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Costing Complex Products, Operations & Support

19 October 2011

by

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Manchester Business School

The University of Manchester

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Abstract

Complex products and systems (CoPS) are major capital goods in which customers play a central role from design through to disposal, such as large defense equipment programs (Davies & Hobday, 2005). The central idea of the research reported here is that the nature of complexity in CoPS (here referred to as *Dynamic CoPS*, typically combat aircraft) may have a significant effect on the range of possible variance in their operations and support (O&S) costs. Operational use and environmental factors also have an important part to play in the cost of supporting Dynamic CoPS, which simple “parts count” approaches may miss.

The research is based around a set of case studies of combat aircraft. The purpose of the case studies is to explore how different approaches in the U.S. and UK to O&S impact, and illustrate, some of the key drivers of costs in O&S.

Comparisons of the approaches to costing derived from the case studies are made to current practice in the U.S. DoD costing community, as well as to current research on complexity. The findings are presented alongside recommendations for enhanced approaches to costing operations and support of Dynamic CoPS.

Keywords: Costing, defense acquisition, products, complexity, operations, support, maintenance, combat aircraft, complex product systems, CoPS, Dynamic CoPS



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Mike Pryce is a research fellow in the Manchester Institute of Innovation Research at Manchester Business School, United Kingdom. He was previously part of the 10 university NECTISE (Network Enabled Capability Through Innovative Systems Engineering) research team, exploring organizational aspects of Through Life Systems Management. Pryce's part of the project looked at availability contracting on the UK's *Harrier* and *Typhoon* aircraft programs, and the design of the CVF aircraft carriers.

He has taught project management on MSc and MBA programs and organized the *Understanding Projects* seminar series at Manchester Business School.

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Pryce has previously worked in the private sector as a process engineer and business analyst and in web applications development. He holds an MSc in the history of technology from Imperial College, London, where he undertook a "failure study" of the Hawker Siddeley P.1154 STOVL aircraft of the 1960s.

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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 organizations that use and support equipment provide an environment in which major uncertainties make predictions of costs highly problematic.

The research reported here seeks to address these matters by exploring the issues that underlie them, and developing methods to complement and enhance existing costing approaches. These are intended to help identify the range of variance in O&S costs from a baseline figure generated using existing methods. The work is structured in the following three main parts:

- an overview of the key issues, the research approach used, relevant literature, and the current practices and knowledge of costing defense systems, and the relationships between them;
- a set of comparative case studies that illustrate the issues identified and are intended to provide the basic material in identifying the nature and scope of cost variance; and
- a discussion of the issues in light of the case studies, and recommendations for enhanced approaches to costing in O&S.

The report is a summary of the current state of knowledge of the research, and also provides a basis for the next stage in the work (also funded by the Naval Postgraduate School [NPS]), that will look at the application, implementation, and further refinement of the new knowledge of costing operations and support. This is to be carried out under the title *Business Models for Cost Sharing & Capability Sustainment* and will be reported in mid-2012.



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Section I. Overview and Background

A. Key Issues in Operations & Support Costs

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 (JSF) program's R&D cost estimates. However, an area of even greater challenge is operations and support (O&S), which is frequently the area in which the largest part of overall weapon system life cycle costs reside. The unpredictability of the role of major weapon systems, the environments in which they will be used, the multi-decade duration of their use, the increasing gaps between programs rendering analogous data "stale," the extent and timing of major platform upgrades, changes in contractor business models, and other factors (Kirkpatrick, 1993), add up to a series of major challenges for cost estimators looking at O&S that are common across many nations and endure over many decades.

The need to make decisions, while still in the early stages in a program, that ensure that force levels and structures can be sustained over full program lifetimes 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 O&S costs turn out greater than their estimated baseline, then military force structures and capabilities may suffer; 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. All of these factors mean that continuous efforts need to 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 (DoDD) 5000.4 (Deputy Secretary of Defense [DEPSECDEF], 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 with this approach is that new technologies (e.g., the move from aluminum to carbon fiber structures) may make it very difficult to “read across” old cost data (Raman, Graser, & Younossi, 2003). For some programs, it is also possible to provide “bottom up” estimates using the composition of more detailed cost estimates for components, subsystems, and so forth, to build up an overall system cost (Arena, Younossi, Brancato, Blickstein, & Grammich, 2008; Office of the Secretary of Defense—CAIG, 2007). However, this approach is often not practical in the early stages of programs, where detailed design data are not available.

This is of significance as it is often at the early design stages that decisions are made that can have a profound effect on O&S costs. Basic configuration choices, such as the use of an existing or new engine; the use of one or two engines; the use of technologies such as low observables (stealth) or new construction materials/methods or computer system architectures/software, are often made before any detailed costing is possible. That they have a profound impact on later costs is borne out in numerous cases, with the Joint Strike Fighter program perhaps the most high profile example of the moment. In addition, the complexity of designing such systems, let alone operating and supporting them, has led to attempts by the Defense Advanced Research Projects Agency (DARPA) to redefine our understanding of complexity and approaches to designing complex systems.

1. The JSF—O&S Costs and Uncertainty

The Joint Strike Fighter serves as a useful example of the issues raised by the effect of system and program design on costs. The whole purpose of the Tri-Service JSF is to deliver enhanced combat capability using new technologies at an affordable price. According to the official website on the JSF,



The F-35 Lightning II Program (also known as the Joint Strike Fighter Program) is the Department of Defense's focal point for defining affordable next generation strike aircraft weapon systems for the Navy, Air Force, Marines, and our allies. The F-35 will bring cutting-edge technologies to the battlespace of the future. The JSF's advanced airframe, autonomic logistics, avionics, propulsion systems, stealth, and firepower will ensure that the F-35 is the most affordable, lethal, supportable and survivable aircraft ever to be used by so many warfighters across the globe. (Joint Strike Fighter, n.d.)

This is a very tall order, but from early on, the assumption was that affordability across the JSF's lifecycle could be realized by having a large scale program that shared significant commonalities. These commonalities lay across three aircraft variants developed by a diverse set of companies in a number of nations, and used by land and sea based air arms around the globe.

While the subsequent travails of the program have led to significant increases in the cost of research, development, test, and evaluation (RDT&E), it is also notable that a fundamental promise of the JSF—to provide higher levels of capability and technology at a similar or lower cost than legacy platforms—appears likely to be significantly breached. An assessment by the Naval Air Systems Command in 2010 indicated O&S costs 40% higher than the *Harrier* and *Hornet* legacy platforms, and showed that “the ability to influence total ownership cost decrease[d] over time” (Burgess, 2010). Although a rebuttal of the assessment was made by the JSF's prime contractor, Lockheed Martin, it is clear that there is a lack of agreement on the JSF's O&S costs (Trimble, 2010).

This is further borne out by work carried out in the UK for an anonymous JSF customer nation, which revealed the inability of current costing methods to give anything other than a wide, near 100% variance¹ “ballpark” figure (Phillips, 2011). Phillips' approach used a “traditional” one, with data analogies based on older

¹ From \$31 billion to \$58 billion for a 100 aircraft fleet over 30 years.



combat aircraft figures. Phillips states that the final JSF O&S figures produced are not predictions, but allow the estimator only to “speculate” at the cost of ownership.

While it is arguable that the JSF’s O&S costs have been in part “locked in” during design (e.g., by the decision to use stealth technology, or three variants of one airframe, etc.), it is clear that the O&S costs are not just unknown, but that there is no clear basis to either generate them or to decide on whether the degree of variance between estimates have any basis beyond speculation. Such uncertainty is not particularly useful to the decision-maker tasked with approving acquisitions that run into many billions of dollars.

2. META—DARPA’s Approach to Complexity

The fact that costs and timescales in RDT&E are uncertain, and that complexity underlies this uncertainty, is currently being addressed by DARPA in its META initiative. META aims to provide “novel methods for design & verification of complex systems” (Eremenko, 2009) and to break out from what is seen as the strictures imposed by systems engineering methodologies. These strictures are assumed as being likely causes of the inability of defense acquisition programs to control timescales and costs in RDT&E, as they fail to grasp the nettle of complexity as it currently exists.

While it may appear that dealing with the issues caused by complexity in development, including reducing development costs, may have a direct bearing on O&S costs, a number of differences need to be noted. In the findings reported in the case studies of this report, an important driver of O&S costs originates in the operating environment of the system and its interaction with the designed-in features of the system. This is a different situation from the more controlled one of RDT&E. As the case studies aim to show, even the most detailed assumptions and plans for the design, development, and testing of a complex defense system can miss aspects that emerge in operations and support as key drivers of costs.



In their vendor briefing for META, DARPA noted this fact, stating that “unmodeled and undesired interactions lead to emergent behaviors during integration” (Eremenko, 2009). This idea that interactions between components in a complex system are important may well be perfectly valid in the context of RDT&E, but an assumption for the research reported here is that in the sphere of O&S, a more important issue is the interaction of the system with its wider operational environment, as well as the wider commercial environment from which much of the support is obtained.

In META, DARPA gives a provisional definition of complexity as component count for mechanical systems, and source lines of code for software-based systems. This is, by DARPA’s own admission, an unsatisfactory definition of complexity, and their work in META seeks to develop new ones (Eremenko, 2009). However, the META work is focused around the interactions within a system. The research underpinning this report differs in that it looks at the interactions both within a system and the wider interactions that impact on that system through the environment in which it is used and supported.

The work reported here can illustrate some of the differences between the issues surrounding cost in operations and support, and those in the more commonly looked at stages of research, development, test, and evaluation. In addition, it aims to show how O&S relates to RDT&E, both in terms of differences and similarities.

B. Research Approach

The research underlying this report 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 by exploring ways of understanding the degree of possible cost variance from the baseline provided by analytical techniques.



1. Primary Literature and Research Questions

The original proposal that led to this research was based on work looking at the use of academic and engineering literatures that explored the development and support of complex engineered systems and combat aircraft (Pryce, 2009).

The two main works that provide the cornerstones of the literature review in this section have been selected as “primary” sources, as they represent, firstly, the leading synthesis of empirical research into the management of civil complex technologies (Davies & Hobday, 2005), and, secondly, the most comprehensively based, and long-term, analysis of the causes and effects of design decisions on the support costs of military aircraft (Reed, 1978).

In the acquisition of complex products and systems (CoPS), such as large defense equipment programs, customers play a central role, from design through to disposal. In addition, it is impossible to separate out the “artifact” from its process of manufacture, with the two often being designed in parallel. CoPS are defined by Davies and Hobday (2005) as “any high-cost, engineering-intensive product, subsystem, system, network, software system, high-technology service, capital good or construct supplied by a unit of production” (p. 21).

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 the customer gets a better product and/or better value for money. The supply of a service to meet O&S-type customer needs, as well as the supply of the original artifact, can constitute separate types of CoPS for Davies and Hobday.

Implicit in this idea is the ability of organizations 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 implication means that in the supply of civil CoPS, it is considered possible to deliver a separate, innovative solution to meet O&S needs that is not limited by the design lock-in characteristics of the artifact. For Davies and Hobday (2005), a key way to deliver such solutions is through the ability to develop systems integration skills, which underlie the ability of firms to “move base” in the value stream.

This provides a possible counter to the notion put forward by Reed (1978) that 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 opportunities to significantly control maintenance costs beyond a design-determined limit are minimized by this. Reed (1978) states that “complex systems exhibit a constant failure rate throughout their life,” with lives of 20 and more years looked at. Reed shows that even “get well” modifications, or the introduction of an updated Mark II version of an aircraft, have little effect on its reliability.

Reed (1978) contrasts this with the previously (and subsequently) assumed idea that failure rates should form a “Bath Tub” curve, with an initial period of increasing reliability followed by a level period of system maturity, that is finally followed by a decrease in reliability as the system becomes old.

However, Reed notes that it is possible that such a Bath Tub curve could match the actual costs of O&S actions. However, he implies that as these costs are linked to the failure rates, there is little scope for controlling them. The increase in costs over time, despite the failure rates staying the same, appear to be due to time-dependent effects in the wider support environment, such as the loss of suppliers of component parts in the supply chain, or of types of maintenance skills, or perhaps the need for one type of aircraft to carry all the overheads of a component repair chain after other aircraft types have left service.



For understanding and predicting the costs of O&S in complex defense systems, both these works present us with problems. The first is that Davies and Hobday are looking at CoPS that are far more predictable and relatively static in their use (telecoms, construction and railways) compared to the more dynamic nature of use that many defense equipment programs face. They are also looking at CoPS in which the artifact and the potential O&S solution can be readily separated from each other. This is, in part, a reflection of the relatively static nature of the CoPS they look at.

The second problem is that Reed notes that the O&S lock-in of costs may only apply to equipment in which system repair is undertaken by the replacement (rather than repair) of components. This is significant, as the replacement of component parts (ignoring the time-dependent effects noted previously) will provide a fixed capital cost, and likely a nearly fixed labor cost for fitting the replacement part, whereas the possibility of repairing a component will provide greater scope for flexibility. This is due to the fact that two different failures in a single type of component can be repaired in different ways, while replacement of the same component type is likely to be the same operation. This is especially true in the case of software, in which all minor fixes can be seen as the equivalent of “patching” a component, with costs likely to vary between each fix, while wholesale changes in modular blocks of software bring less flexibility and higher, essentially fixed costs.²

These two issues mean that there is a need to explore further whether the nature and type of equipment being considered affects O&S costs, in this case regarding combat aircraft, as well as whether the nature of O&S activities affects the degree of cost lock-in. For our purposes, we will use the term *Dynamic CoPS* to mean a complex engineered system that operates in a complex environment, with

² The re-certification of safety critical systems is a large, fixed cost that is to be avoided if possible. This point was forcibly made by several interviewees.



neither its operating environment, the role it performs, or the nature and scope of its support systems (including both government and contractors) remaining constant.

The research presented in this report can be seen as answering the following three questions:

- Is it the case that 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 the case that by exploring the way Dynamic CoPS are used and supported, that assumptions that we are constrained by design lock-in of costs can be modified?
- How can we design new equipment, or modify old equipment, to benefit from such an approach?

2. Research Design

The research design to explore these questions is one of a set of detailed case studies, based on the following:

- 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 U.S. F/A-18 *Hornet*, primarily in its first generation (A-D designation) variants, with some data from the later E/F *Super Hornet* also used; and
- the UK *Tornado* strike (GR designation) aircraft, used as a control.

The main comparisons in this report are between UK and U.S. *Harrier* costs, as these are the most readily comparable, and as they are the cases for which the most detailed data and greatest number of interviewees were available.

The U.S. F/A-18 program and the UK *Tornado* are also featured. The data used has been made available mainly by UK sources, although the numbers have been made comparable to data from the U.S. Navy Visibility and Management of



Operating and Support Costs (VAMOSC) database³ and the Operating and Support Cost Analysis Model (OSCAM) cost modeling tool.⁴ This work was further extended by using U.S. originated data, also sourced from VAMOSC, reported by other researchers in the costing and O&S fields, such as Raman et al. (2003) and Price and Coolahan (2011), to assist in the findings.

An understanding of the VAMOSC database structure, its uses, and possible failings was also obtained in order to ensure that the data was used correctly and that its original context was understood, as well as to relate it to the wider framework of U.S. Defense costing under DoDD 5000.4 (DEPSECDEF, 2006).

3. Interviews and Other Data Sources

A number of anonymous⁵ interviews were carried out as part of the research for this report. These were loosely structured, and all interviewees were free to terminate the interview when they wished.

In all cases before interview, a copy of the research proposal that led to this project was provided to prospective interviewees. In addition, e-mail correspondence before the interview gave an idea of the types of questions to be asked.

During interviews the author allowed participants to talk freely about issues that they thought mattered, both during and after their answers to prepared questions. All interviewees agreed to allow follow-up questions to be e-mailed, and in several cases secondary telephone interviews were carried out.

³ Notably the “old” VAMOSC system, before restructuring of the database in 1999.

⁴ The understanding of OSCAM was greatly helped by the “walk through” provided by Dale Sherman of the Society for Cost Analysis and Forecasting.

⁵ A number of interviewees were happy to be named, while others wished to remain anonymous. In order to give equivalent weight to the views of all interviewees, anonymity has been preserved for all.



In addition, informal discussions with contacts made during the research led to correspondence with contacts that were not available for a formal interview but were happy to provide written information to be used in the research.

Additional sources of formal data were obtained from BAE Systems and via the Society for Cost Analysis and Forecasting. In all cases, the people providing the data were available to explain the sources and limitations of it, as well as to make clear the limits of its use.



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Section II. Case Studies

The case studies provide the main empirical content of this report. They are based on a number of combat aircraft programs and are intended to show the nature of the issues that emerge in operations and support. They are also intended to show how these issues, seen as interactions, can explain the causes of cost variance in O&S, as well as suggesting possible ways of using this knowledge to develop better costing tools.

The cases could also serve to highlight, in a form of “backcasting,” how the approaches put forward in Section III of this report could have been utilized in the JSF program. It is telling that the data used in these cases were mostly available at the early stages of the JSF’s evolution in the mid-1990s.

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 variance in its possible O&S costs. An initial assumption, to be tested using the cases, is that the greater the degree of complexity, the narrower the room for maneuver in reducing O&S costs. Essentially, the idea tested is that greater complexity brings greater cost lock-in, similar to that expounded by Reed (1978). Figure 1 shows an overview of the case studies to be looked at.

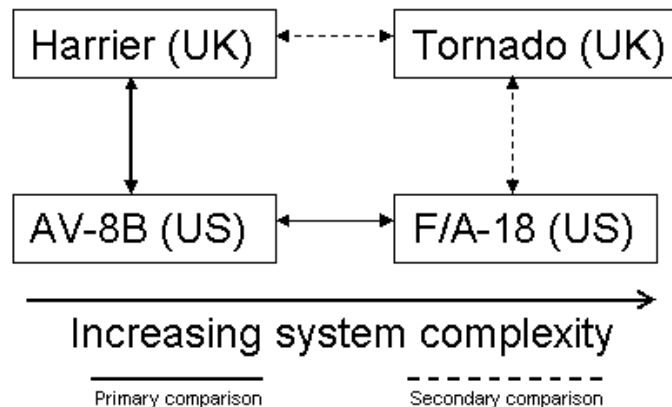


Figure 1. Aircraft Program Comparison Framework



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, and so forth, may vary; and
2. the UK’s *Harrier* GR.9 upgrade and the U.S.’s AV-8B OSCAR upgrade, to explore how design lock-in issues were tackled in system updates never imagined by their original designers or users.

It should be noted that it is an assumption in this report 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 to mean that they result in rectification actions which 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.

A. 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 source lines of code that matter, but rather the total number of interactions between engineered components, the way an aircraft is used, and the organizations undertaking the O&S activities on the aircraft. The latter two areas are referred to as the *environment*, that is, all that is external to the system itself.

The assumption is that the overall effect of these interactions, whether they originate from designed-in features or from the wider environment, would be revealed by comparisons between the number and type of defects experienced during service use of the aircraft and the related failures these defects produced on the aircraft.

The defects are here called *arisings*, and the failures *operational effects*, in line with UK O&S language. 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. An important aspect is that the link between arisings and operational effects is not necessarily a technical one, but subject to operational use and maintenance patterns. The purpose of this detailed examination of these figures is to see how such use patterns interact with the aircraft to produce an overall pattern of O&S costs.

1. O&S Data Analysis

Figure 2 provides an overview of the level of arisings and operational effects on the aircraft platforms that form the basis of the case studies. The data presented are relatively old (mid-1980s), but have the great value of being for a similar period of use for each platform and having been cross checked from a number of data sources that have additional contextual explanations for their sources. Finding data that are comparative on such a basis is essential to allow meaningful comparisons to be made.

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

Sortie length effects:

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

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

Figure 2. Aircraft Reliability and Failure Rates

Note. Numbers are per 1,000 flying hours.

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, and so forth, to be compared. These can be considered as forming much of the *environment*, external to the technical features of the aircraft.

Second, for the AV-8B, F/A-18A/B, and *Tornado*, the data presented is for early production batches during a period in which they were still being introduced into service. This may mean that there was an improvement in reliability in subsequent years, although discussions with one interviewee, who used this data in support of *Harrier* aircraft, revealed their belief that for all but the *Tornado*, the data were robust. The *Tornado* data was complicated by the persistent unreliability of the type during the 1980s and the changes introduced in a major “get well” program. Cross checking with figures given by Hurcombe (1989) indicates that the *Harrier* I and AV-8B data would be accurate, and gives an explanation for the *Tornado* data that would indicate it was not inaccurate.

Third, and of great significance for this research, was the difficulty in comparing U.S. and UK data which use different “accounting” practices. Access to the old VAMOSC database, and cross checking with the work of Raman et al. (2003), indicates that much of this difficulty can be avoided by the use of the old VAMOSC data, which has been used here.

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. data to UK formats does mean that accounting allocations need to be made that may be slightly wrong, hence the spread of data points for the AV-8B and the F/A-18A/B.

The comparison between the three *Harrier* variants in Figure 2 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 as they were flown at lower altitudes. 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, and so forth (see Beier, 1987). Flight at low level and high throttle settings exacerbate these problems. On the other hand, naval operations introduce issues of corrosion not present on land, although the youth of the *Sea Harrier* fleet for the period under study happily makes this relatively unimportant for the period covered by these data.

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. These sortie lengths are a product of the operational pattern experienced by the aircraft, and of their different roles, with the *Harrier I* used for ground attack, and the *Sea Harrier* primarily as an air combat fighter.

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 some revised airframe systems. However, the retention of major parts of the airframe (manufactured in the UK), most significantly the rear fuselage that experiences the harshest loadings in the *Harrier* (and the systems—hydraulics, electrics, conditioning—contained within it), as well as the undercarriage units, that were all derived from the first generation *Harriers*, allows a good basis for comparison between the three types of *Harrier*.

The data shows that the AV-8B *Harriers* had similar, if slightly lower, arising rates to the *Sea Harrier*, but much lower operational effects rates. In part this was due to environmental factors, such as weather. Put simply, the weather in Yuma, Arizona, is much drier than at Yeovilton in the UK, while operations from ships in the North Atlantic, as well as on combat operations in the South Atlantic, had an adverse effect on *Sea Harrier* rates. This is due to moisture causing electrical failures, rather than any corrosion. 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 favorable operational effects figure.

Although the main data presented in Figure 2 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 that 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, and so forth—but the data appear to reveal the fact that the F/A-18A/B was inherently more reliable by design than the *Tornado*. An attempt at controlling UK/U.S. accounting differences using old F-4 *Phantom* data did not provide any greater insight. Additional data showed that later batches of *Tornado* were significantly more reliable, as a result of the get well program reported by Hurcombe (1989).

This program was very costly, with the equivalent of more than 100% of the basic *Tornado* component count being replaced. Indications from this data, as well as from interviews undertaken with experienced aircrew now working in industry, 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, but that during operational deployments (notably to warm, dry climates), the correct servicing and spares approach was followed, significantly improving reliability.

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 has



shown that a significant factor behind this lay in the use of improved manufacturing techniques for the *Harrier* and *Hornet* at what is now Boeing, St. Louis. Cross checking with F-4 *Phantom II* data appeared to back this up. This was further reinforced by an interviewee who was familiar with first and second generation *Harriers* and *Hornets*.

In short, the use of more accurate assembly techniques, derived in part from computer aided design and computer aided manufacture, allowed for improved repeatability in the installation of equipment. This meant that a smaller number of mechanical interactions between poorly secured components emerged in service than on previous aircraft types.

This data illustrates the idea that interactions are not simply about the number of components parts, but rather are caused by a range of factors. It can certainly be said that the number of components, and the number of their interactions, is not the proper measure of complexity. The number of components in the *Harrier* variants was not greatly different between them, but the data shown in Figure 2 reveals widely varying arising and operational effect rates. These differences come about through the effect of interactions both within the system and without it, in the wider environment of manufacture, use, and support. Factors such as sortie rates, operational flight profiles, the nature of maintenance patterns, manufacturing technologies, and so forth, are the sources of the total set of interactions that the aircraft components endure.

2. Undercarriage Example of Detailed O&S Matters

To understand the factors that affect O&S more deeply, an example of a part of the aircraft that was largely common to all three variants of the *Harrier* was



required. The main undercarriage (landing gear) units were selected.⁶ Data for the share of overall O&S LCC 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 are largely typical of other major systems, that is, it is not unusual in its percentage of overall costs. This was seen as making the undercarriage a good candidate to explore in further detail.

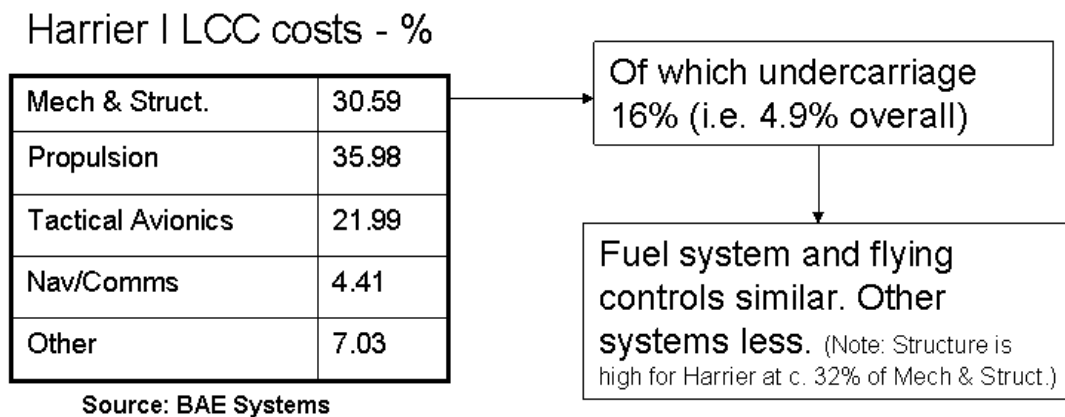


Figure 3. RAF *Harrier I* LCC O&S Costs

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 as their failure during take-off or landing can lead to total loss of the aircraft. Undercarriage units are exposed to heavy stresses throughout their lives, and are subject to widely varying loads depending on the overall pattern of use of the aircraft to which they are fitted.

⁶ 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, for example, some strengthening and lash-down lugs for ship-borne use.

These factors can lead to a heavy, but variable, maintenance burden, with frequent inspections required, and repair or replacement of damaged units often required. For naval aircraft, or short take-off and vertical landing (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 is a more specialized trade in the U.S., to the extent of personnel specializing down to the level of main or nose gear support. In the UK, maintenance is based on a more general trade structure, but that may also mean that all units are inspected on an equal basis of periodicity and degree.

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 near 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 was being operated from. These ship build quality differences were not part of the original design assumptions, or subsequent modeling undertaken for a new ski-jump design fitted to UK aircraft carriers and its effect on the aircraft's operating limits, and led to unexpected, and unexplained, cracking in the undercarriage units.

Upon investigation, down to individual aircraft and mission levels, it was discovered that the undercarriage 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 in order to avoid a catastrophic failure mode that could not be



predicted. Such a failure would lead to loss of an aircraft and likely serious damage to the ship. However, it was avoidable. The issues of the variability of carrier deck design on the class of ships concerned were known to the aircraft design team at least a decade before, with pitting and so forth causing problems on both deck and in the hangar (Brooklands Museum, 1985). However, in the calculation of undercarriage loads carried out during the design of the *Sea Harrier*, a smooth deck was assumed, based on design rules created by the UK Ministry of Defence (National Archives, 1978).

3. Summary of Case Study 1

The undercarriage example has been given to illustrate the peculiarities of the individual incidents that make up the totality of 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 and 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, and so forth, are adjusted, the fewer interactions, and the fewer failures occur.

In summary, while it is true that the design stage may well lock in some aspects of O&S, and it is true that 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. Rather, the total fleet average of arisings and operational effects are caused by a wide variety of interactions between systems on board the aircraft,



between the aircraft and its wider operational and support environment, and beyond, into the interactions of these factors with changes in production and design made without any ability to predict their likely outcomes.

B. Case Study 2: *Harrier* Upgrades

The first case study illustrated how the factors influencing O&S are affected by operational use and other environmental factors. In this second case study, 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 also look at how these costs can be contained through the use of technological and managerial innovations, such as the use of commercial off-the-shelf (COTS) technology insertion.

The second case explores the update of the mission computer on the UK's *Harrier* GR.9 program, undertaken by BAE Systems, and also looks at the comparable Open Systems Core Avionics Requirement (OSCAR) update for the U.S. Marine Corps' AV-8B. As Roark, Devers, Myers, Suchan, and Walt (2008) have noted, it is harder to have visibility of costs when O&S is implemented by a contractor, a problem which is apparently beginning to undermine the utility of VAMOS-type data. This means that to understand how contractors undertake such activities will be valuable to understanding the causes of O&S costs that may not be captured in the data used in current, analytical cost estimation techniques, such as those recommended by DoDD 5000.4 (DEPSECDEF, 2006).

1. *Harrier* GR.9

The Royal Air Force's *Harrier* GR.9 was the last version of the *Harrier II* family introduced in the UK. As such it is similar to the U.S. Marine Corps' AV-8B in basic structure, systems, and powerplant, but differs in its fit of mission avionics. To update the previous RAF version of the *Harrier II* (the GR.7) to become the GR.9, a mission systems update, termed the Harrier Integrated Weapons Programme (IWP), was 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, the latter a two-seat training version.

A principal feature of the GR.9 upgrade was a state-of-the-art MIL-STD-1760 Stores Management System (SMS), 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 test. 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 program had a value of £500 million, including support costs. The update program was managed through the Future Integrated Support Team (FIST), a joint industry/UK Ministry of Defence (MoD) initiative, with engineering design undertaken at BAE Systems Farnborough, and development and flight test based at BAE Systems' Warton site. The scope of the *Harrier* GR.9 upgrade work managed by FIST involved the following:

1. baseline recovery, re-design, and re-implementation of significant aspects of the avionic system, and associated subsystem design;
2. procurement, integration, and test;
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. 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. 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/equipment and their embodiment to upgrade to GR.9 standard across the *Harrier* fleet. (Interviews, Pryce, 2009)

The overall program was implemented in a new way. Traditionally in UK service, first line (e.g., preparation for flight) and second line (e.g., hangar based checks) maintenance had usually taken place using military personnel on the main operating base (or aircraft carrier), with major updates, repair, and overhaul (third and fourth line maintenance) either taking place at a specialized, Ministry of Defence owned and operated facility separate from the main operating base, or in a *return to works* program where aircraft are returned to the manufacturer/support company for work to be carried out.

However, the modifications for the *Harrier* GR.9 update were embodied using a novel organizational structure. The Joint Upgrade and Maintenance Programme (JUMP) involved both scheduled maintenance and upgrade activities centered on a single main base location, with industry and military personnel co-operating in so called *depth* servicing (combining some second and all third and fourth line work). This was carried out using a *pulse line*, involving concepts adapted from lean manufacturing, to speed up the work and reduce costs.

It was therefore a very complex program, involving many participants in 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 that emerged after the program was planned. These tested the ability of the technical systems and organizations involved in the update effort to adjust to new requirements while still implementing the existing plan.



At the heart of the *Harrier* GR.9 update was the use of a COTS mission computer system, provided by GE Aviation (formerly Smiths Aerospace). 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* (see the discussion on this later in this section), but development was handled by the UK FIST team as if this was a new project. Key to the program's successful execution was the fleet of development test aircraft. With all *Harrier* aircraft, there are additional issues that exacerbate the testing cycle for modifications and new variants. Vibration levels for *Harrier* avionics are not based on a fixed standard to which a system can necessarily be certificated before use on the aircraft (Interview, Beier, 1987), unlike other aircraft, which can use such standards. Due to the intense, engine induced vibration experienced in the rear fuselage of the *Harrier*, special certification of aircraft systems are required. These can possibly extend the testing cycle of upgrades and/or limit COTS insertion. Of particular importance is that when safety critical systems are being updated, COTS "can rapidly lose their attraction" (according to a BAE *Harrier* interviewee).

As with the example of the *Harrier* undercarriage given in Case Study 1, the mission computer is a safety critical item. This, in part, explains why the testing cycle can be 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 pre-planned, incremental capability levels to the mission computer operational flight program (OFP)—as well as the need to change OFP software in response to emerging RTI needs in light of urgent operational requirements emerging from operations in Afghanistan—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 allowed clear 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 capabilities and technologies, and also made visible to all stakeholders what was being done, and what needed to be done in the future.

Central to the ability to do this was BAE Systems' control of the OFP. Rather than control of the OFP software residing in the supplier of the computer itself, or in the customer's O&S organization, BAE ensured that they had full control over the software upgrade. This allowed them to use the tools and development environment with which they were familiar. The OFP was particular to the *Harrier* GR.9, not being based on a modular re-use of software. In addition, GR.9 COTS software languages such as C++, as used on the OSCAR program, were used less than the older Ada language, which had a well understood development environment. As the OFP was frequently updated, such control allowed BAE systems to speed up the overall development process in response to the needs from Afghanistan.

In order to meet the needs of the operational force in Afghanistan, BAE Systems carried out a number of privately funded RTI programs. One of these was to add a new targeting pod capability onto the *Harrier*. It was found that the enhanced target identification and weapon delivery capability desired could be realized with the integration of the Sniper Pod, provided by Lockheed Martin, and called the Advanced Targeting Pod (ATP) when used on the *Harrier*.

A meeting between BAE Systems and Lockheed Martin in early September 2006 confirmed the feasibility of an RTI program. In a compressed program of hardware and software development, aircraft integration, rig testing, and certification,



the team conducted the first flight just two months after the first RTI integration meeting.⁷

BAE Systems further developed the ATP solution and gave interim clearance advice to enable the Operational Evaluation Unit to conduct trials in less than four weeks from receipt of the Request for Quotation.

Allied to the delivery of the ATP, the *Harrier* fleet was also fitted with new laser guided (Paveway IV) bombs. The integration of these followed the same type of accelerated, RTI program. The data provided by one interviewee shows that this approach reduced timescales on this RTI exercise from 18 months down to three months, with the cost of the integration effort reduced from £15 million to £5 million. It is clear that this approach can work, and deliver greatly reduced O&S costs on system update activities.

This is an interesting case, as the basic ATP system is identical to the internal targeting system to be used on the Joint Strike Fighter, which will serve from UK aircraft carriers.⁸ Current costing of the trials and evaluation of the JSF in the UK are based on clearance for the internal targeting system on board the UK's new aircraft carriers using a far slower testing cycle than was shown to be possible in the *Harrier* ATP exercise. Interviewees from the BAE *Harrier* team were quite clear in their belief that translation of the *Harrier* development environment into the JSF's testing of the targeting system was both possible and would be much cheaper, quicker, and less risky than current plans. By understanding the development environment used by the *Harrier* team, the JSF program could reduce costs in both testing and evaluation

⁷ From September 2006 to April 2007, the RTI programme was funded by BAE Systems, with a contract from the MoD only following in May 2007. This required BAE Systems and the MoD to partner closely, with trust essential to enable this.

⁸ Currently intended to be the F-35C version, previously the *B*, STOVL version.



and subsequent support of the targeting system in UK service.

In this environment of technical, contractual, organizational, 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, and illustrates some of the tools that are needed. It is notable that by accurately costing their work in advance, BAE Systems made good profits on their *Harrier* upgrade work, while delivering substantially reduced O&S costs to the customer.

2. USMC OSCAR Update

The OSCAR program 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).

Unlike the UK's *Harrier* GR.9 update, in the OSCAR program for the AV-8B the OFP was developed as part of a modular OFP "family" for a number of aircraft programs (Logan, 2000). This meant that there was not as close a coupling between the introduction of the new, COTS mission computer and the delivery of the software for the OFP, with the latter using C++ technologies in order to deliver the modularity required. It also meant that the costs of developing the OFP were spread across a range of programs.

The implementation of the OSCAR upgrade was, therefore, superficially similar to the *Harrier* GR.9 update, but in practice they were carried out very differently. A key problem found in OSCAR was that the flight testing timescales were the key driver of the overall update cycle, with the testing cycle taking longer to implement than the rate of *churn* in the delivery of new generations of chips (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 time-scale 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 the early promises of COTS.

In the OSCAR update, the sharing of a common OFP with other platforms and the use of COTS technology that was developed separately from the OFP, meant that costs were hard to identify, but what is clear is that timescales, of both the overall program and of individual capability upgrades, took much longer to implement than on the *Harrier* GR.9. The costing of either program could not use data from the other (BAE and Boeing interviews) in a useful way, beyond the overall update ballpark figures being similar—\$145 million for initial OSCAR RDT&E estimates (Defense Technical Information Center, 1999, exc. shared OFP costs) and £150 for the *Harrier* GR.9, on a roughly equivalent basis (Pryce, 2009).

3. Overview of Case 2

With the changes to the OFP being unpredictable, an important way to minimize costs on the *Harrier* GR.9 upgrade, and in ongoing O&S activities such as RTI, was to minimize the time it took to implement them. While this is a simple enough idea, the example of how the UK GR.9 program 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 organizational structures can allow, to overcome such “hard” technical features, as well as accommodating the unpredictable changes to O&S activities that operational service revealed, is a key to controlling future O&S costs.



Section III. Discussion and Recommendations

A. Research Questions Answered

This report seeks to show that the causes of operations and support costs are many and varied. In Section I, the following three main questions were posed for the research:

- Is it the case that 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 the case that by exploring the way Dynamic CoPS are used and supported, that assumptions that we are constrained by design lock-in of costs can be modified?
- How can we design new equipment, or modify old equipment, to benefit from such an approach?

In the light of the case studies, answering these questions provides some insight into the significance of the research and its bearing on the existing literature.

The issue of predictability of O&S costs for Dynamic CoPS can be seen as depending on understanding the interaction of Dynamic CoPS with their wider environmental context. As the data presented in the first case study shows, once these types of issues are identified, they can illustrate the causation of the differences in O&S figures between similar platforms used and supported in different contexts. Once these issues are understood, an attempt at making predictions of other platforms can be attempted. However, what needs to be borne in mind is that the numerical data, stored in databases such as VAMOSC, are not the end product that is used to produce predictions of O&S costs for future systems, as currently happens using modeling tools such as OSCAM to meet the demands of DoDD 5000.4 (DEPSECDEF, 2006). Instead, the data needs to be interpreted through the prism of the understanding of wider environmental issues (this is illustrated in Figure 4 below).



Regarding the basic question of technological lock-in of costs, it appears that Reed (1978) and others who advocated 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. However, to understand and use this data in a meaningful way requires an understanding, and a way of using, the environmental interactions that underpin the data.

With more technically complex and 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 numbers, even when the data is available and substantial. Here an understanding of the wider environment that causes many of the arisings and operational effects that underlie O&S costs may be of considerable use.

Regarding the design of new systems, or the modification of old ones, the research has led to the interesting finding that it is inside companies that much of the capability to use existing data and experience lies. It seems that Dynamic CoPS can benefit contractors through O&S contracting arrangements, despite their much higher levels of unpredictability compared to static CoPS, with the cases drawn from *Harrier*, at least, showing that this is possible. As such, Davies and Hobday’s (2005) work may be applicable.

However, it may not be directly applied in an easily repeatable form without understanding the wider environmental factors embedded in the experience of contractors’ engineering and management teams. While using the *solutions* approach that Davies and Hobday (2005) propose in O&S support of combat aircraft is possible, it currently depends on a detailed, in-depth, highly contextual knowledge



of the wide range of environmental factors that lead to O&S costs, and the variance caused by relatively minor changes in the interactions between the system and its wider environments on these costs.

1. Case Studies Review

The findings throw into question the idea of using past data to project future costs of new systems based on simple assumptions of similarity of role, parts count, or equivalent weight, and so forth (i.e., approaches that are based on the innate characteristics of a platform or system). If there are significant differences in the O&S costs and the causes of the costs, between similar platforms, then it is essential that the causes of these differences are understood in detail before being applied to future designs. A number of factors that are external to the system that affect its O&S costs need to be taken into account, too. It may be that the future design is particularly susceptible to some particular issue that is “lost in the noise” of aggregated data derived on a systems based view, but which may be clearly illustrated if we look at wider environmental factors that lie outside the platform.

A case in point, given in the case studies, 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, this 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, modeled as part of the design and clearance program, it could well have failed in service use, leading to expensive re-design, re-manufacture, and modification work for the entire fleet, or to the aircraft carriers. If the simple, baseline assumptions of the nature of ski-jump ramp design had been widened to look at possible worst case scenarios, the issue may have been accounted for earlier, and its costs would not have come as a surprise.

Similarly, the *Harrier* GR.9 case illustrates how, despite minor overt differences from the AV-8B as a platform, the mission system upgrade was carried



out via quicker testing cycles, leading to lower costs than might otherwise have been incurred. This was enabled by the use of very different managerial and organizational structures, as well as the different use of software tools. Such specific differences between two apparently similar cases would need to be understood before planning and costing the system upgrade of another platform similar to the *Harrier*, with the O&S infrastructure to deliver the update, and the capture of any data to be used to plan the work and to estimate costs, needing to be understood on the basis of the range of variance achieved between *Harrier* variants.

This use of a concept of a wider environment as the context from which O&S costs derive, via interactions of the systems and platforms in use by the armed services with this wider environment, lies at the heart of the recommendations to be made in this report. However, the example of the *Harrier* updates also shows how this understanding of the environmental context can also benefit RDT&E. This means that the concept of wider, environmental interaction could also have a place in the re-definition of complexity being carried out by DARPA under the aegis of META.

Building on these findings lies at the heart of the ongoing research program that this report is based on. 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.

2. Recommendation for a New Costing Method

This report has shown that in order to understand all the factors that lead to O&S costs, we need to look beyond the scope of systems and platform and their innate characteristics. We need to understand all the interactions between a Dynamic CoPS-type system and its operating and support environment in order to fully understand what its O&S may cost.



In order to apply this understanding to the costing of new systems, it is considered that a new approach to costing O&S, beyond the analytically based approach spelled out in DoDD 5000.4 (DEPSECDEF, 2006) should be pursued. An overview of the current and proposed approaches is given in Figure 4.

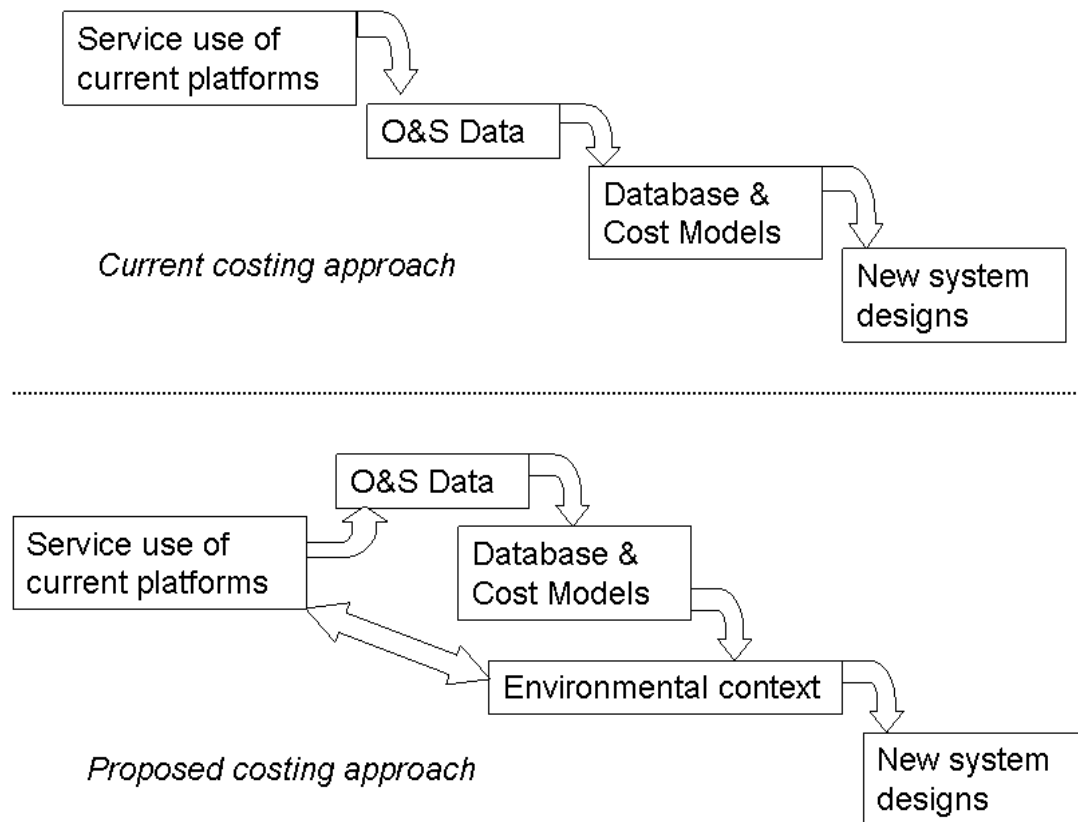


Figure 4. Current and Proposed Approaches to O&S Costing

In order to implement this new approach, it is recommended that for each new system, the interactions of not just components in the system, but of these components and the system as a whole with its wider environment, be examined.

While DARPA, under the META initiative, is looking at interactions between system components for RDT&E, this proposed new approach to costing in O&S would look at a broader range of factors than META, but would do so in a less defined way. This is because for systems under design, the level of O&S support is very hard to pin down in hard numerical terms, as the patterns of operational use,



the nature of the support system, the approaches used by contractors, and so forth, would be very hard to define when the system is at an early stage.

However, as the research for this report has shown, the wider environment of patterns of use, support structures, and so forth, do allow significant scope for the control of O&S costs. If the nature and significance of the interactions with the environment can be identified for existing systems, and compared to the likely occurrence or significance of similar interactions for new systems, then it is possible that the range of variance in likely O&S costs from those generated by the methods defined under DoDD 5000.4 (DEPSECDEF, 2006) can be estimated.

The basic concept would be to generate, for each environmental interaction, a range of costs for a given set of capabilities, depending on whether or not the environmental interactions are expected to generate costs higher or lower than those derived from the DoDD 5000.4 originated baseline cost figure. A simplified overview is given in Figure 5.

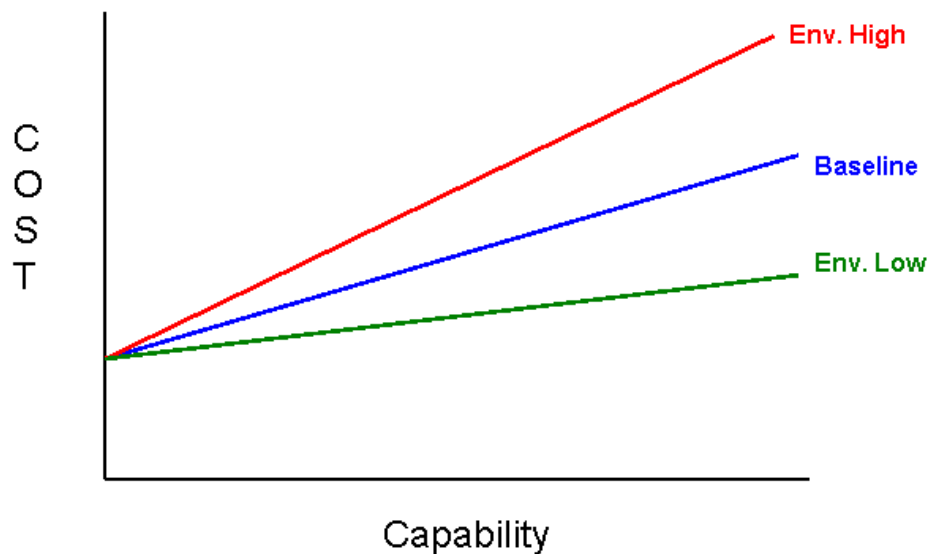


Figure 5. The Effects of Costing Based on Environment

Note. Env. = Environmental interaction impact on costs.

A possible example of how this might work, derived from the case studies described previously, would be the cost of the capability of the targeting system of the Joint Strike Fighter. Using data from previous targeting systems, and comparing on the basis of component counts and lines of code, essentially as in DoDD 5000.4 (DEPSECDEF, 2006) based approaches and in the initial approach given by DARPA's META, would give the baseline figure, shown in blue in Figure 5. This would vary according to the capability desired from the targeting system.

Adding in environmental interaction factors from the case studies, we could see that the experience of the Rapid Technology Insertion approach used on the *Harrier*, with its environment of reducing cycle times and costs for the testing and integration of a new system on the aircraft, and its functioning in a service environment (e.g., on board ship or in dispersed, STOVL operations), could benefit the overall cost estimate. This would give a lower figure than the baseline one, shown by the green line in Figure 5.

However, the consideration of other environmental factors could adversely affect the O&S costs of the targeting system. Again, based on the case studies, the effects of the different loads experienced by the nose undercarriage on the STOVL and carrier (B and C) versions of the F-35 JSF may impact the targeting system, as it is installed near the nose undercarriage unit, and vibrations, impacts, and so forth, may adversely affect it. Although the baseline costs will assume that the vibrations and other factors are as stated in specifications for vibration given by national design standards (Beier, 1987), the unpredictability of vibration in STOVL operations, or the vibrations and shocks caused by dispersed operations or uneven deck surfaces, may exceed these vibration levels and cause higher than expected failure in the targeting system. Consideration of these factors may produce the red line of O&S costs in Figure 5, where costs are higher than the baseline.

In order to carry out these assessments of environmental factors, modeling the various interactions experienced or expected would need to be carried out for each type of interaction, and the relationship between each modeled interaction type



would also need to be related. The models would need to consider the nested interactions between a component, the wider system, and the operational and support environments. Figure 6 shows a generic process model and two versions of the model from the JSF targeting pod example given.

The cost modeling would be carried out using actual data from current systems, with the environmental data cross read between old and new systems, with components and systems data generated using existing (DoDD 5000.4; DEPSECDEF, 2006) or newly developed (e.g., META) approaches. It would be necessary to control for different levels of technology, such as when using data from metal structures to model those made of composite material.

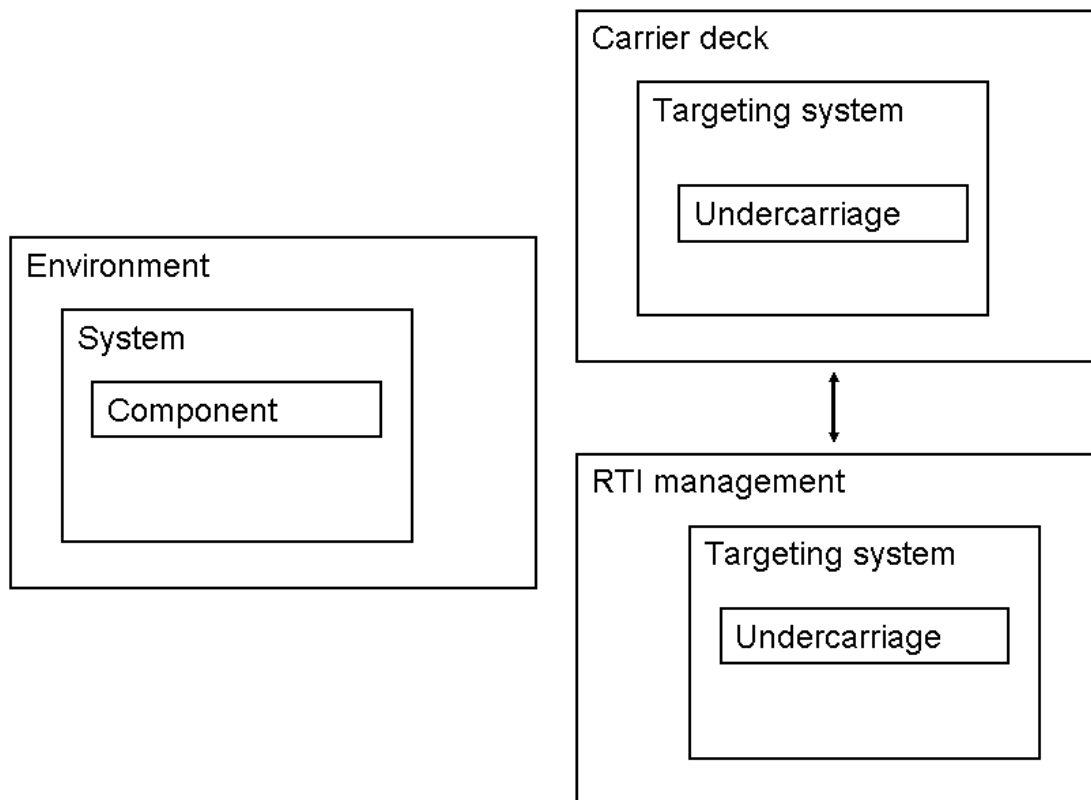


Figure 6. Interaction Models for Costing O&S

3. Implementation of Findings and Further Research

The research reported here has shown that there is scope for changing the costs of O&S of complex systems such as Dynamic CoPS. While the RDT&E costs may be locked in by the overall design of the system, there is much greater scope for controlling costs in O&S.

The research has taken place with companies who have considerable experience in O&S activities, supporting systems they have designed, as well as ones designed by others. While this has revealed the extent of the knowledge and experience of the contractors concerned in understanding O&S, in advance of government costing processes such as DoDD 5000.4 (DEPSECDEF, 2006), the research has also proposed an outline methodology that would allow government costing activities to benefit from the understanding gained from contractors' experiences.

It is proposed that in order to test out this costing methodology, that further work be carried out with contractors in order to see if it is practical. A proposal that features this activity as part of its work plan has been accepted for funding by NPS under call number NPS-BAA-11-002, under the title *Business Models for Cost Sharing & Capability Sustainment*, and will be reported in mid-2012. In particular, the importance of a flexible, nuanced, and in-depth understanding of the cost estimates for O&S, without which business models to carry it out cannot be sustained, will be explored in that work.

The empirical work reported here has led to the belief that the costing approach proposed is indeed feasible, as it is a more formalized statement of how contractors currently operate. If it can be shown that this approach works in a wider setting, for example, in government costing communities, then this research will have advanced the state of the art in O&S costing methods. No doubt this will involve considerable further effort, but in the meantime, the author is happy to hear from, discuss with, and present to colleagues and researchers in similar fields in



order to further understand this constantly changing, and constantly fascinating, subject.



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