tornado (B)	2122	140.0
AV-8B (A)	1096-1330	24.1-29.8
F/A-18A/B (B)	1265	33.5

Notes: Some AV-8A/C (A) and UK/US Phantom (B) data used for comparison

Sortie length effects:

Increasing sortie duration by factor ‘t’ increases occurrences by function $\sqrt{t}$ and decreases rates per flying hour by the ratio $1/\sqrt{t}$

Sources: MACE/BAES/VAMOSC

Figure 2. Aircraft Reliability and Failure Rates
Note. Figures are per 1,000 flying hours.

The comparison between the three Harrier variants illustrates a number of issues. RAF Harrier sorties were of lower duration than Royal Navy ones, as well as being more punishing on the airframe since they were flown at a lower level. The Harrier is well known for subjecting much of its avionics and airframe systems to a punishing acoustic, thermal, and vibration environment, which is the cause of many system failures and was not amenable to prediction using standard methods, test spectra, etc. (see Beier, 1987). Flight at low level and high throttle settings exacerbate these problems, which the data clearly show. However, the box on the right of Figure 2 illustrates that these differences can be simplified into a general statement on the effect of sortie lengths on the occurrence rates for arisings and operational effects, at least for aircraft of a similar technology level.

The Royal Navy Sea Harriers were of a similar technology level to the RAF aircraft, although built five to ten years later, with more modern avionics and some system improvements incorporated. The AV-8B Harriers of the USMC shown in Figure 2 were of a new generation design, incorporating a new wing made of carbon fiber, new avionics, and substantially revised systems. However, the retention of major parts of the fuselage, made in the UK, that were derived from the first generation Harriers allows a good basis for comparison. The data in Figure 2 illustrate that the newer Harriers were more reliable overall. In part, this is due to the new technology as well as to the aircraft being new in service, although they were about the same age as the Royal Navy Sea Harriers and operated from shore and ship in a similar fashion, although on different mission profiles.

The data show that the AV-8B Harriers had similar, if slightly lower, arising rates to the Sea Harriers but much lower operational effect rates. In part, this was due to environmental factors—the weather in Yuma, Arizona, is much better than at Yeovilton in the UK, while operations from ships in the North Atlantic as well as operations in the South Atlantic had an adverse effect on Sea Harrier rates. The greater fuel capacity, and more efficient wing for cruising flight, of the AV-8B allowed longer sorties than those of the Sea Harrier, helping to give a favourable operational effects figure.

Some of the comparisons between the U.S. and UK Harriers were made possible by some data for the USMC's own first generation Harriers. However, conversion of U.S. figures to UK formats do mean that accounting allocations need to be made that may be slightly wrong, hence the spread of figures of the AV-8B and the F/A-18A/B. Although the main figures presented here relate to comparisons between the Harrier family, data are also provided for the more complex F/A-18A/B and the British PANAVIA Tornado GR.1. In the case of these aircraft, it was thought that the major design differences would make comparison more difficult. However, there was some hope in the fact that they are both twin-engined types, and that the complexity of the "swing wing" on the Tornado may have some equivalent in the added complexity of the "navalization" features for the F/A-18 Hornet.

However, as Figure 2 shows, it is apparent that the differences in the arisings and operational effects figures were very significant. This is explicable in part due to factors mentioned in relation to the Harrier data—different mission profiles, different environmental effects, etc., but the data appear to reveal the fact that the F/A-18A/B was inherently more reliable by design. An attempt at "controlling" UK/U.S. accounting differences using old F-4 Phantom data did not provide any greater insight. Additional data recently acquired, and still being analyzed, do show that later batches of Tornado were significantly more reliable. Indications from this data, as well as from interviews undertaken, are that this is in part explicable due to the RAF failing to support the Tornado using the maintenance strategy for which it was designed. This was later rectified, with a marked improvement in reliability, albeit at great cost.

This data analysis is still progressing and is being associated with analysis of the later F/A-18E/F Super Hornet (e.g., by using insights from Raman et al., 2003). However, it is interesting to note the relative similarities between AV-8B and F/A-18 data in Figure 2, both aircraft originating at the same time from the same design team and sharing some systems. Analysis of these similarities, and their causes, is also ongoing and will be reported more fully at the end of the research.

What theses data are beginning to illustrate is the idea that interactions are not necessarily about the number of components parts but rather are caused by a range of factors. The number of components in the Harrier variants were not greatly different between them, but the figures shown in Figure 2 are. These differences come about through the effect of sortie rates, operational flight profiles, and environmental factors etc., which are the sources of the interactions that the aircraft components and the overall system endure.

To understand the factors that affect O&S more deeply, an example of a part of the aircraft that were largely common to all three variants of the Harrier was required. The main undercarriage (landing gear) units were selected[1]. Data for the share of overall O&S LCC

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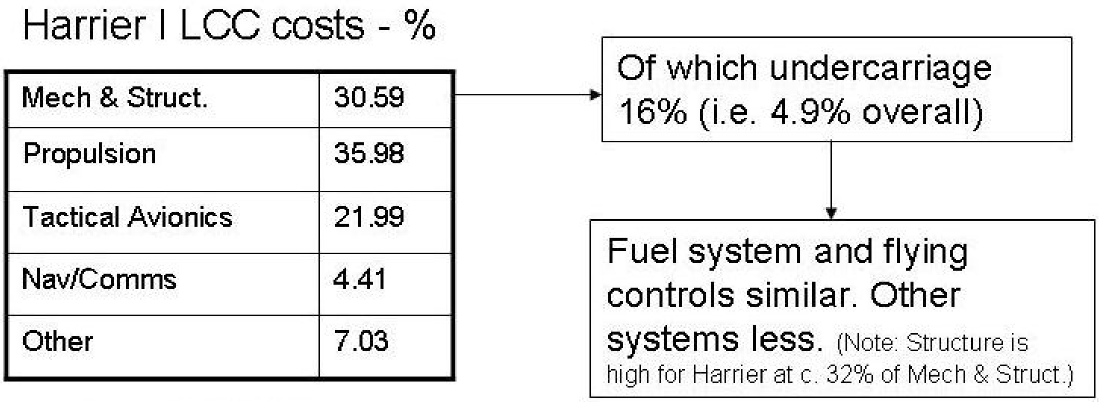
[1] The Harrier has an unusual "bicycle" main undercarriage unit, with wingtip outriggers on the RAF Harrier I/Sea Harrier and mid-wing outriggers of different design on the AV-8B. However, the main units have only minor differences (e.g., some strengthening and lash-down lugs for ship-borne use).

costs of the RAF Harrier I's undercarriage are shown in Figure 3. It can be seen that the undercarriage's share of the LCC O&S costs can be seen as being "typical" of other major systems (i.e., they are not unusual in their percentage of overall costs). This was seen as making them a good candidate to explore further.



Harrier I LCC costs - %

Mech & Struct.	30.59
Propulsion	35.98
Tactical Avionics	21.99
Nav/Comms	4.41
Other	7.03

Of which undercarriage 16% (i.e. 4.9% overall)

Fuel system and flying controls similar. Other systems less. (Note: Structure is high for Harrier at c. 32% of Mech & Struct.)

Source: MACE/BAES

Figure 3. RAF Harrier I Undercarriage (and Other System) LCC O&S Costs

Undercarriage units of combat aircraft are high-value items that are designed to meet an operating life according to a certain assumed spectrum of use. They are built to last and are safety-critical because their failure during takeoff or landing can lead to total loss of the aircraft. Undercarriage units are exposed to heavy stresses throughout their life. These factors can lead to a heavy maintenance burden, with frequent inspections required and repair or replacement often required. For naval aircraft, or STOVL aircraft such as the Harrier, there are many additional sources of fatigue and other damage to the undercarriage, compared to land-based aircraft. One key difference between UK and U.S. undercarriage O&S is that maintenance of such units are a more specialised trade in the U.S., to the extent of personnel specialising down to the level of main or nose gear support.

Operations on the Harrier have led to constant discoveries of undercarriage O&S issues that needed to be addressed. Although the main undercarriage was very robust, being designed to operate off base and to take many unusual loads, such as landing while flying backwards, these discoveries were nearly impossible to predict and meant that the real-world experience of the undercarriage in use differed from the original design spectrum that they were built to meet. For example, as Burton (1996) reports, seemingly minor differences in the build quality of the ski-jump ramps of the UK's Invincible Class light aircraft carriers seriously affected the life of the undercarriage units, depending on which ship the aircraft was being operated from. These build quality differences were not part of the original modelling undertaken for a new ski-jump design and its effect on the aircraft's operating limits and led to cracking in the undercarriage units.

This damage suffered was not particular to the role or mission profile of the aircraft, or to the type of Harrier, but to the particular ship of a class that they were operating from. The damage was expensive to repair but absolutely necessary. This one example is given here to illustrate the peculiarities of the type of incidents that make up the data presented in Figure 2 and to give an idea of how they can emerge unexpectedly. However, the fact that the Harrier's undercarriage was of a robust design meant that there were not any failures—just arisings that were repairable (and are similarly so for the AV-8B; see Hullander &

Walling, 2008). The rate and nature of these arisings, however, were not “designed in,” although the original characteristics of the undercarriage units were. The arisings were due to the peculiarities of the aircraft’s use.

These types of issues have emerged in a range of other examples in the research. Not just the type of operational flight profile but even who is flying the aircraft can have an effect. As one interviewee (ex-Tornado aircrew) put it: “If the same aircraft is flown by the same people every day it doesn’t break.” Put simply, the fewer times switches, ejector-seat rigging, etc., are adjusted, the fewer interactions and the fewer failures occur. So while it is true that the design stage may well lock in some aspects of O&S—some parts are more liable to break than others and some are easier to fix, depending on how they are designed—this is not the whole story.

Case Study 2. Harrier GR.9 COTS Upgrade

The first case study illustrated how the needs for O&S can be affected by operational use. In the second case, we will explore how the interactions in contracting for O&S and their link to operationally urgent updates can be key drivers of costs. We will also look at how these costs can be contained though the use of COTS technology insertion and the innovative approach taken to it. The case explores the update of the mission computer on the Harrier GR.9 program, undertaken by BAE Systems. As Roark et al. (2008) have noted, it is harder to have visibility of costs when O&S is implemented by a contractor, which means that understanding how contractors undertake such activities will be valuable to understanding the causes of O&S costs.

The Royal Air Force’s Harrier GR.9 mission systems update was termed the Harrier Integrated Weapons Programme (IWP), devised to bring together a number of discrete weapon-system enhancement projects. The IWP formed the basis of the GR.9 and T.12 aircraft. Principally, a state-of-the-art MIL-STD-1760 Stores Management System (SMS) was required which, combined with the new High Order Language (Ada) Operational Flight Programme (OFP) software and a new Open System Mission Computer (OSMC), permitted the aircraft to interact with new weapons and sensors.

In April 2002, BAE Systems received an interim contract for the development of the full GR.9 aircraft. A further £150 million contract was signed in January 2003 for non-recurring work, mainly software development and flight testing. The first aircraft flew in May 2003, with an initial batch of aircraft completed by the end of 2003. Operational release occurred in September 2006. The full modification programme had a value of £500 million, including support costs. The update programme was managed through the Future Integrated Support Team (FIST), a joint industry/MoD initiative, with engineering design undertaken at BAE Systems Farnborough and development and flight testing based at BAE Systems’ Warton site. The scope of the Harrier GR9 upgrade work covered the following:

1. baseline recovery, re-design, and re-implementation for significant aspects of the avionic system, together with associated sub-system design;
2. procurement, integration, and testing;
3. a complete recovery and rewrite of the software for the central computer controlling the avionic and weapon systems (some 250,000 lines of code);
4. a major airframe change and the rewiring of the aircraft (over five miles of wiring per aircraft was removed or replaced);

5. the selection and integrated management of major international vendors through competitive tender;
6. providing structural and aerodynamic clearances;
7. the management of five instrumented development Harriers to provide test clearance and certification of each capability; and
8. the manufacturing of parts and equipment and their embodiment to upgrade to GR9 standard across the Harrier fleet. (Pryce, 2009)

It was therefore a very extensive program, involving many participants in the industry, government, the RAF, and the Royal Navy (who operated the GR.9 after their own dedicated Sea Harrier fleet was retired in 2006). Matters were further complicated by the need to incorporate unplanned rapid technology insertion (RTI) activities as a result of ongoing UK Harrier operations in Afghanistan. These tested the ability of the technical systems and organisations involved in the update effort to adjust to changing needs.

At the heart of the GR.9 update was the use of a commercial off-the-shelf (COTS) mission computer system. This shared a common chassis and some cards with the OSCAR mission computer that was used by Boeing to update the USMC’s fleet of AV-8B Harriers. The OSCAR programme had seen the first major use of COTS computing by a U.S. combat aircraft and was, overall, a success. However, it did reveal that, while Moore’s Law may allow a doubling of computer power every eighteen months, the integration and testing cycle on combat aircraft was the key driver of program timescales and associated costs (Adams, 2002; Hoppe & Winter, 1996).

In addition, the timescales during which combat aircraft operate, with the need for ongoing support for decades, is a major issue for COTS insertion—the chips used may well be out of production, and possibly unsupported by their original commercial supplier, many years before the military aircraft they are installed in stop flying. These two timescale issues (testing slowing down COTS insertion, with use ensuring COTS chips’ long-term use instead of rapid replacement) have perhaps been behind the apparent lack of delivery of all the early promises of COTS.

With the Harrier, there are additional issues that exacerbate the testing cycle. Vibration levels are not based on a fixed standard to which a system can necessarily be certificated before use on the aircraft (Beier, 1987). Special certification of aircraft systems is therefore required on Harriers, possibly extending the testing cycle and further slowing and/or limiting COTS insertion. In this environment of technical, contractual, organisational, and operational complexity, with a multitude of interactions between different factors affecting O&S, it is very difficult to know how contractors can plan and/or profit from O&S activities without adding cost upfront (or locking it in for later) due to the difficulties of estimation that such uncertainty brings. However, it appears that the Harrier GR.9 case study does highlight that it can be done.

As with the example of the Harrier undercarriage given above, the mission computer is a safety-critical item. This, in part, explains why the testing cycle is so long—it is necessary to ensure that the safety of the system has been proven, and analytical models or bench testing are not adequate to do this. However, the need to incorporate both pre-planned, incremental capability levels to the mission computer operational flight program (OFP), as well as changing OFP software in response to emerging RTI needs in light of urgent operational requirement emerging from Afghan operations, meant that a stable, relatively slow approach to the testing cycle was not possible.

In order to get the required results in the shortest possible time, BAE Systems' Harrier GR.9 team decided to use a number of shortcuts in developing the safety case of the mission computer. These consisted of both simple tools and methods of working that gave visibility and allowed communication to all participants in the company, its suppliers, and customers in the RAF and Royal Navy (Lucas, 2008). This considerably speeded up the insertion of new technology. Central to the ability to do this was BAE Systems' control of the OFP, rather than control residing in the supplier of the computer itself, or in the customer's O&S organisation. Since the OFP was frequently updated, such control was what allowed BAE systems to speed up the process. The OFP was particular to the Harrier GR.9, unlike on the OSCAR program for the AV-8B, where the OFP was developed as part of a modular OFP "family" for a number of aircraft programs (Logan, 2000). In addition, on GR.9 COTS, software languages such as C++ (as used on the OSCAR program) were used less frequently than the older Ada language, which had a well understood development environment.

With the changes to the OFP being unpredictable, an important way to minimise costs on the Harrier GR.9 upgrade, and in ongoing O&S activities such as RTI, was to minimise the time it took to implement them. While this is a simple enough idea, the example of how the UK GR.9 programme was able to implement them much more quickly than on the U.S. OSCAR program, despite the use of a similar computer and airframe, shows that the issue of design lock-in is not as limiting as may be expected. The flexibility that organisational structures can allow to overcome such "hard" technical features as well as accommodate the unpredictable changes to O&S activities that operational service revealed is a key to controlling future O&S costs.

Discussion, Summary, and Conclusions

In this brief paper, we have seen that the causes of operations and support costs are many and varied. In particular, this variance occurs on platforms such as the Harrier family of aircraft, which are notionally quite similar.

This finding in itself calls into question the idea of using past data to project future costs of new systems. If there are significant differences in the O&S costs and the causes of the costs between similar platforms then it is essential that they are understood in detail before being applied to future designs. It may be that the future design is particularly susceptible to some particular issue that is "lost in the noise" of aggregated data.

A case in point given in this paper is the operation of UK Sea Harrier aircraft from ski-jump-equipped aircraft carriers. The fact that one of these ships caused damage to aircraft undercarriage units was not catastrophic in this case, but in large part, it was due to the undercarriage being of robust design, thanks to very different original requirements. If the undercarriage had been designed by the assumed loads for the ski-jump, modelled as part of the design and clearance programme, it could well have failed in service use, leading to expensive redesign, remanufacture, and modification work.

Similarly, the Harrier GR.9 case illustrates how, despite minor overt differences from the AV-8B, the mission system upgrade was carried out via quicker testing cycles, leading to lower costs than might otherwise have been incurred. Such specific differences between two apparently similar cases would need to be understood before planning and costing the system architecture, O&S infrastructure, and update roadmap of a new platform based on data from them.

Regarding the basic question of technological lock in of costs, it appears that Reed (1978) and others who advocate this view are not correct. Clearly, patterns of operational use, approaches to O&S, and relatively minor differences between successive versions of an aircraft can have a significant impact on O&S activities and, thereby, on associated costs. In the case of related, relatively simple aircraft, as with the Harrier family, this still allows useful data to be gathered on the effects of complexity factors over and above "parts count"–type estimates. Their relative similarity allows for this.

With more technically complex, higher parts count aircraft that are unrelated, it appears that it is not possible to use data from one to predict the O&S costs of another — the Tornado and F/A-18 comparison shows that similarly complex (in parts count terms) aircraft can have very different O&S figures.

Regarding the idea that Dynamic CoPS can benefit contractors through O&S contracting arrangements, despite their much higher levels of unpredictability, compared to static CoPS, the cases drawn from Harrier, at least, show that this may be possible. As such, Davies and Hobday's (2005) work may be applicable. However, it may not be directly applied in an easy form, since using the "solutions" approach they propose to O&S support of combat aircraft would require a detailed, in-depth knowledge of the nature and degree of the variance of possible O&S effects and of the wide range of factors that cause them. These seem much wider, and more unpredictable, than in static CoPS.

Building on these interim findings lies at the heart of the ongoing research program that this paper derives from. With a clear idea of the effect of all the factors, and their interactions, that cause O&S issues and their related costs, it is thought that a more useful method of applying data from existing programs to future ones can be developed. This work is due to be reported by September 2011.

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Costing Complex Products, Operations & Support

Dr Michael Pryce,

Manchester Business School,

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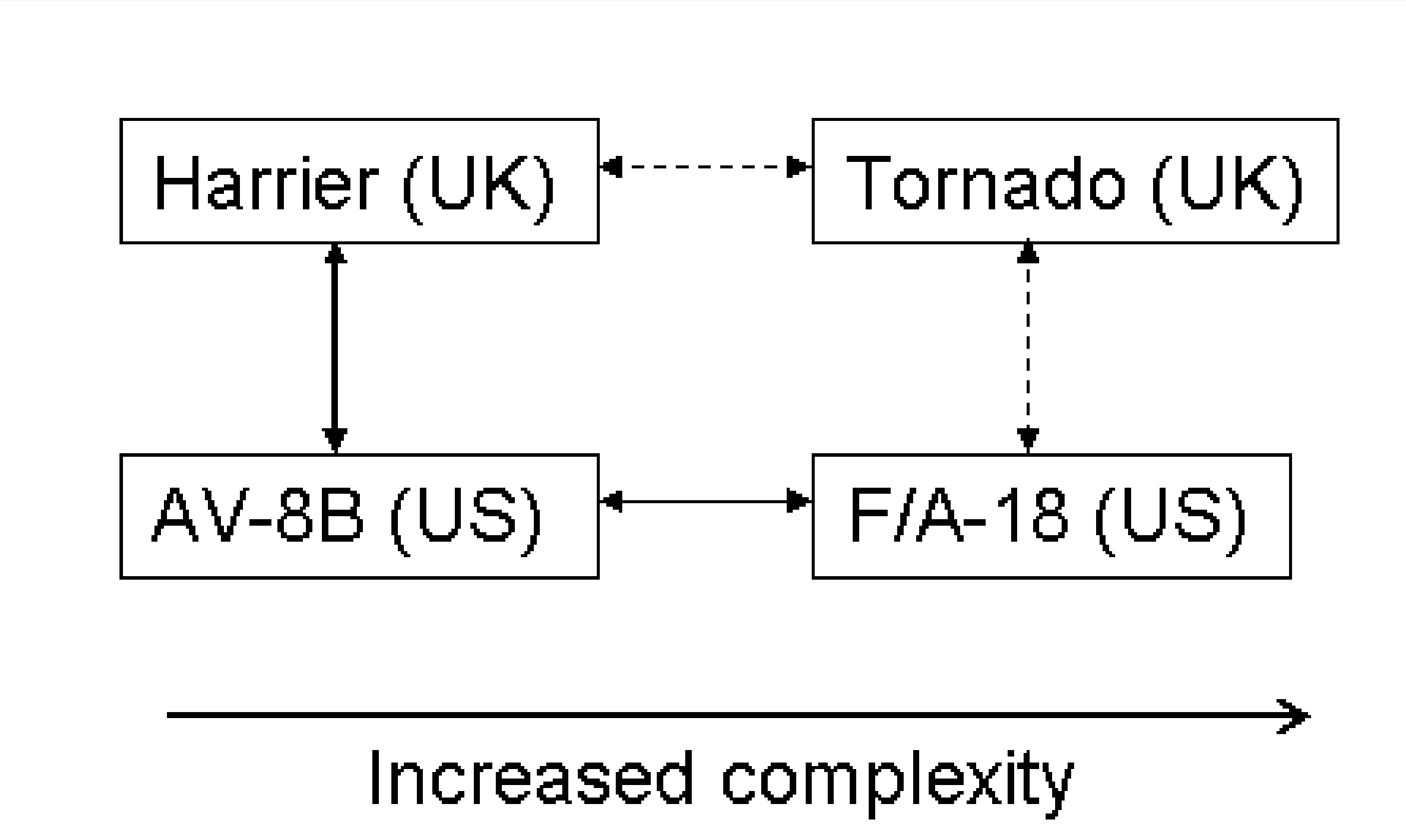
Background

- D.Phil (PhD) in ASTOVL design/policy
- CoPS Innovation Centre, UK
- Understanding nature of design
- Differences and implications
- MBS - NECTISE - Harrier
- Business models for innovation

Research Overview

- Intent is to ‘capture’ complexity/cost variance at early stage of a project, using experience of prior ones.
- Interactions key aspect to be explored, plus ‘core/periphery’.
- “If the same aircraft is flown by the same people every day it doesn’t break.”
- UK based work plus US interviews.
- Aircraft based so far. Ship research also.

Cases



Initial findings

Type	Arisings	Op Effects
RAF Harrier 1 (A)	2564	61.9
RN Harrier 1 (A)	1449	51.9
Tornado (B)	2122	140.0
AV-8B (A)	1096-1330	24.1-29.8
F/A-18A/B (B)	1265	33.5

Notes: Some AV-8A/C (A) and UK/US Phantom (B) data used for comparison

Sortie length effects:

Increasing sortie duration by factor ‘t’ increases occurrences by function √t and decreases rates per flying hour by the ratio 1/ √t

Sources: MACE/BAES/VAMOSC

Initial findings review

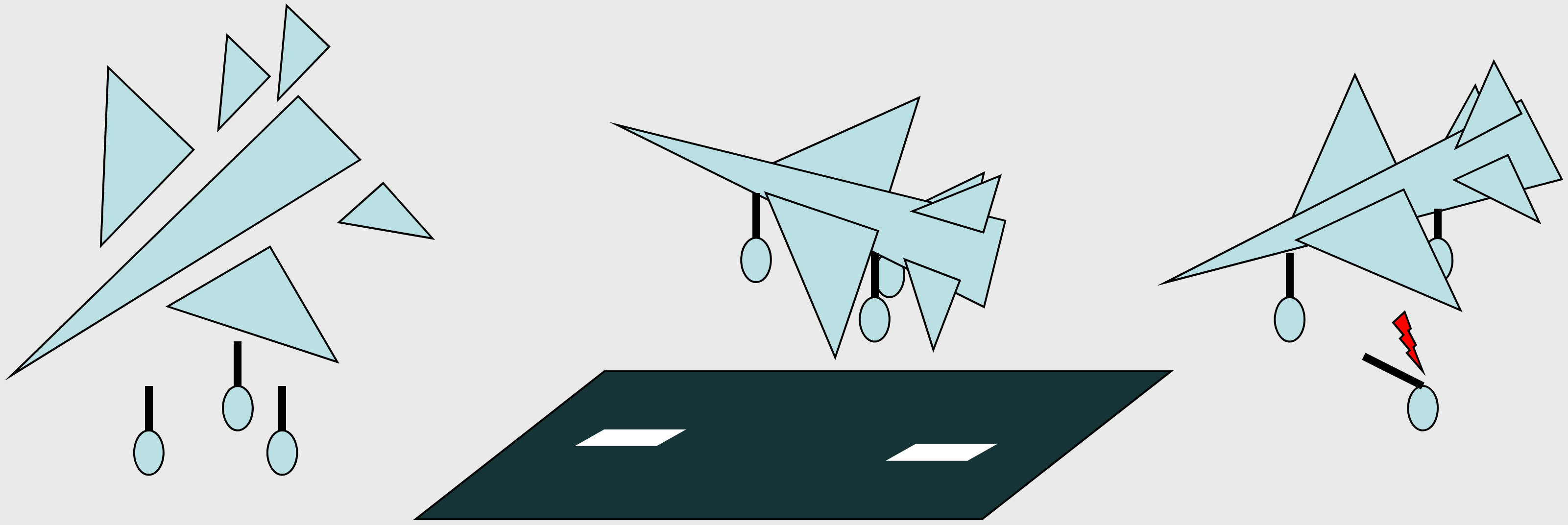
- Assumption is that prediction of these rates (Arisings/Op effects) are more accurate than predictions of costs.
- Literature bears this out.
- Are good proxies for costs, but do not give cost figures.
- Differences mainly due to operational factors, e.g. sortie profile (high/low altitude etc.) as well as length. Also differences in US/UK ‘accounting’, different services’ trade structures etc.
- These are largely peacetime rates, but UK Harrier does include some combat deployment. Peacetime vs. deployed rates are affected by servicing/spares policy (repair vs. replacement).

Undercarriage example

Undercarriage – high value, long lead time. Special material/firms. Built to last.

Exposed to heavy loads throughout life. Emerging technologies – composite struts/electric braking.

Heavy maintenance burden, frequent inspection, many sources of fatigue/damage. Special trade in US.



Undercarriage costs

Harrier I LCC costs - %

Mech & Struct.	30.59
Propulsion	35.98
Tactical Avionics	21.99
Nav/Comms	4.41
Other	7.03

Source: MACE/BAES

Of which undercarriage 16% (i.e. 4.9% overall)

Fuel system and flying controls similar. Other systems less. (Note: Structure is high for Harrier at c. 32% of Mech & Struct.)

OSMC/OSCAR

Similar hardware.

Different approaches.

- COTS benefits.
- But ‘old way’ too.
- ‘It depends!’

Summary

- How to go from ‘thought to thing’ in an affordable way?
- Is supporting what we build affordable?
- Can we learn from old systems when new ones differ?
- Is it possible to ‘capture’ the future in costing?

Thank You