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Options for Reducing Costs in the United Kingdom's Future Aircraft Carrier (CVF) Programme

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Preface

The United Kingdom's Ministry of Defence (MOD) is currently in the assessment phase of a programme to produce two new aircraft carriers to replace the three existing *Invincible*-class carriers. These ships are currently scheduled to enter the Royal Navy inventory in 2012 and 2015, respectively. These Future Aircraft Carriers (CVFs) could be the largest ships ever constructed for the Royal Navy.

Because of the complex nature of the CVF programme, the MOD wanted an independent, objective analysis that evaluated the economic implications, schedule impact, and technical risks of adopting new technologies and alternative manufacturing options. The analysis was divided into the following tasks:

- Reducing support costs and other whole-life costs (WLCs)[1]
  - Building databases and analytic tools that would allow the evaluation of cost-reducing measures
  - Evaluating existing or emerging technologies, subsystems, or processes that might reduce acquisition or annual support costs
- Reducing manpower requirements
  - Identifying instances of manpower reduction in other relevant acquisition programmes

[1] WLCs include the costs of owning as well as procuring equipment, i.e., not only the costs of acquisition, but also those of operating (including manning), maintaining, and disposing of the equipment.

  - Identifying and evaluating high-leverage manpower reduction options and laying out a strategic roadmap for implementing them
- Drawing lessons from experience
  - Reviewing the use of contractor teaming by the US Department of Defense in acquiring the *Virginia* class of attack submarines.

This document is the final report on the first two tasks. The *Virginia*-class contractor teaming study has already been submitted to the MOD (Blickstein, Held, and Venzor, 2003).

In pursuing the first two tasks, we have adopted a common approach: We first have sought to understand current construction, support, and complementing plans to establish a baseline against which cost-reduction measures could be taken. Next, we identified such measures. Finally, we evaluated the cost-reduction measures to determine which of these might have the most substantial effects, while attending to matters of technological maturity and risk.

In executing this approach, we have relied extensively on the experience of relevant acquisition programmes inside and outside the United Kingdom. We have interviewed personnel at the MOD, the two CVF contractors, the US Navy, and commercial shipbuilders and support firms. We have also drawn on RAND models developed for other acquisition-related projects.

The research was undertaken when the project was in its competitive stage, which included two competing companies. In January 2003, it was announced that an alliance comprising the MOD, BAE Systems, and Thales UK had been selected for the project. Following this announcement, the Thales design was selected to take forward. This design has subsequently been developed and matured.

Although we have identified numerous cost-reduction measures, our evaluation of those measures has not often been as rigorous or definitive as we might have hoped, principally because the CVF design is still evolving; hence it was not always possible to obtain data at a sufficient level of detail on aspects of the design as it stood. These difficulties have seriously hampered our efforts to establish a baseline. We have, however, made qualitative judgements as to which measures might be most attractive from manpower reduction and other viewpoints. We have also provided analytic paradigms and protocols that should help the MOD in making more definitive savings projections once reliable data become available.

This report should be of special interest not only to the MOD's Defence Procurement Agency but also to service and defence agency managers and policymakers involved in shipbuilding on both sides of the Atlantic. It should also be of interest to shipbuilding industrial executives in the United Kingdom.

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Summary

The United Kingdom's Future Aircraft Carrier (CVF) acquisition project has been designated a 'Beacon' programme by the Ministry of Defence (MOD) because of the opportunity for substantial whole-life savings. To help realise the project's Beacon potential, the MOD called for an independent, objective analysis of new technologies and alternative manufacturing options. The RAND Corporation was asked to perform that analysis and, in particular, to identify and evaluate options for reducing support costs and other whole-life costs (WLCs) and for reducing manpower.

The research was undertaken when the project was in its competitive stage, which included two competing companies. In January 2003, it was announced that an alliance comprising the MOD, BAE Systems, and Thales UK had been selected for the project. Following this announcement, the Thales design was selected to take forward. This design has subsequently been developed and matured.

The precision of the RAND analysis has been limited by the fact that, at the time of the study, the design of the CVF was still evolving; therefore, there was an unavailability of detailed design and manning data. However, we derive qualitative judgements and present some analytic paradigms that should be of value to the MOD.

Cost Analysis Tools

The evaluation of initiatives to reduce CVF WLCs requires a set of analytical tools to understand the trade-offs among various cost elements. We present four such analytic paradigms:

- A total WLC model that examines the interactions among acquisition, operating, maintenance, and personnel costs and permits the quick evaluation of trade-offs and cost-reduction initiatives.
- A method for understanding the cost of each day of carrier operations. We calculate a daily cost exceeding £500,000.
- A means of trading off acquisition and operating costs. This approach suggests that a £1,000 per year savings for each of the two planned carriers would justify a £25,962 up-front investment across both ships.
- A way of making a similar trade-off between initial technology and subsequent manpower costs. Replacing the median crewmember would save £1.2 million.[2]

Acquisition Cost Savings

While the focus of our efforts was on support costs and manpower, we identified several options that might lead to lower CVF construction costs:

- using more advanced outfitting, especially for electrical, piping, and HVAC (heating, ventilation, and air conditioning), than is currently used by most UK shipbuilders
- setting the start of the second ship to minimise total labour costs at the shipyards constructing the large blocks
- centralising the procurement of material and equipment

[2] That is, if the net present values of all individual crewmembers' lifetime compensations were ordered from highest to lowest, the median of that distribution would be £1.2 million.

- considering the use of commercial systems and equipment in place of military standard equipment wherever there is no adverse impact on operations or safety
- ensuring that comprehensive design reviews by all functional parties are complete so that the design of the ship is acceptable to all before construction commences
- minimising changes during ship construction and quickly resolving any that must be made.

Support Cost Savings

To identify ways of reducing support costs, we first consider avenues through which annual costs might be reduced, regardless of who is responsible for doing so. Second, we consider contractor logistics support (CLS), in which the burden for most cost-reduction choices is shifted to the contractor.

Minimising Annual Support Costs

The MOD faces challenges in maintaining the CVFs. The drop in fleet size from three ships to two will end the current arrangement in which there is always one carrier in refit. That arrangement has certain advantages, e.g., a ship off which to cannibalise parts and workload stability at the refit facility. The MOD and its support contractor will also have to maintain the CVFs with vastly less reliance on dry-docking.

The MOD might gain from designing some systems to commercial standards. We infer from studies for the US Navy that the use of certain hotel-related commercial systems in the CVF might save as much as a net £400 million in WLCs across both ships.

Paint is also a major maintenance expense. If higher-quality paint were used, the scheduled sixth-year dry-docking might be eliminated, which could yield substantial savings.

Contractor Logistics Support

We do not think the MOD can have a CLS arrangement in which the contractor is responsible for every aspect of making a carrier available and is paid solely for available vessel days. The ship is too costly and complicated for a contractor to assume full financial risk for not having the ship operate.

Instead, CLS on the CVF will be a modified version in which considerable responsibilities are left to the Defence Logistics Organisation or the weapon system manufacturers. However, such modified CLS might be prone to 'seam' problems in which different participants blame one another for why the ship does not operate correctly.

CLS implementation difficulties aside, there is reason to be optimistic about CVF maintenance costs. Because the MOD has expressed considerable ambition for cost reduction through new maintenance paradigms, long-run advantages may accrue. Furthermore, many of the most problematic aspects of carrier maintenance may well have been addressed in the choice of ship design.

Personnel Cost Savings

As background, we begin with a review of how the Royal Navy and its original design contractor, Thales UK,[3] approached complementing, then suggest some ways of improving the practice. Next, we identify a number of complement-reduction initiatives on other naval platforms. Finally, drawing from these case studies, we identify and evaluate a number of complement-reducing measures and suggest directions for the future.

Estimating the CVF Complement

The Royal Navy's complementing process takes technology as a given and uses inherited assumptions about hours of work and mix of trades and rates. The process may be regarded as a review and assess-

[3] The design is now the responsibility of both Thales and BAE Systems, working together as the Aircraft Carrier Team.

ment by an honest, experienced broker. It does not produce any recommendations for reorganising work or for adding technology, materials, or equipment. With no systematic evaluation of the complement-reducing potential of evolving technologies and work processes, decisions in the current complementing system may be overly influenced by culture and by outdated policies and practices.

Thales UK, in contrast, appears to have taken a zero-based approach to complementing. It has estimated the work to be done and computed the number of manpower slots necessary to accomplish it. Thales' complementing process yielded a distribution of labour that differed substantially from the Royal Navy's breakdown for the CVF.

As further complementing work is done, the following points should be kept in mind:

- A principal, persisting goal must be observed. Minimising WLCs and minimising crew size, for example, will each result in a different complement.
- Some CVF systems will be inherited from the current carrier class. These systems might bring inefficient manning with them.
- Ambitious plans to cut manpower by investing in technology can be impeded by constraints on the up-front funding.
- Operational commanders may be reluctant to accept smaller complements because they would reduce the margin for error in situations threatening ship safety.

Complement-Reducing Initiatives on Other Platforms

To assist in identifying manpower-reduction options potentially relevant to the CVF, we reviewed several efforts by various navies to reduce complements:

- **Transfer of US ships to the Military Sealift Command** (MSC). As sealift ships have been shifted from US Navy manning to MSC manning, largely with civilians, billets have dropped dramatically.

- **US carriers.** Of particular interest is the Smart Carrier programme, a series of innovations implemented chiefly during *Nimitz*-class refits.
- **The US Navy's Smart Ship.** In an experiment aboard the guided-missile cruiser USS *Yorktown,* significant complement reductions were achieved with core/flex manning, e.g., forgoing underway watches in reduced-threat environments, making more manpower available for other duties.
- **The US Navy's Optimal Manning Experiment.** Innovations on the destroyer USS *Milius* and the cruiser USS *Mobile Bay* permitted reductions in crew size without affecting performance.
- **The LPD-17 and other amphibious ships.** Smart Ship principles were applied; e.g., ship system operators were brought into the design process to suggest efficiency improvements.
- **The Royal Netherlands Navy.** The Dutch are constrained by tighter manpower ceilings than apply in the United Kingdom and therefore accept somewhat higher risks while spreading out most predictable tasks to permit accomplishment by small crews.
- **DD(X).** This is a set of technologies that will be used on future US surface combatants.

The more incremental initiatives such as the various Smart Ship programmes have either shown or are intended to show complement reductions of 15 to 20 percent. Much higher reductions are hoped for in the case of DD(X) and certain Dutch ships.

Identifying and Evaluating Complement-Reduction Options

We identified 57 feasible complement-reduction options of potential relevance to the CVF. Of those, we judged 12 to have appreciable potential for complement reduction and to be advantageous in other respects. Six of these twelve emerged as particularly promising:

- Leaving machinery spaces unmanned, a policy change facilitated by technologies such as remote sensing of spaces.
- Consolidating watches.

- Employing a core/flex manning concept.
- Using civilians to augment the ship's crew for nonwarfare responsibilities.
- Emphasising broad skills and a cross-trained workforce, so that a smaller crew could perform the same number of activities.
- Using conveyors to aid crewmembers in loading stores from the shore to the ship.

We do not know what options have been assumed in the planning complement estimate devised for the CVF and thus do not know if the target is optimistic. There are reasons, though, to believe that the target will be reached:

- There is strong fiscal motivation to realise savings.
- Complement reduction is a key CVF design goal.
- The immaturity of the design may allow for further savings.
- Operating and personnel policies will continue evolving towards sailor multifunctionality.
- As new technologies prove their worth, old manpower-intensive approaches to tasks will fall away.

Initial complement targets have historically proved optimistic, however, and progress toward the complement goal could be complicated by some remaining challenges. For example, many complement-reducing options are not technological but procedural, and efforts to implement such changes can encounter institutional resistance.

We conclude by offering some general guidelines towards better defining complement-reduction options and pushing them closer to realisation:

- Consider the implications of a revolutionary CVF complement for the Royal Navy personnel structure.
- As CVF design proceeds, continue the emphasis on complement reduction and human systems integration.
- Focus on manpower-intensive activities for possible reductions.

- Place a premium on designing or selecting systems that do not require highly specialised personnel to operate.

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Among those who provided information in their specific areas of expertise, we particularly want to acknowledge CDR R. A. (Dan) Doxsey and Alistair Rankin, CVF IPT, from whom we learned about support of Royal Navy ships. Mike Fowles, also of the CVF IPT, was especially helpful in regard to the support of current operating carriers, and CPT Bob Leeming and CDR Julian Morris of the Warship Support Agency aided us in understanding the Defence Logistics Organisation's approaches. CDR Malcolm Lewis, Fleet Time Engineering, told us about maintenance at Fleet Support Limited, Portsmouth. Adrian Burt of Vosper Thornycroft and Ken Blacklock and his colleagues at Babcock Marine were also generous in hosting RAND visits. E. Dail Thomas of the US Naval Sea Systems Command compared and contrasted US Navy and Royal Navy paint practices. Mike Cottrell and his colleagues in the C-21A programme office at Tinker Air Force Base in Oklahoma City aided our understanding of contractor logistics support for that aircraft.

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Several of our RAND colleagues contributed importantly to this project. Lowell Schwartz provided key research assistance relative to the analysis of support cost-reduction options, in particular with respect to UK cost estimation regulations and requirements. Deborah Peetz also aided us in the support cost-reduction analysis, e.g., in locating sources related to paint and CLS issues. Frank Camm offered valuable insights on issues related to CLS. Fred Timson provided data on US carrier maintenance cost drivers.

Of course, all this information has been filtered through our own interpretations, so none of these individuals should be viewed as endorsing what we say here.

Abbreviations

AAAV	Advanced Amphibious Assault Vehicle
ADCF	Air Defence Command Frigate
AE	auxiliary dry-cargo carrier
AEM/S	Advanced Enclosed Mast/Sensor (system)
AOE	fast combat support ship
CAD/CAM	computer-aided design/computer-assisted modelling
CCTV	closed-circuit television
CFE	contractor-furnished equipment
CG	guided-missile cruiser
CIC	combat information centre
CLS	contractor logistics support
CM	corrective maintenance
COTS	commercial off-the-shelf
CPC	competing prime contractor
CV	carrier vessel
CVBG	sustained carrier battle group
CVF	Future Aircraft Carrier
CVN	carrier vessel, nuclear (US)
CVS	*Invincible*-class carrier
DD	destroyer

DDG	guided-missile destroyer
DLO	Defence Logistics Organisation
DRP	defect rectification period
ECDIS	electronic chart display and information system
FIRST	Fleet Integrated Readiness Support Team
FM	facilities maintenance
FY	fiscal year
GFE	government-furnished equipment
HMS	Her/His Majesty's Ship
HSI	human systems integration
HVAC	heating, ventilation, and air conditioning
ICAS	Integrated Condition Assessment System
IFF	identification of friend or foe
IMO	International Maritime Organization
IPT	Integrated Project Team
JSF	Joint Strike Fighter
LAN	local area network
LHD	helicopter/dock landing ship
LPD	amphibious transport, dock
LSD	dock landing ship
MARPOL	International Convention for the Prevention of Pollution from Ships
MCS	Machinery Control System
MOD	Ministry of Defence
MSC	Military Sealift Command (US)
MSCL	A US consulting firm
NASA	National Aeronautics and Space Administration (US)
NATO	North Atlantic Treaty Organization
NOMISETS	Naval Optimised Manning Integration Systems Engineering Tool Set

NPV	net present value
OBA	oxygen breathing apparatus
OEM	original equipment manufacturer
OM	operational manning (or watch-standing)
OME	Optimal Manning Experiment
OPV	offshore patrol vessel
OUS	own-unit support
PM	preventive maintenance
QPL	qualified products list
RCM	reliability-centred maintenance
RNN	Royal Netherlands Navy
SCBA	self-contained breathing apparatus
SOC	scheme of complement
TBT	tributyltin
TOPMAST	Tomorrow's Personnel Management System
UPC	Uniform Product Code
USAF	United States Air Force
USS	United States Ship
VCHT	vacuum collection, holding, and transfer
VHF	very high frequency
VT	Vosper Thornycroft
WLC	whole-life cost

CHAPTER ONE

Introduction

The United Kingdom's Future Aircraft Carrier (CVF) programme is intended to replace the current *Invincible* class of aircraft carriers, designated CVS. That class comprises three ships—HMS *Invincible, Illustrious,* and *Ark Royal*—that are scheduled to go out of service between 2008 and 2015. The CVS class was designed during the Cold War, principally for antisubmarine warfare, area air defence, and command, control, and communications. The CVF class focuses less on antisubmarine warfare and more on offensive air and littoral operations in support of land forces.

Plans call for the construction of two carriers, for delivery in 2012 and 2015, respectively. To allow for higher sortie rates, ships of the new class will carry more aircraft and will displace at least twice as many tons as those of the CVS class. The new carriers will be configured, at least initially, to launch the short-takeoff-and-vertical-landing version of the Joint Strike Fighter (JSF). However, the ships will be adaptable by way of refit to launch conventional-takeoff-and-landing aircraft, should the Royal Navy eventually replace the JSF with such aircraft.

The CVF programme is being executed through the UK Ministry of Defence's (MOD's) Smart Acquisition, a six-step process comprising concept development, assessment, demonstration, manufacturing, in-service operation, and disposal (Director General Smart Acquisition, 2004, p. 7). It departs from previous acquisition approaches that were dominated by frequent, detailed milestone reviews involving hierarchies of stakeholders and by concerns over adherence to a multitude of established procedures and plans. A Smart Acquisition programme is governed by a relatively small Integrated Project Team (IPT) that is allowed substantial latitude in setting its own plans and procedures as long as it meets a limited set of milestones.

The two CVFs together are projected to entail real, discounted whole-life costs (WLCs) of about £4.5 billion.[1] A principal motivator of the new acquisition approach has thus been the desire to find opportunities to save money over the course of a system's entire life. In previous acquisition paradigms, purview of the various stages of a ship's development and life was the responsibility of different parties. Net whole-life savings might not be realised if they could only be achieved by increasing costs during one stage. The IPT has a primary responsibility to press for such savings—to find, for example, improvements that require higher manufacturing costs if they also yielded more than offsetting savings in service.

The CVF project has been designated a 'Beacon' programme by the MOD because it involves particular opportunities for whole-life savings while completing a high-performance system to an exacting schedule. The CVF IPT is viewed as having the opportunity to demonstrate clear commitment to Smart Acquisition goals and generate invaluable lessons for other IPTs about how to make Smart Acquisition work in the concept and assessment phases. To help realise the CVF project's Beacon potential, the CVF IPT called for an independent, objective analysis of the economic implications, schedule impact, and technical risks of adopting new technologies and alternative manufacturing options. The RAND Corporation was asked to perform that analysis.

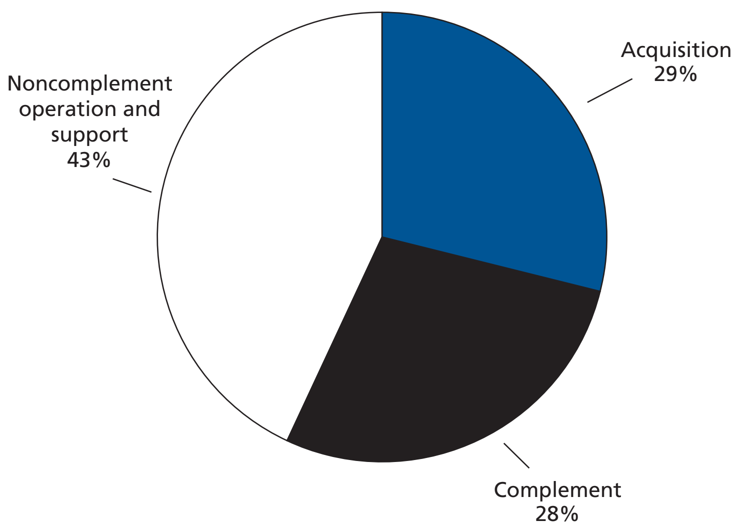
In thinking about the cost of a carrier, people often focus on acquisition, but personnel and other aspects of operation and support

[1] Whole-life costs include the costs of owning as well as procuring equipment, i.e., not only the costs of acquisition, but also those of operating (including manning), maintaining, and disposing of the equipment. See Director General Smart Acquisition (2004, p. 14).

are also major influences on WLCs (see Figure 1.1). Those elements inform the objectives of the current analysis:

- Reduce support costs and other WLCs
  - Build databases and analytic tools that would allow the evaluation of the costs, benefits, and risks of cost-reducing measures (see Chapter Two of this report).
  - Evaluate existing or emerging technologies, subsystems, or processes that might reduce costs (see Chapter Three, for acquisition savings; Chapter Four, for annual support cost savings; and Chapter Five, for contractor logistics support [CLS]).

Figure 1.1
Most Whole-Life CVF Costs Are Expected to Accrue After the Ships Are Acquired



SOURCE: CVF IPT.
RAND *MG240-1.1*

- Reduce manpower requirements
  - Review current complement establishment procedures (Chapter Six) and identify instances of manpower reduction in other relevant acquisition programmes (see Chapter Seven).
  - Identify high-leverage manpower reduction options and evaluate their risk, technological availability, and effects on manpower and WLCs, and lay out a strategic road map for implementing those options (Chapter Eight).
- Draw lessons from experience
  - Review the use of contractor teaming by the US Department of Defense in acquiring the *Virginia* class of attack submarines and draw lessons potentially applicable to the CVF contractor alliance (already reported in Blickstein, Held, and Venzor, 2003).

In pursuing the first two objectives, the topic of this volume, we have adopted a common approach. We have first sought to understand current construction, support, and complementing plans to establish a baseline that could be modified in an effort to reduce costs. Next, we identified such cost-reduction measures. Finally, we evaluated these cost-reduction measures to determine which might have the most substantial effects, while attending to matters of technological maturity and risk.

In executing this approach, we have relied extensively on the experience of relevant acquisition programmes inside and outside the United Kingdom. We have interviewed personnel at the MOD, the Aircraft Carrier Team companies (BAE Systems and Thales UK), the US Navy, and commercial shipbuilders and support firms. We have also drawn on RAND models developed for other acquisition-related projects.

As is apparent in the following chapters, we have identified numerous cost-reduction measures. Our evaluation of those measures has not often been as rigorous or definitive as we might have hoped, principally because the CVF design is not close to completion. Also, it was not always possible to obtain data at a sufficient level of detail on aspects of the design and plans for manning as they stood. These difficulties seriously impeded our efforts to establish a baseline, which hampered us in two ways: We could not tell whether a cost-reduction measure had already been incorporated by the contractors into the design, and we could not translate possible percentage reductions into absolute numbers. We have, however, made qualitative judgments as to which measures might be most attractive from manpower reduction and other viewpoints. We have also provided analytic paradigms and protocols that should help the IPT in making more definitive savings projections once reliable data become available.

CHAPTER TWO

Cost Analysis Tools

The evaluation of initiatives that potentially reduce whole-life costs for the CVFs requires a set of analytical tools and models to understand the trade-offs between various elements of cost. This chapter describes four analytical tools used during the RAND analysis:

- A total WLC model that examines the interactions among acquisition, operating, maintenance, and personnel costs and permits the quick evaluation of trade-offs and cost-reduction initiatives. The model also includes provisions for measuring the impact of uncertainty in various cost estimates and can, therefore, develop median cost estimates with 10 percent and 90 percent confidence bounds, as required for MOD cost analyses. The model is flexible and based on commercial software.
- A method for understanding the cost of each day of carrier operations. With the information available to us, we calculate a WLC of over £500,000 per day. If that number may be taken as the value of having a carrier operational for a day, it provides a basis for assessing the feasibility of unavailability penalties in a logistic support contract or warranty.
- A means of trading off initial acquisition costs and annual operating costs. This approach, based on standard present-value estimation, helps address the question of the break-even point between initial acquisition cost and reduced annual operating costs. It suggests that a £1,000-per-year savings for each of the

two planned carriers would justify a £25,962 up-front investment across both ships.

- A way of making a similar trade-off between the initial acquisition cost of technology to reduce the size of the ship complement and the subsequent annual cost of different personnel skills and grades. Replacing the median crewmember would save £1.2 million.

Whole-Life Cost Model for Cost-Benefit Analysis

During the development of any weapon system, project teams make complex trade-offs in capability and design. Sometimes, these trade-offs involve increasing one type of cost to reduce another. For example, a team might choose a more reliable (and expensive) piece of equipment to reduce upkeep and operating cost. More reliable equipment might also reduce the need for spare parts and redundant systems. For the example just mentioned, the trade-off is a balance among production, operations, and upkeep costs. How does one know whether a particular trade-off provides the best value? Cost-benefit analysis is a discipline in which trade-offs can be examined in an equitable fashion. Often, cost-benefit analysis requires a cash-flow analysis looking at the timing of various costs and expenditures. With the timing determined, the cost is converted into a net present value (NPV). Such analysis often requires the development of a WLC model. In this section, we will describe a simple whole-life cost[1] model for the CVF programme. With this model, the CVF IPT can quickly evaluate trade-offs or cost-reduction initiatives.

Approach

Assessing the whole-life cost of any weapon system is a difficult task. The fact that an aircraft carrier has a potential useful life of up to 50

[1] Throughout this section, we use the term 'cost' in its more general sense. Some analysts make a distinction between cost and price. When we refer to cost, we mean cost including fee and profit—the definition of price.

years and is one of the most complicated and expensive weapon systems procured today makes the task even harder. It is exceedingly difficult to forecast costs over a 50-year period. In addition, some elements of the WLC are one-time expenses (e.g., the acquisition cost), while others recur each year that the ship operates (e.g., personnel costs). Thus, a complicating factor is the need to understand both the timings and magnitudes of the various costs for the carrier fleet.

For the WLC model of the CVF, we included the following WLC elements that were based on the cost summary provided by the CVF IPT:[2]

- Nonrecurring costs
  –Prime contractor office
  –Trials
  –Research, development, testing, and evaluation
  –Support products
  –Facilities
- Production costs
  –Labour
  –Material and equipment (including government-furnished)
- In-service costs
  –Upkeep
  - commodities management and infrastructure
  - spares
  - naval equipment and general stores
  - modernisation

  –Personnel
  –Operations
  - petroleum, oils, and lubricants
  - in-service trials

  –Facilities, reference equipment, and training
  –Prime Contract Office activities
- Disposal

[2] The various elements include overhead costs as appropriate.

Another consideration in developing a WLC model for the CVF programme is the need to include uncertainty analysis in the evaluation. The Defence Procurement Agency employs three point cost estimates (at 10, 50, and 90 percent confidence intervals) to portray cost risk and uncertainty. Given that cost-reduction initiatives might have differing degrees of certainty, any WLC model used for cost-benefit analysis must include the capability to evaluate uncertainty. For example, reductions in crew size are difficult to quantify exactly. An investment in new technology (which is typically easier to evaluate, i.e., more certain) might be thought to reduce the crew size by a specific number of sailors. However, such reductions are difficult to forecast. Correctly reflecting the uncertainty for the benefit (reducing crew sizes) will allow the IPT to better judge whether a reduction initiative is cost-effective and how it affects overall programme cost risk.

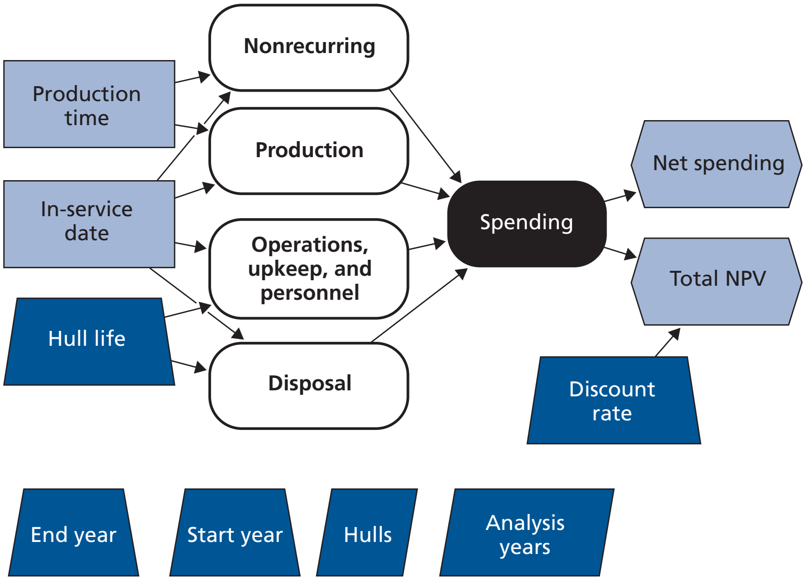
Last, any model developed for cost-benefit analysis must be easy to modify or expand. Typically, it is very difficult to identify all the possible reduction initiatives that will need to be considered when a cost model is developed. Thus, any model must be capable of being altered or adapted so that all initiatives can be considered. The WLC model must broadly consider the full spectrum of WLC and have some degree of modularity.

To address the issues of adaptability and uncertainty in the WLC model, we chose to build the model in Analytica, sold by Lumina Systems. Analytica is a commercial decision analysis software system, which includes a Monte Carlo simulation capability. Models built within the Analytica system are modular and thus are more adaptable and easily modified than a traditional spreadsheet model. We show the high-level view of the architecture for the model in Figure 2.1.

Figure 2.1, an 'influence diagram', illustrates how the various components and variables of the model interact. Each box represents a sub-model, variable, or constant.

It may be helpful to walk through the general flow of the model for clarification. In the diagram, calculations flow left to right. Starting at the left, the production time, in-service date, and hull life

Figure 2.1
High-Level Architecture or Whole-Life Cost Model for the CVF Programme



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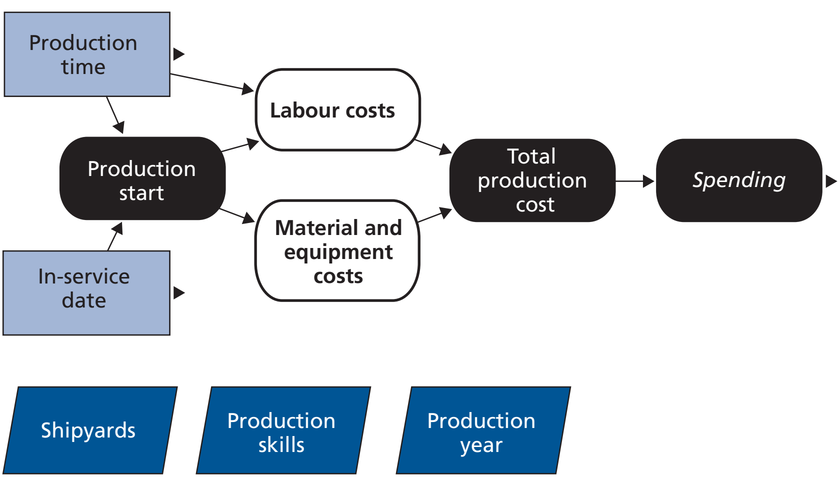
variables are the major variables that set the timings of all cash flows. All expenditures are keyed relative to these inputs. So, knowing the in-service date and production time, one can sequence the cash flow (i.e., the budgetary authority) for the nonrecurring and production costs. The linking arrows in the diagram show this relationship. The boxes at the bottom of the figure are other inputs to the model. The end year and start year specify the period for analysis, and the hull variable specifies the number of ships in the class. The nonrecurring; production; operations, upkeep, and personnel; and disposal ovals represent the major elements of the WLC introduced earlier and are each sub-models. These sub-models contain the cost accounting equations that combine the input variables with various cost factors contained in the model. In other words, each of these WLC elements has an influence diagram. As an example, we show the production element's diagram in Figure 2.2.

For each sub-model, an annual cash flow is determined. The outputs from all four of these sub-models are combined into a single cash flow: the 'spending' object. From there, two output metrics are calculated: net spending, which is a simple summation of the spending over the entire analysis period, and the total NPV, which is the NPV of the spending.

Cost-Benefit Analysis Example

Suppose the CVF IPT wants to consider a trade-off where it could add an additional £1 million of equipment to the ship and reduce the number of junior enlisted sailors by 40 heads. Is this addition of equipment cost-effective from a whole-life perspective despite increasing the production cost? We present a notional evaluation of this case in Figure 2.3. The figure shows the cumulative probability plot of the total NPV for two cases: Baseline (the CVF baseline) and

Figure 2.2
Production Cost Influence Diagram



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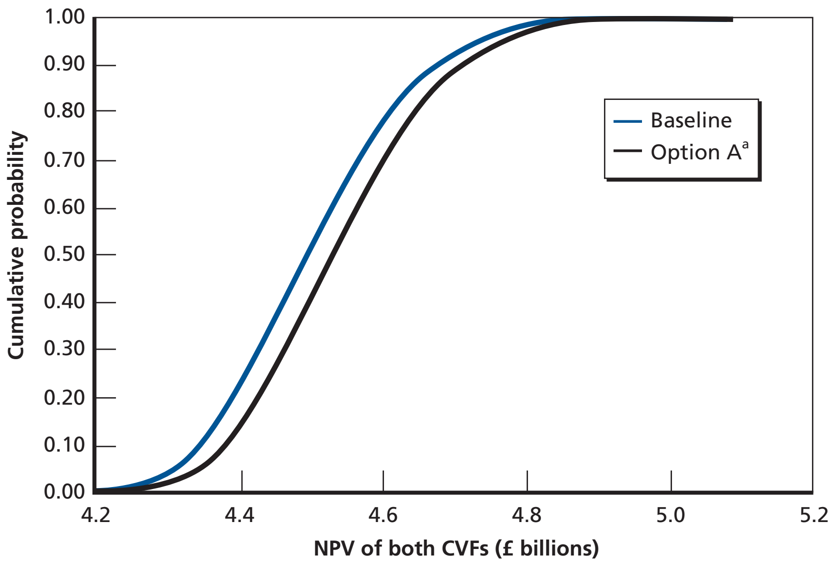
Option A (one in which the improvement to reduce crew is made). At the median of the probability distribution, Option A costs less than the baseline by £35 million, which indicates a net overall reduction in WLC.

Summary

For the CVF programme, we have developed a simple WLC model that the IPT can use to quickly evaluate trade-offs and cost-reduction initiatives. The model is flexible, based on commercial software, and includes uncertainty analysis. There is a caveat, though: The tool does not estimate costs—in other words, an analyst will need to enter the relevant factors for each cost element.

Figure 2.3
Cumulative Probability Plots of CVF Net Present Value, Baseline, and Option to Reduce Crew with Up-Front Investment



[a]Option A = £1 million investment per ship to reduce baseline crew by 40 junior enlisted personnel per ship.

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Calculating Cost per Day of Carrier Operations

The CVF programme is considering the use of a contractor logistics support contract for maintaining and supporting the two carriers. Under this arrangement, the contractor would be required to provide a minimum number of operating days per ship per year and would incur a cost penalty for each day under the operating requirement. (For more about CLS, see Chapter Five.) A question arises about the appropriate size of such a cost penalty. Having a carrier available for a day is of a certain value to the United Kingdom, so the penalty for a lost day might be equated to that value. That value cannot be estimated directly, but it might not unreasonably be assumed to at least equal what the nation pays for the carrier on a daily basis. Here, we present a CVF life-cycle cost tally that suggests British taxpayers, in effect, will pay more than £500,000 for every day a CVF is available for operation.

Figure 2.3 suggests a real, discounted total cost of this programme of about £4.5 billion. How much time will the two carriers be operating? According to the User Requirements Document, CVF-1 is to join the fleet in October 2012 and CVF-2 in August 2015. During 'ordinary' years, each CVF will spend 46 of 52 weeks in operation. However, every six years, each CVF will be in a heavier maintenance cycle (including, under current plans, a dry-docking for some weeks) for half the year. CVF-1's dry-dock years are to be 2018, 2024, 2030, and 2036; CVF-2's are 2021, 2027, 2033, and 2039. We assume each carrier will retire on its 30th anniversary.

With these assumptions and the UK Treasury's prescribed 3.5 percent real interest rate, we can then compute a discounted sum of available CVF ship-years.[3] In 2003 present value terms, we find the

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[3] It may seem unusual, but we believe it appropriate to discount ship-years symmetric to discounting future cash flows. The Treasury's Green Book (2003, Section 5.49, p. 26) notes 'the discount rate is used to convert all costs and benefits to "present value", so that they can be compared'. In this context, ship-years are the benefit, so they should be discounted. (The US Office of Management and Budget Circular A-94, 1992, has very similar language: 'All future benefits and costs, including nonmonetized benefits and costs, should be discounted.')

Royal Navy will get 21.65 available ship-years out of the CVF fleet.[4] If we divide £4.5 billion by 21.65 available CVF ship-years, we get about £200 million per active ship-year, or about £570,000 per active ship-day, in 2003 pounds.

We suspect no CLS contractor would agree to pay such an availability penalty. If whatever penalty the MOD is able to negotiate is subtracted from £570,000, the difference may be taken as a measure of availability risk borne by the government. (Of course, some of the risk will be borne whether CLS is employed for support or not.)

While we have carried out the cost-per-day calculation principally to arrive at an appropriate value for a CLS availability penalty, the number has other uses. For example, cost per day can serve as a convenient way to roughly reckon the intangible cost of having the ship out of service for any reason. It underscores the potential value of eliminating the six-year dry-docking or other steps that might result in more available ship-days.

While we have figured the cost at more than £500,000, the MOD may alter the method in certain ways, depending on its purposes. The discount rate might be changed, as long as the same rate is applied to both available ship-years and pounds, or the base year might be changed.

Comparing Acquisition Costs with Annual Operating Costs

An important question the MOD must consider is how much up-front investment it would be willing to undertake if such investment

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One has to discount future ship-years to avoid counterintuitive findings. For example, suppose the MOD could save one pound by delaying the CVFs for five years. Clearly, one would not want to do that, but the sum of undiscounted ship-years would be the same, irrespective of when the ships entered the fleet. Reasonable cost-benefit analysis, in other words, requires discounting ship-years as well as costs.

[4] This tally may seem low, but the first 'full' year of CVF operation—actually 46 weeks or 0.88 available ship-years—in 2013 is worth only 0.63 available ship-years today when discounted. Later available years are even further discounted.

resulted in savings over the lives of the ships. Suppose the MOD identified an investment that would save £1,000 in real, discounted terms during each full year that a ship is operating. How much would that be worth at present?

For CVF-1, the 2003 present value of £1,000 per year would be

$$\frac{1,000}{4*(1+d_{GB})^{9}}+\sum_{i=1}^{29}\frac{1,000}{(1+d_{GB})^{9+i}}+\frac{3,000}{4*(1+d_{GB})^{39}},$$

where d_{GB} is the Green Book–prescribed real interest rate. In that expression, the middle term is the sum of the discounted amounts in each of the 29 'full' years of operation; the first term is the amount for the 2012 quarter-year; and the third term is for the 2042 three-quarter year. The analogous expression for CVF-2, which starts operating in August 2015, is

$$\frac{5,000}{12*(1+d_{GB})^{12}}+\sum_{i=1}^{29}\frac{1,000}{(1+d_{GB})^{12+i}}+\frac{7,000}{12*(1+d_{GB})^{42}}.$$

Using the current Green Book rate of 3.5 percent, the present value of £1,000 of savings per year is £13,613 if the savings are on CVF-1 and £12,349 if the savings are on CVF-2. (CVF-2's present value is slightly lower, since the ship's years of operation are more distant.) Combining the two ships' totals, we see it would be worthwhile, in present value terms, to spend £25,962 today across both ships if such an investment resulted in £1,000 of savings per year that each ship is operating. With the prescribed real interest rate, spending more than £25,962 today to save £1,000 per owned ship-year would not be worthwhile.

This calculation can be generalised in a number of ways. Projected annual savings different from £1,000 per owned ship-year would obviously scale up or down the £25,962 estimate proportionally.[5] Another possibility is that savings might not be realised every year. For example, they might only be realised in every sixth docking year. If there were estimated to be £1,000 of savings per year that a ship is docked, the 2003 present value of such an investment would be

$$\frac{1,000}{(1+d_{GB})^{15}}+\frac{1,000}{(1+d_{GB})^{21}}+\frac{1,000}{(1+d_{GB})^{27}}+\frac{1,000}{(1+d_{GB})^{33}}$$

for the CVF-1 and

$$\frac{1,000}{(1+d_{GB})^{18}}+\frac{1,000}{(1+d_{GB})^{24}}+\frac{1,000}{(1+d_{GB})^{30}}+\frac{1,000}{(1+d_{GB})^{36}}$$

for the CVF-2. With the 3.5 percent discount rate, the CVF-1 docking year sum is £1,799 and the CVF-2 docking year sum is £1,622. Therefore, savings of £1,000 per docking year would justify an up-front cost of, at most, £3,421.

Comparing Acquisition Costs with Annual Personnel Costs

As part of our review of how complementing is done, we calculated the present discounted value of the WLCs of removing one median-paid crewmember from the CVF. That value amounted to £1.19 million over all enlisted and officer ratings, at a 3.5 percent discount rate applied over 30 years. Whether a given labour-saving up-front investment is justified depends, of course, on the specific ratings replaced. However, a million pounds per person can serve as a rough

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[5] For a savings of other than £1,000, factor 1,000 out of the numerators and substitute the savings; e.g., the numerator of the first term in the CVF-2 formula becomes $5x$, where x is the savings.

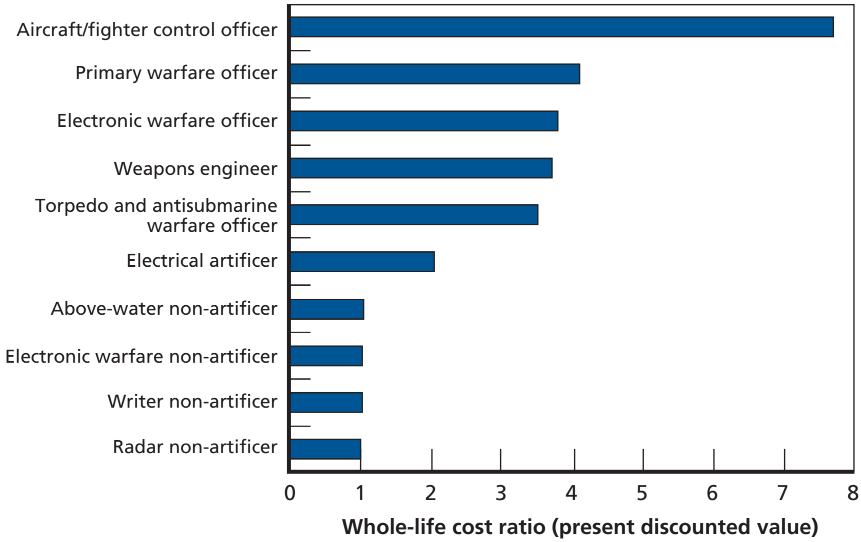
criterion for initial screening to suggest whether technologies have any chance of earning back their initial costs.

We also considered trade-offs to reduce cost within the prospective CVF complement and looked at how certain exogenous issues might affect decisionmaking about the complement. We review these topics in the following subsections.

Trade-Offs Within the Complement

Could the Royal Navy reduce complement costs by moving towards a different skill mix? Figure 2.4 shows the WLCs of an officer in each of five skill categories and of an enlisted person in each of five skill

Figure 2.4
Whole-Life Cost Ratio for Selected Ranks and Trades



SOURCE: The Defence Procurement Agency's Pricing and Forecasting Group, annual marginal cost rates, 2002–2003.
NOTE: Raito refers to designated ratings' cost divided by the cost of the least expensive enlisted personnel. No discount rate is given because the ratios do not change with the discount rate, as long as the same rate is used across all positions.
RAND *MG240-2.4*

categories.[6] Costs are given as a multiple of the WLC of the least-expensive person shown.

For just the complement cost (excluding accommodation and feeding expenses), it can be less costly to exchange two, four, or even eight junior ranks for more senior ranks. The implication is that substituting less-costly ranks and trades on a one-to-one basis for more costly ones may be as useful in reducing complement whole-life costs as reducing numbers of people.

A broader analysis suggested that, even within officer ranks, there are substantial differences in costs. If the Royal Navy is to minimise costs, it should seek, where possible, one-to-one occupational shifts away from aviators and towards warfare and engineering officers, and away from the latter towards junior officers and supply officers. (We did not perform a similar broad analysis for non-officer ranks and trades, but it is likely that cost-effective substitutions could be found as well.)

Other Issues Affecting Complement Cost

Training. The Royal Navy's training establishment is striving for efficiencies that should lead to lower training costs. This planned reduction in cost could lower the WLC of the CVF complement by an estimated 2 to 4 percent. The IPT should thus consider using different cost factors (incorporating reduced amortised training costs) for future costs than those used to calculate current costs. There are two factors to be aware of, however. First, if the WLC of the complement is lower, the up-front trade-off for technology to reduce complement becomes pricier. That is, the return from using technology to substitute for complement is less. Second, the CVF complement relies on using a more flexible (cross-trained) workforce to achieve manpower reductions. This implies a need for more training,[7]

[6] The top five bars in the figure are for officers and the others for enlisted personnel. An artificer is a trained, skilled technician. A non-artificer is an apprentice who is learning a trade or skill and who may or may not have had training.

[7] On the value of cross-training, see Chapter Eight's sections on 'Shipwide Options' and 'The Way Forward'.

and if, spurred by efficiency expectations, training budgets are falling at the same time, some risks will accrue.

Discount Rate. The discount rate used in the calculation of WLC can affect complement decisions. Figures 2.5 and 2.6 show the effect of discount rate on the WLC of various ranks. As the discount rate decreases, the WLC increases for a constant size complement. Thus, the savings in WLC from a constant up-front technology investment are greater. For example, at a 3 percent discount rate, the elimination of a petty officer could result in the ability to invest £830,000 in 2003. At a 4 percent discount rate, the elimination of the same person would justify only £730,000 for 2003 investments. Technology investment that might not have a return at high discount rates could have a positive return at lower rates, which justifies spending more money up front to realise the in-service savings from removing one person. Like a higher-skill or -rank mix, lower discount rates warrant greater acquisition-phase technology investments to stem higher complement-driven WLC.

Figure 2.5
Whole-Life Costs for Enlisted Personnel Ranks, by Discount Rate

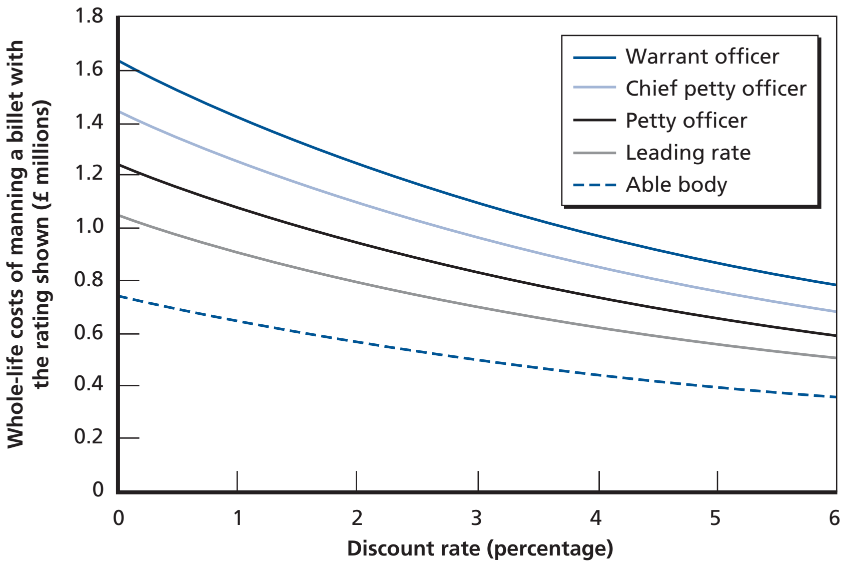


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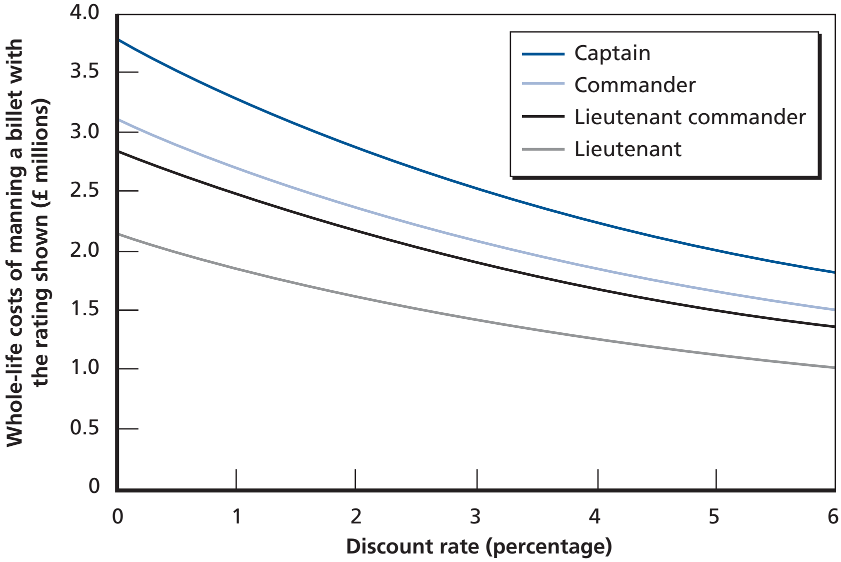
Figure 2.6
Whole-Life Costs for Officer Ranks, by Discount Rate



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CHAPTER THREE

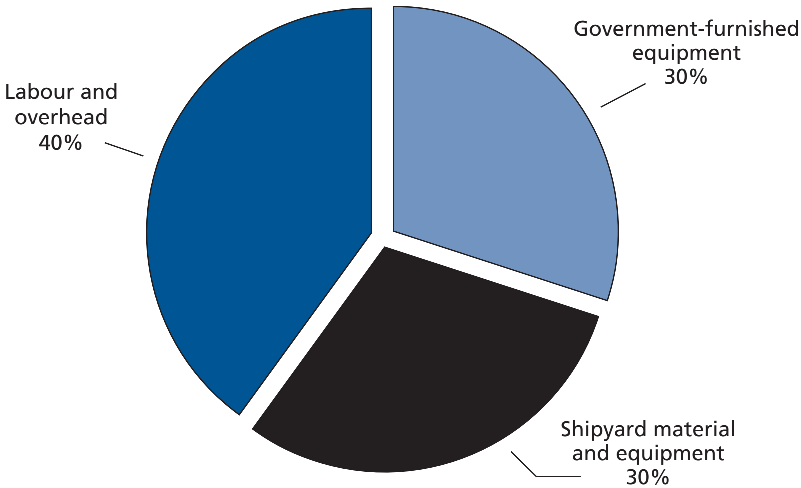
Acquisition Cost Savings

In this chapter, we examine options that may lead to lower construction costs of the two CVFs. Roughly, based on the costs of US aircraft carriers and preliminary data from BAE Systems and Thales UK, the construction costs of an aircraft carrier are distributed as shown in Figure 3.1. Notionally, 40 percent of the construction cost of a carrier is for labour and overhead, 30 percent for government-furnished equipment (GFE), and 30 percent for shipyard material and equipment. Below, we first address options to reduce labour costs, then options to reduce material and equipment costs, and finally other options that should be considered to reduce acquisition costs.

Reducing Construction Labour Costs

We identified and evaluated two potential ways to reduce the construction labour costs of the two CVFs: using a higher level of advanced outfitting during the construction of the large blocks and carefully planning the construction start of the second ship. These options reduce not only the direct cost of shipyard labour but also the variable portion of overhead costs.

Figure 3.1
Notional Breakout of Carrier Construction Costs



Increasing the Level of Advanced Outfitting at the Block Construction Shipyards[1]

Modern ship construction techniques involve building the total ship from various modules. Although the terminology differs from shipyard to shipyard, small pieces called units or assemblies[2] are combined into larger pieces called blocks, which are themselves combined into still larger pieces called grand blocks or rings. The grand blocks or rings are typically placed into a dry dock and combined to form the complete ship.

Building the pieces is composed of two functions—the cutting and welding of structural elements and the outfitting of the structure

[1] See Schank, Lee, and Pung (2004).

[2] Units or assemblies can be either structure pieces or 'packaged products'. For example, machinery units are groups of equipment installed and connected on a common foundation. Other examples include complex piping units or even modular cabins.

with the electrical, piping, and other ship system material and equipment. Outfitting tasks include the following:

- **Structural**—installing equipment foundations, doors, ladders, hatches, and windows
- **Piping**—installing and welding pipes, including spools and connectors
- **Electrical power distribution**—installing the power distribution system downstream of the main power switchboards, including hanging and pulling cables and installing local switchboards and ancillary electrical equipment
- **Heating, ventilation, and air conditioning (HVAC)**—installing air handling units, ducting, and ancillary equipment
- **Joinery**—installing accommodations such as cabins or berths, dining facilities, food preparation areas, and rooms for meetings or other administrative activities
- **Painting and insulation**—covering the structure and accommodations of the ship.

Advanced outfitting involves performing the outfitting tasks as early in the construction process as possible—that is, at the unit, block, or grand block stages. Common shipbuilding belief holds that advanced outfitting leads to lower production hours and therefore lower costs, compared with performing outfitting tasks when the ship is complete (i.e., in the dry dock after the grand block stage). The belief that the amount of work multiplies as construction progresses is embodied in rules of thumb such as '1-5-10', i.e., what takes one hour to perform at the unit or block level takes five hours at the grand block level and ten hours once the ship is complete.

Advanced outfitting reduces labour hours for several reasons. The smaller units and blocks are typically built in covered production shops where material and equipment are readily available and the piece can be positioned to reduce or eliminate complex and time-consuming tasks (e.g., positioning the piece such that the welding and installation of equipment and material is accomplished 'hands down'). These advantages are less available at the grand block stage, although grand blocks may also be built in covered facilities or in an open staging area alongside the dry dock. Although typically not a covered area, the platen can also facilitate the positioning of material and equipment needed to construct the grand block. Once grand blocks go into the dry dock, the outfitting task becomes harder and more time consuming. Material, equipment, and the labour force must be brought to the ship in the dock, working conditions are more confined, and the weather can affect productivity.

In advanced outfitting practices, shipbuilders in the United Kingdom are somewhat behind the commercial shipyards elsewhere in Europe and in Asia. UK shipbuilders do a larger portion of the outfitting tasks at the complete ship level, particularly with regard to electrical power distribution, piping, and HVAC.

Literature reviews and analysis of available data suggest that advanced outfitting can reduce labour hours from 20 to 50 percent depending on the outfitting task and the type of ship. Because the outfit hours are 50 percent or more of the total hours used to build an aircraft carrier, employing greater levels of advanced outfitting can have a significant impact on total construction hours.

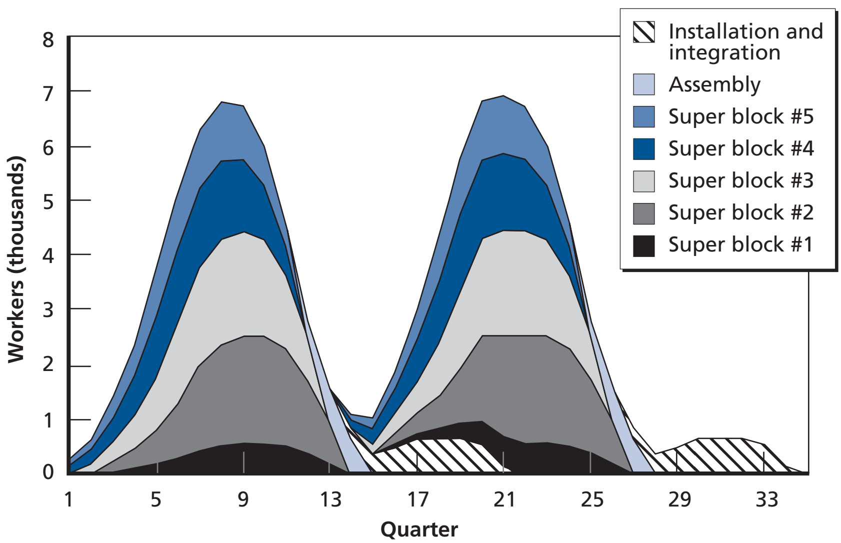
The CVF IPT has a goal of 80 percent or more outfitting at the large-block stage. Our analysis suggests that this is reasonable and achievable, but only if the construction shipyards change their current outfitting processes. The shipyards involved in large-block construction should compare outfitting processes among themselves and with those in other European and Asian shipyards. They should then adjust their construction methods to optimise the level of advanced outfitting at each shipyard. Also, larger degrees of advanced outfitting are possible only if the ship design is near completion and if the required material and equipment are available. The CVF Alliance would, therefore, have to work hard to facilitate higher degrees of advanced outfitting.

Setting the Construction Start for CVF-2

The proposed build plan for the CVFs involves up to four separate shipyards building blocks of the ship concurrently and then transporting them to another shipyard for final assembly, test, and delivery. As currently planned, each of the block construction shipyards will have a large workload over the block construction period for the first ship and then a gap until starting the construction of the blocks for the second ship. This potential delay between the completion of the first ship's blocks and the start of the second ship's can have significant workforce implications. In the absence of other work in the shipyard, the shipbuilders may have to make redundant a large part of their workforce and then reconstitute that workforce to start construction for the second ship. This workforce turbulence adds to labour costs and can adversely affect worker proficiency.[3]

Figure 3.2 shows the potential workforce demands for the two CVFs, with a gap of three-quarters between the completion of the

Figure 3.2
Potential Workforce Demands for the Two CVFs, Assuming Super Block Build



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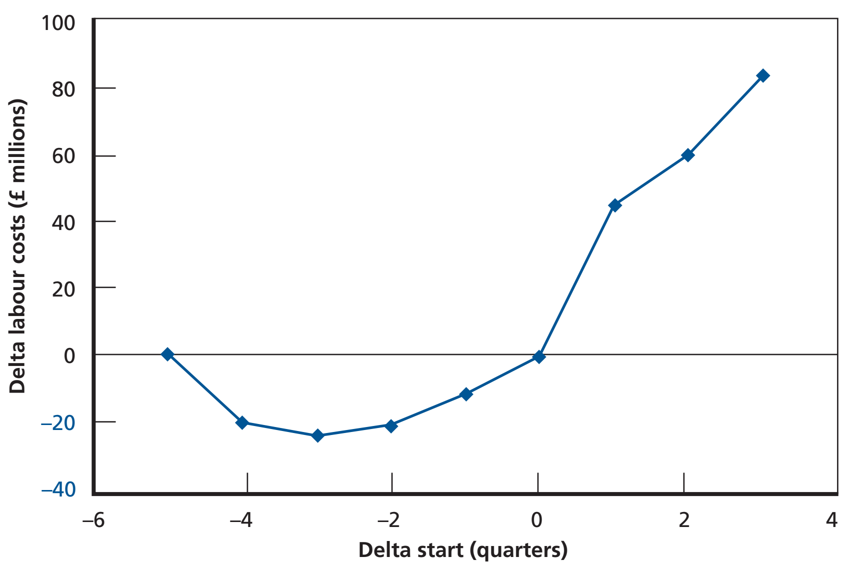
[3] RAND has previously examined the cost implications of production schedules for the US aircraft carrier programme. The analysis showed that starting the construction of CVN-77 two years earlier than planned, but holding the delivery date constant, could reduce overall construction costs by several hundred million dollars. See Birkler et al. (1998).

first ship's large blocks and the start of the second ship's construction. The workloads and schedules reflected in Figure 3.2 are based on data received from Thales UK in mid-2002 and RAND analysis of potential total workload demands of the ship designs at that time. The size of the CVFs, the overall build philosophy in terms of the numbers and sizes of the large blocks and the construction schedule, and the allocation of work between the block construction shipyards and the assembly shipyard are all somewhat in flux. Therefore, the profiles shown in Figure 3.2 are illustrative only.

Using RAND models developed during research for the US Navy and the MOD,[4] we estimated the difference in labour costs at the block construction shipyards for different production gaps. Figure 3.3 shows the resulting costs for different construction starts for the

Figure 3.3
Cost Impact of Varying Start Date of CVF-2



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[4] See Arena, Schank, and Abbott (2004).

second CVF. Earlier starts of the second ship could result in more than £20 million of labour cost savings for a construction gap of three-quarters less than the plan reflected in Figure 3.2; that is, starting construction of the large blocks for the second ship as the construction of the first ship's blocks is ending will minimise labour costs. Widening the gap further than the plan results in higher labour costs.

Labour costs are reduced when shipyard workloads are fairly consistent over time for each skill group. The ability to stabilise demands depends on the timing of the projects in the yard. Therefore, the impact on labour costs of different start dates for the second CVF varies depending on the other work in each particular shipyard. The start date for the second CVF should be carefully planned at each shipyard to minimise costs, based on the scheduling of block arrival at the assembly yard and of all other work in the yard.

Reducing Construction Material Costs

As noted, the cost of material and equipment, either GFE or contractor-furnished equipment (CFE), will account for more than 50 percent of the construction costs of the CVFs. We examined two options for reducing these costs: centralising material procurement and using commercial versus military specifications wherever practical.

Centralised Material Procurement

Typically, each shipyard involved in building a class of ship will order the equipment and material it needs for construction. Four or more shipyards will be involved in building the CVFs, each requiring valves, pumps, structural elements, and various other material and equipment. Centralising the procurement of the required material and equipment can lead to reduced costs through economic order quantity buys. Also, centralised procurement can lead to standardisation of the material across all the shipyards involved in CVF construction.

The US Navy's DDG-51 programme and the MOD's Type 45 programme each use a form of centralised procurement of material and equipment. Each construction shipyard draws from the centralised contract as needed during construction. This practice can lead to cost savings of 10 to 20 percent.

The CVF Alliance should work with the shipyards to identify the types and quantities of material and equipment and identify alternative suppliers for the items. They should then compete the centralised buy among the qualified suppliers to achieve the best price.

Use of Commercial Systems and Equipment

A second option for reducing material and equipment costs is to consider using commercial systems and equipment versus systems and equipment with military specifications wherever the commercial systems do not adversely affect the safety and operations of the CVFs. Military equipment is designed to more stringent shock and damage standards than are commercial systems. These standards provide more robustness but add to the overall cost.

Standards for the CVF should take into account lessons learned from the construction of HMS *Ocean,* which used primarily commercial standards. Because HMS *Ocean* was procured under aggressive cost targets, the Royal Navy sacrificed some operational capabilities. It is important for the Alliance to carefully consider trade-offs between operational capability and price. Should the Alliance decide to upgrade capability later, it will pay a greater price than at initial procurement. One way to mitigate this penalty is to build in extra capacity for planned upgrades.

Because HMS *Ocean* is the only assault helicopter carrier in the Royal Navy, there is great pressure to get the most out of the ship. This means that its maintenance and docking schedule must be managed very closely. HMS *Ocean*'s initial docking period was three years late because of operational requirements. Given that two CVFs will replace three CVS carriers, there may be similar operational demands.

The ship must be robust enough to operate beyond its scheduled maintenance rotations.

The Alliance must clearly define its requirements to the shipbuilders. In HMS *Ocean*'s case, some of the initial requirements sent to the contractor were vague. Because the contractor was under the pressures of a fixed price contract, lower standards were observed than those envisioned by the MOD. By ensuring the shipbuilder understands the requirement, the Alliance can avoid rework and additional cost.

The Alliance must be very selective when determining which ship systems will be built to 'commercial' standards and which will be built to 'military' standards. Applying the wrong standard to systems will lead to increased cost or decreased capability (or possibly, in some cases, both). Commercial standards can be used as long as the Alliance understands their potential limitations, and those limitations do not compromise the ship's operational performance. Military standards will almost certainly be required for combat systems. But commercial standards may be adequate for 'hotel' functions, such as food service, trash management, laundry, and HVAC.

When looking to implement commercial standards in portions of the CVF, the Alliance must ensure that the shipyards understand both the cost and production implications that these commercial standards will have. Few of the shipyards have experience building commercial ships and may not fully understand how to estimate costs for the commercial standards. The exception may be Swan Hunter, because its management has worked in a commercial environment, and possibly the former Govan, because of its past as a commercial yard and its experiences building HMS *Ocean*. Based on our discussions with various UK and US shipyards, military shipyards are accustomed to building to a much more demanding standard. It may be difficult for them to adopt a 'lower' standard. Shipyards will have to make a conscious effort to ensure that their employees and working practices reflect the greater commercial emphasis that will characterise the CVF programme. (In the next chapter, we will identify several commercial systems that may be applicable to the CVFs and estimate the cost impact of using these systems.)

Other Possible Ways of Reducing Acquisition Costs

There are some other options the Alliance should consider in attempting to control the acquisition cost of the CVFs. These options are primarily at the Alliance and MOD levels. They relate to the maturity of design prior to construction start, the frequency of change orders, and the use of computerised design tools.

It is very important that the shipyards assembling the large blocks have a nearly complete production design before construction begins. A nearly complete design will allow the shipyards to plan their production processes and will facilitate advanced outfitting and centralised material procurement. Construction costs increase when production does not flow smoothly or when work is not accomplished in the most cost-effective sequence. It may be more cost-effective to delay the start of block construction, and even the delivery date of the first ship, than to start construction before designs are firmly established.

The Alliance must strive to reduce the number of changes that occur throughout the programme. From our experience, military programmes typically have a larger number of changes during ship construction than do commercial programmes. Changes contribute to cost. Figure 3.4 shows the average percentage cost increase due to change orders for military and commercial ships based on the data received from a survey of US, UK, and other European shipbuilders.

Not only are military programmes subject to greater frequencies of change, but their changes tend to occur later in the construction process than is the case for commercial programmes. Other things equal, changes later in construction add more to cost. Figure 3.5 shows the pattern of change orders for commercial and military programmes based on recent surveys of US, UK, and other European shipbuilders. Changes during assembly, outfitting, testing, and trials are most costly to shipbuilders.

In addition to minimising the number of changes during the construction of the CVFs, the Alliance should strive to resolve change requests as quickly as possible. Buyers of commercial ships resolve

Figure 3.4
Percentage of Total Cost Due to Change: Military Versus Commercial

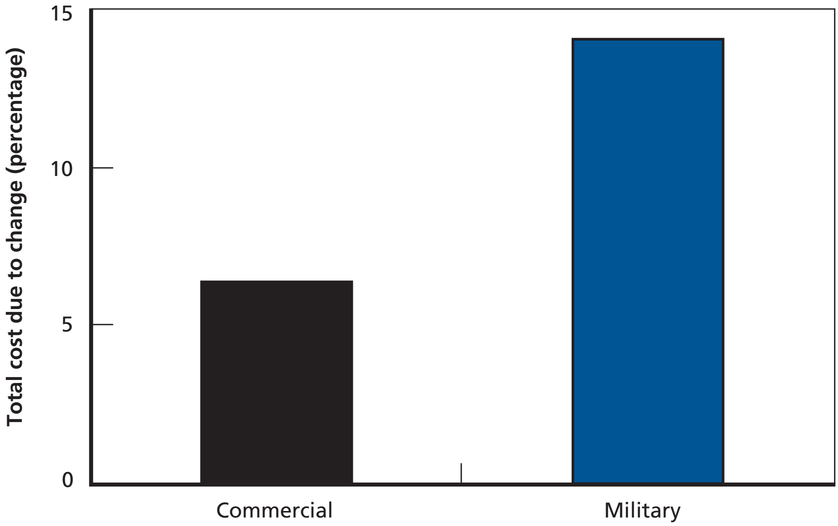

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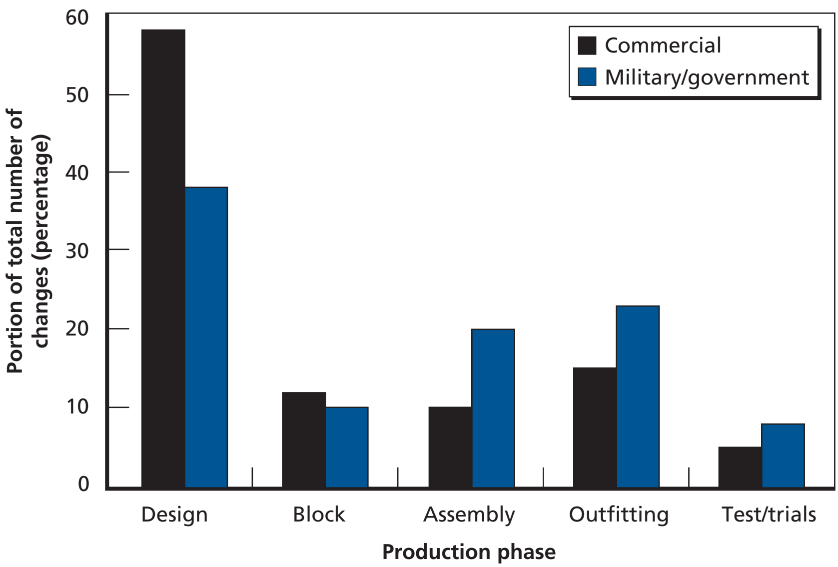
Figure 3.5
Timing of Change Orders for Military and Commercial Programmes



RAND *MG240-3.5*

issues quickly, on the order of two to three weeks. Changes for military ships take more than twice that amount of time. Commercial ship buyers typically have a small number of representatives at the shipyard with authority to resolve most change requests. For military ships, there are typically several groups or organisations that have interest in the ship. These organisations are typically involved in change request resolution, which slows the approval process.

Intelligent, three-dimensional solid computer-aided design/computer-assisted modelling (CAD/CAM) systems are rapidly becoming part of the standard design process for all contractors. The benefits of such systems are difficult to quantify in terms of cost and schedule, but most experts agree that the systems yield higher-quality products and reduce the number of design changes later in programmes, thereby affecting costs.

A principal issue that arises with respect to design tools is whether the diverse tools in use by potential CVF designers are sufficiently interoperable. We collected information on the actors and actions involved in the design process, the specification of information-sharing requirements, and experience with US military shipbuilding. We concluded that use of a single tool is likely to yield higher-quality designs and reduce costs that result from rework, technical deficiencies identified late in the design process, and change orders. For example, in the US *Seawolf* programme, data were translated from the design agent's electronic design system to the construction firm's system. There were many problems; more than 50,000 construction drawing change requests had to be issued, partially contributing to the project's significant cost growth. For the *Virginia*-class programme, a single CAD/CAM system was used, and drawing changes fell by 90 percent.

Summary

Several options could lead to lower CVF construction costs. They include the following:

- Using more advanced outfitting, especially for electrical, piping, and HVAC, than is currently used by most UK shipbuilders. The IPT has a goal of getting 80 percent of outfitting done by the large-block stage of construction. This achievement is possible only if the shipyards change their outfitting practices.
- Setting the start of the second CVF to minimise total labour costs at the shipyards constructing the large blocks. If the large blocks for CVFs could be started nine months earlier, some £20 million in labour costs might be saved.
- Centralising the procurement of material and equipment and having all the participating shipyards draw from the centralised suppliers.
- Considering the use of commercial systems and equipment in place of military standard equipment wherever there is no adverse impact on operations or safety. Hotel-related functions might be suitable areas for commercialised equipment.
- Ensuring that the design of the ship is nearly complete before construction commences.
- Minimising changes during ship construction and quickly resolving any changes. Lessons might be learned from the commercial sector, where change requests account for only half as much of a ship's cost in the military sector and where a greater proportion of changes is requested in earlier stages of acquisition.

CHAPTER FOUR

Minimising Annual Support Costs

In this chapter, we examine options that could lead to reductions in annual operating and support costs. We first describe the maintenance practices for the current CVS carriers and then the proposed concept for the CVF. We then identify areas that are potentially large contributors to annual operating costs. Based on these cost drivers, we examine several systems adopted by the commercial cruise industry that offer the potential to reduce acquisition and operating costs for the CVFs. Finally, we discuss the painting of the ship, especially the potential impact on dry-dock requirements.

Maintenance of CVS Carriers

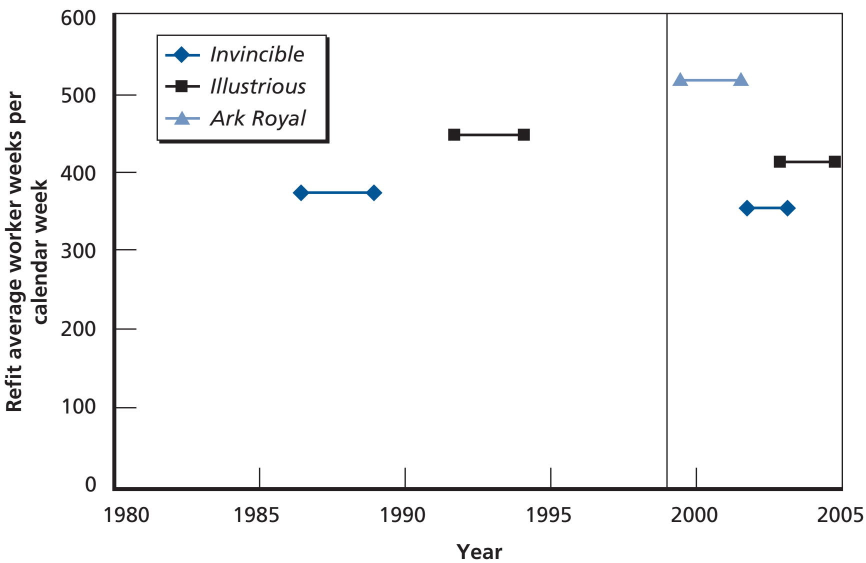
Of the three CVS-class aircraft carriers, HMS *Invincible* was commissioned in 1980, HMS *Illustrious* in 1982, and HMS *Ark Royal* in 1985. Vickers Shipbuilding and Engineering in Barrow-in-Furness designed and built the *Invincible*; Swan Hunter Shipbuilders in Wallsend built the *Illustrious* and *Ark Royal* using the *Invincible* design (Sharpe, 2000).

Like other Royal Navy ships, the CVS carriers receive a cycle of maintenance and upkeep. Some maintenance occurs while the fleet possesses the ship ('fleet time maintenance'), whereas more serious maintenance and upkeep takes place during 'non-fleet time', when the ship is in the possession of a repair facility.

There has been flux in the ships' maintenance plans. The MOD changed the prescribed CVS maintenance cycle in 1998. Also, in the late 1990s, CVS 'refits' (maintenance in dry dock) were moved from Devonport Management Limited in Plymouth to the Rosyth repair shipyard, which is owned and operated by Babcock BES.

The first CVS refit was on the *Invincible*, lasting from May 1986 to November 1988 at Devonport (see Figure 4.1). The *Illustrious* had a refit at Devonport between September 1991 and January 1994. Rosyth's first CVS refit started in June 1999 when the *Ark Royal* entered the yard. Since that time, Rosyth has had at least one CVS carrier in its possession, with the exception of a two-month period starting in July 2001 when the *Ark Royal* left the yard and the *Invincible* arrived in September. The *Illustrious* arrived in November 2002 prior to the *Invincible*'s January 2003 departure.

Figure 4.1
The Timing and Intensity of CVS Refits



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The CVS refits have averaged between 350 and 500 worker-weeks per calendar week, as shown in Figure 4.1. Refits to the left of the vertical line were at Devonport, and those to the right were at Rosyth. The most recent *Invincible* refit was 'tailored', i.e., smaller, reflecting the fact that the ship is to be retired relatively soon.

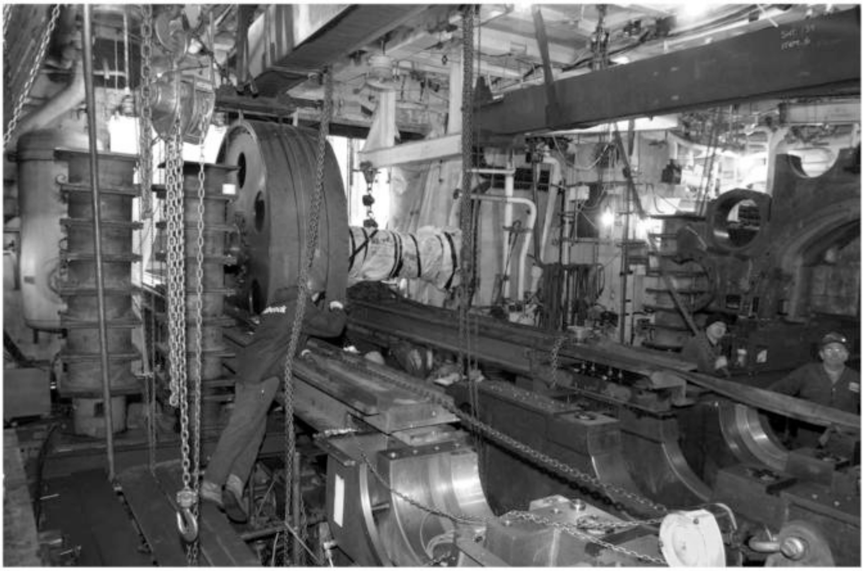
Even with the comparatively low magnitude of the *Invincible* refit, since the refits moved to Rosyth, the shipyard has had a relatively steady stream of CVS work, allowing it some advantages of workforce stability. Indeed, Figure 4.1 somewhat understates the stream of CVS-related work the refit yards have received. There are also comparatively brief defect rectification periods (DRPs) following refits where, after the vessel has had sea trials, the shipyard again works on the ship. As noted, the *Invincible*'s tailored refit ended in January 2003, but the ship returned to the yard for a short period in February and March for DRP work.

The most time-consuming parts of the refits have been the installation of new equipment, e.g., weapon systems. Such new installations are referred to as 'updates'. The refit shipyard has been dependent on delivery of the new equipment by its manufacturer; this process has been prone to delay, we were told.

By contrast, the process of maintaining the carrier, or 'upkeep', has been more predictable and more within the control of the refit shipyard. For both the recently completed *Invincible* refit and the ongoing *Illustrious* refit, however, gearbox damage has required that a hole be cut in the side of the ships to remove and replace the damaged unit. Unfortunately, the CVS carriers were designed such that this process is difficult, with considerable disruption to adjoining parts of the ship. 'Work in way' of removing the *Invincible* gearbox included three auxiliary boilers and associated system pipe work, intakes, and exhausts. There was also fuel and steam system pipe work and significant cable removal necessary to clear the access. Figure 4.2's photo depicts the process of the *Invincible* gearbox removal.

We were told considerable cross-CVS cannibalisation has occurred. The ship in refit has been stripped of parts (most notably, but not exclusively, its weapon systems) for the benefit of the two operating carriers.

Figure 4.2
Removing a Gearbox from the HMS *Invincible*



SOURCE: Courtesy of Ken Blacklock of Babcock BES.
RAND *MG240-4.2*

Maintenance of CVFs

The MOD envisions a distinctly different maintenance approach for the CVFs. Most centrally, only two CVFs are to replace the three CVS carriers. Hence, having a carrier in refit at almost any point in time is no longer acceptable to the MOD.

The MOD's February 28, 2001, Use Study details the MOD's CVF maintenance plans. The CVFs are to have a 26-week docking period no more than once in a six-year period. The MOD wanted to extend this cycle to once every 12 years, but neither BAE Systems nor Thales UK would commit to such an extension. Thales UK noted, for instance:

> the need for warships to hold certification issued by the MOD Sea Technology Group will continue. We are further advised that it is unlikely that either verification of certification via the classification society, or re-validation of certification beyond 6 years without physical survey, will be acceptable. (Thales Naval, 2002b, Section 7.1.3.2)

CVF dockings are not to be as extensive as CVS refits. Indeed, 'major refits, as currently understood, would not be undertaken' (Use Study, Section 4.3.1). During a six-month docking period, only a few weeks would be spent in dry dock.

Given the MOD-prescribed dry-dock constraints, it would seem as if little beyond hull painting would occur during a dry-docking.[1] Certainly, a CVS-like gearbox repair could not be undertaken. Instead, MOD specified that the CVF would be designed such that a broken gearbox, for example, could be removed and replaced while the ship is at its homeport, Portsmouth, without having massive disruption to the rest of the ship.[2] Indeed, both BAE System's and the chosen Thales UK designs allow a repair of that sort to be much more of a pull-out/plug-in action that could be done outside a dry dock.

The MOD assumes that substantial savings can be achieved from reliability-centred maintenance (RCM) (Use Study, Section 4.3.1). John Moubray defines RCM as a process used to determine the maintenance requirements of any physical asset in its operating context.[3] Potential sources of failure are identified and then strategies are implemented to reduce the probability and/or cost of failure. Traditional scheduled mid-life overhauls may or may not be appropriate, depending on a given part's failure pattern. An alternative is on-condition (or condition-based) maintenance, where action is taken if and only if there are indicators that costly failure is about to occur.

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[1] See the section on paint issues later in this chapter.

[2] For that matter, if the CVFs use electric-drive propulsion, there may be no large gearboxes of the sort found on the CVS class.

[3] This paragraph's material is a distillation of the first chapter of Moubray's *Introduction to Reliability-Centered Maintenance* (2000), online at www.maintenanceresources.com/ReferenceLibrary/RCM/RCM1.htm (last accessed September 2004).

The goal is to ensure that only the most effective forms of maintenance are chosen for each asset.

Cost Drivers

As we considered how the CVF class might be most cost-effectively supported, we naturally focused on the ships' largest cost drivers. Table 4.1 shows Thales UK's estimates of its ships' 20 largest acquisition and in-service cost drivers, on a percentage basis.

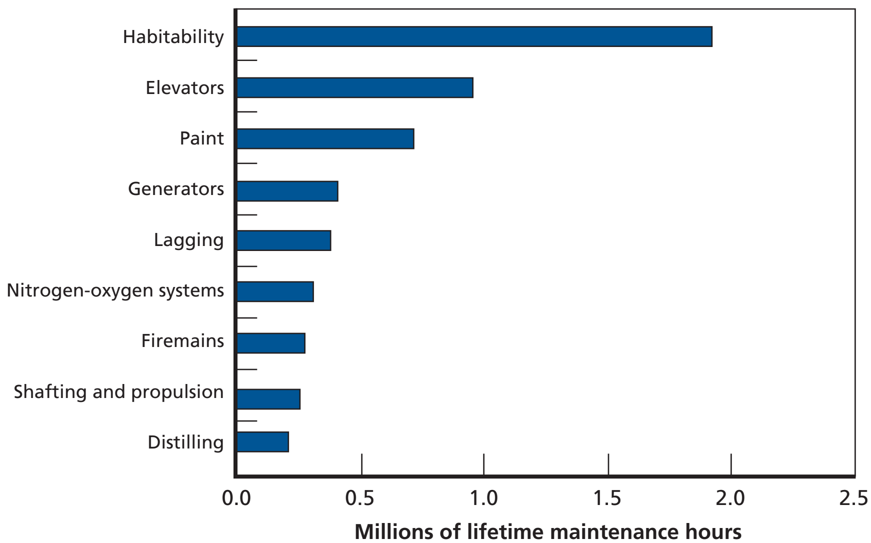
Table 4.1
Thales UK's CVF Acquisition and In-Service Cost Drivers

Work Breakdown Structure (WBS) Code	Item	Percentage Contribution
X1-01	Complement	26.3
P0-07	Prime contractor profit and management reserve	5.9
J0-01	Support joint venture	4.6
X1-02	Fuel	4.4
J0-02-05	Training	3.4
K1-02-XX-02-622	Interior and exterior paint	2.7
P0-09	Value-added tax	2.4
A1-01-01	Gas turbine alternators	2.2
T1-01-03	Communications	2.1
T1-01-05	Communication transfer infrastructure	2.0
K1-02-XX-01-04	Structural decks	1.9
P0-01	Project management (project controls)	1.8
T1-01-01-11	Multifunction radar	1.8
T0-01	Information systems integration agent	1.8
T0-02	Combat system shore test facility	1.5
P0-04	Design authority (technical directorate)	1.5
K0-01-04	Whole ship design	1.5
K1-02-XX-05	Electrical	1.5
T1-01-06	Navigation/integrated bridge systems	1.3
T1-01-01-09	Inner-layer missile system	1.2
All Others		28.2

We also obtained US Navy data on the lifetime organisational, intermediate, and depot-level maintenance hours of the recently retired nonnuclear aircraft carrier, the USS *Constellation*. Figure 4.3 shows that ship's nine largest categories of lifetime maintenance. Not surprisingly, they are somewhat different from Table 4.1's, which includes acquisition and complement costs.

Obviously, not all the cost categories in Table 4.1 and Figure 4.3 would be easy to cut (e.g., contractor profit, value-added tax). Nevertheless, these largest cost drivers are the most obvious places to begin carefully scrutinising. In the next section, we discuss possible sources of savings for systems relating to habitability; we then take up issues related to paint.

Figure 4.3
Largest Categories of USS *Constellation* Lifetime Maintenance



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Cruise-Ship Insights

Cruise ships are a useful paradigm for consideration of options for minimisation of WLCs of the CVFs. Cruise ships, like carriers, are large vessels that carry thousands of people. They are held to very high standards, in terms of both customer comfort and environmental responsibility. Cruise ships are profitable only if they are operating, so they have availability standards far beyond those of military vessels.

There is robust competition among both cruise-ship manufacturers and maintainers resulting in a flow of innovations. We think some of these innovations might be transferred to carrier manufacturing and support.

MSCL Inc., a naval research firm with whom RAND has worked closely, undertook a 1999 study of potential application of commercial systems to US aircraft carriers, with particular reference to the then-upcoming production of CVN-77.[4] In this section, we summarise some of the firm's insights that might be considered for the CVF. Indeed, as mentioned in Chapter One, we could not tell if some of these ideas might already be included in CVF planning, but we wanted to note them in any case. They all reflect the principle set out in the preceding chapter that MOD should seriously consider systems designed to commercial standards where military standards are not essential.

Sewage

MSCL investigated the use of a vacuum collection, holding, and transfer (VCHT) system. The company calculated, based on US Naval Sea System Command estimates, that the overall sewage, grey water, and food waste volume could be reduced to about 70 percent of what it is now if vacuum systems were used instead of the gravity drain systems currently used. If there is 30 percent less to dispose of, the costs of disposal will be significantly decreased. MSCL argued that VCHT maintenance on aircraft carriers could be done by just

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[4] See, in particular, MSCL Inc. (1999).

one person. Further, acquisition cost savings of £1–2 million might be achieved through the use of commercial VCHT materials.

It is noteworthy that, in 1999, some of the technologies evaluated to process wastes onboard and reduce waste disposal costs in the future were still in early development and so were not pursued. However, they could be far enough along now to consider for the CVF. Cruise ships realise the following CVF-relevant benefits from using freshwater VCHT sewage collection technology and freshwater food waste pulpers:

- reduced maintenance and therefore manpower 'from the equivalent of 10 persons to about 1'
- reduced life-cycle costs, amounting to $46 million FY98 NPV (£32 million FY03) if applied to CVN-77.
- elimination of saltwater from ship's heads and galleys, which results in further savings in maintenance and manpower.

Freshwater

In recent years, as the cruise-ship industry has been switching from reverse osmosis to steam distillation for the production of freshwater, the US Navy has been moving in the opposite direction. *Nimitz*-class carriers, however, still use distillation.

Some cruise ships must produce even more freshwater than aircraft carriers do. The *Grand Princess,* which has the largest capacity, uses waste heat from engine exhaust and cooling systems to boil water for most of its freshwater needs. It also has an oil-fired boiler as a supplementary source. Older cruise ships have been fitted with reverse-osmosis systems as further supplements.

MSCL estimated the WLC of the 400,000-gallon-per-day CVN-77 distillation system at $27.8 million NPV (FY98), including the costs of acquisition and installation, consumables, maintenance, and personnel. Analogous costs for the 350,000-gallon-per-day *Sun Princess* system amounted to $7.9 million. Some of this difference is due to greater shock hardening and other military specifications in the Navy system and to the Navy's more costly preventive (versus corrective) maintenance approach. After taking military needs and practices into account, it would seem that approximately $12 million in savings might still be realised.

The Navy has been switching to reverse osmosis because of its lower cost and greater reliability. Such a system was considered for CVN-77. MSCL estimated the whole-life NPV of such a system at $15.7 million FY98. Cruise-ship operators, however, have found reverse-osmosis systems to be less reliable and higher in maintenance costs than steam distillation. The reasons for this disparity in experience are unclear. Regardless, whether the Navy goes with steam distillation or reverse osmosis, it would appear that approximately $12 million NPV FY98 (£8 million FY03) in WLCs could be saved.

Trash

MSCL examined how the cruise industry handles waste management and looked at various options for US aircraft carrier trash disposal. The *Sun Princess* carries about 3,200 crewmembers and passengers who combined generate about 4.3 tons per day of trash and up to 2.7 lbs per person per day of food waste.

The central feature of cruise-ship waste management is the shipboard incinerators. One or two operators from a total Waste Management Department of five run the waste management systems 24 hours per day. Each operator works ten hours per day, six days per week, eight months per year. The ships' waste management requires very little sorting compared with a carrier. About 75 percent of trash is burned—food waste, oil waste. Noncombustible trash is compacted and stored for off-load ashore. Policy prohibits the discharge of any waste to the ocean, except for incinerator ash, where permitted by MARPOL.[5] The *Sun Princess* has two incinerators, and there is a shredder located above each incinerator. The systems could be about half their current size if it were not for food waste. Crew or contractors perform incinerator maintenance. The shredders are cleaned and sanitised daily. Twice each month, each incinerator is shut down and the ship's waste crew checks and cleans it. This maintenance con-

[5] As designated by the MARPOL/International Maritime Organization (IMO) specified standards for marine pollution.

sumes one man-day of labour. Once per year, two subcontracted technicians from the supplier perform a checkup and adjustment costing about $5,000. Glass and metal compacting devices are commercial and cost up to $15,000 each. Service life is up to 10 years. Aluminium cans are compacted and donated or sold ashore for about $200 per week.

A US carrier has approximately 3,200 crewmembers, not including the Air Wing, who combined generate between 1.5 and 3 tons of trash per day. Currently, a crew of 18, including two supervisors, four maintenance petty officers, and 12 E-1 to E-3 personnel, manages the carrier's suite of equipment.

In comparison with the *Sun Princess*, CVN-75 processed less trash, yet the cost is almost 10 times that on the *Sun Princess*. This much larger expense is partially attributed to the greater number of waste management personnel on the carrier, which is partially due to the amount of sorting done. On the CVN, all plastics, metal, glass, and textiles are sorted, and food is sorted from plastic; however, on the *Sun Princess*, only metal and glass is sorted from all other waste.

Total WLCs are $55 million less (FY98 NPV) on the *Sun Princess* than on US carriers (see Table 4.2). Factors contributing to the difference include the following:

- Personnel is the largest cost for the Navy or cruise ship; the Navy personnel average approximately $67,000 per person, whereas the cruise-ship personnel average approximately $24,000 per person.
- The Navy equipment is Navy-unique and a large number of machines are required, whereas the cruise-ship equipment is commercially available.
- Maintenance costs reflect the noncommercial nature of the equipment, relative to the cruise-ship equipment.
- The Navy depends on shore disposal for much of the waste—which is one of the drivers of the high cost for trash

Table 4.2
Costs of Trash Handling: Current US Navy Carrier Versus Commercial Cruise Ship

	Current Navy Practices ($Millions FY98 NPV)	*Sun Princess* ($Millions FY98 NPV)
Personnel	26	2.5
Equipment and acquisition	7	2
Equipment maintenance	4	0.5
Disposal of waste ashore	21	1
Consumables	2	0
Total	60	6

disposal—whereas cruise ships incinerate most of their waste onboard.
- The Navy spends approximately $2 million NPV for plastic and burlap bags.

The MSCL study suggested two options. The first option was to incinerate plastic wastes and other 'incidental wastes for which there is no other option'. This process would allow elimination of plastic waste processors and associated manpower. The second option was to incinerate plastics *and* all combustible trash (excluding food waste, which is burned on the *Sun Princess*) and use commercial metal and glass processing. The latter was estimated to yield the larger whole-life net benefit. If implemented on CVN-77, option two would cost $13 million over the life of the ship (including minor up-front costs), thus saving a total of $48 million FY98 (£34 million FY03).

Heating and Ventilating Systems

MSCL compared the cost of installing and operating *Nimitz*-class heating and ventilation with the cost of installing and operating commercial heating and ventilating systems on a large cruise ship (similar systems are also used on European warships). Waste disposal and heating and ventilation are the only subsystems on a cruise ship that have dedicated staff for operation and maintenance. There are ancillary benefits to the commercial system as well.

The commercial system on a cruise ship is one-thirteenth as costly (on an NPV whole-life basis) to acquire, install, operate, and maintain as the system installed on a CVN. The cruise ship uses three dedicated people; the CVN-77 is estimated to use 45 low-ranking personnel to operate and maintain the system. Comparisons are shown in Table 4.3. It appears that the cruise-ship systems are more efficient in terms of the number of personnel and their cost.

Moreover, the study concludes that reduced maintenance would be needed throughout the CVN with a commercial system because dirt and salt are filtered out. Reducing the amount of cleaning work to be done could reduce crew size. The study cites data showing that each of the 5,458 enlisted personnel aboard a fully manned *Nimitz*-class carrier spends about 8.4 hours per week cleaning the ship. Using a 12-hour workday, seven days per week, means the cleaning workload is full-time labour for 550 sailors, about 10 percent of the enlisted crew. Based on tests of certain filters and coalescers, the study estimates cleaning could be reduced by 20 percent, or about 100 people who could be freed for other duties or removed from the ship. This infers that designing the CVF to use commercial heating and ventilating systems has a high potential payoff, which was estimated at $148 million FY98 (£104 million FY03).

Table 4.3
Heating and Ventilating Costs and Manpower: US Navy Carrier Versus Commercial Cruise Ship

	Total NPV Cost (FY98)	Personnel (Number)	Personnel NPV Cost	Percentage of Total Cost
CVN-77	$188,410	45	$58,622	31
Cruise ship	$14,295	3	$3,001	21
Factor	13.2	15	19.5	

Joinerwork and Furnishings

Joinerwork and furnishings contribute importantly to noise suppression, fire protection, and ship's force comfort. The cruise-ship industry has made advances in all three respects in recent decades while keeping costs below those often paid by military owners. MSCL asked a marine-engineering and cost-estimating firm and a commercial marine joinerwork and furnishings provider to estimate costs for officer and enlisted quarters on a US Navy ship and a commercial ship, respectively. After dividing by the number of persons housed, the estimates could be scaled to a ship of CVN-77's size and a commercial equivalent. The estimated acquisition costs were $61 million FY98 for the military ship and $24 million for the commercial. Discounted to present value from the projected CVN-77 installation date yielded a savings of $29 million NPV (£20 million FY03).

Summary

It was estimated that a total of $283 million FY98, or £198 million FY03, of WLCs could be saved by employing commercial practices for trash, food waste management and sewage, freshwater production, heating and ventilating, and joinerwork and furnishing systems (see Table 4.4). Achieving these cost savings requires investments in technology, as indicated above, and, in some cases, changes in policy and procedure, which may have other soft costs or implications.

Table 4.4
Net Savings from Employing Cruise-Ship-Like Practices for Hotel Functions on CVN-77, Relative to Prevailing US Navy Practices

	Savings Net of Investment (£Millions FY03)
Sewage	32
Freshwater	8
Trash	34
Heating and ventilating	104
Joinerwork and furnishings	20
Total	198

The savings cited are for one ship, so it is conceivable that employment of commercial-like practices for hotel functions would save £400 million across both CVFs. However, the cost savings will vary by platform, and it is possible that making some of these changes may not result in cost savings. We will not know until the design is complete. However, it is likely that employing the technologies and practices we have reviewed will result in some savings.

Paint Issues

Paint is a central issue in aircraft carrier maintenance and also has implications for safety and performance. If a ship is not painted appropriately, corrosion problems will shorten its life. Having antiskid paint on an aircraft carrier's deck is a safety issue. Also, antifouling paint on a ship's hull is important to prevent organic buildup that would slow the ship and/or increase its fuel consumption. To better understand paint-related issues, we met with British and American paint experts and also undertook a review of the recent literature on this topic.

There is a marked divergence between British and American views on paint for the CVF. As discussed above, both BAE Systems and Thales UK felt the carriers need to go into the dry dock for repainting no less seldom than every six years. At least in part, this perspective emanates from a requirement to abide by Lloyd's Registry standards.

The US Navy does not follow Lloyd's standards because it believes that commercial paint standards are not germane to Navy ships.[6] Military ships are not insured, so it is irrelevant to follow standards set by an insurer. Also, the US Navy feels it uses higher-quality paint than is typically used commercially, in part because of its expectation of keeping its ships longer than would typically be true

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[6] Conversation with E. Dail Thomas II, director, Corrosion Control Division, US Naval Sea Systems Command, May 15, 2003.

of a commercial ship owner. In contrast to the planned six-year CVF paint cycle, the US Naval Sea Systems Command's Web site www.nstcenter.com asserts 'the US Navy underwater hull coating systems are designed to last through a ship's docking cycle, which may exceed 10+ years'. The Navy does, however, do underwater hull cleaning between paintings.

A major issue that surfaces in the commercial paint literature is the January 1, 2003, international ban on the application of antifouling paints based on tributyltin (TBT). TBT is a man-made tin-based compound that is considered the most toxic material ever added to the marine environment. Unfortunately, TBT has permeated the marine food chain around some shipyards and harbours (Champ, 2002).

US Navy ships do not use TBT paints.[7] Instead, as shown in Table 4.5, the Navy has a qualified products list (QPL) of non-TBT paints that have been demonstrated to meet their standards. US Navy QPL information is publicly available through www.nstcenter.com should the Royal Navy choose to access it.

Table 4.5
US Navy List of Products Qualified Under Military Specification MIL-PRF-24647: Paint System, Anticorrosive and Antifouling, and Ship Hull

Manufacturer	Plant Location(s)
Akzo Nobel's International Paint	Houston, Texas; Union, New Jersey
Ameron Protective Coatings Group	Alexander, Arizona; Riverdale, California
Hempel Coatings (USA) Inc.	Houston, Texas
Sherwin Williams Co.	Houston, Texas

SOURCE: Qualified Products List of Products Qualified Under MIL-PRF-24647: Paint System, Anticorrosive and Antifouling, Ship Hull, QPL-24647-6, 14 April 2000. Online at http://portal.nstcenter.com/Document%20Library/Military%20 Specifications/24647/QPL-24647.pdf (last accessed October 2004).

[7] Conversation with E. Dail Thomas, May 15, 2003.

As one might expect, higher-quality paint and commensurately more skilful application will increase CVF acquisition costs.[8] The resulting benefit from such an approach is somewhat uncertain. However, on a very simple arithmetic level, some increase in acquisition costs would be justified if the use of higher-quality paint eliminated the six-year repainting. The Treasury's Green Book prescribes the use of a 3.5 percent real interest rate, which implies a present discounted value 19 percent less than the cost six years hence. With this benchmark, we see even an 80 percent increase in acquisition painting costs would be justified if it eliminated the six-year repainting ($0.80 < 1/1.035^6 = 0.81$).

A full cost-benefit analysis would be more complex, however. Some painting that occurs during ship construction will never be repeated, e.g., for deeply buried interior tanks. Hence, for this type of painting, the trade-off is between increased acquisition costs for higher-quality paint and painting and reduced long-run corrosion damage costs that are distant but potentially very expensive.

Another question is whether eliminating the six-year hull repainting would eliminate the need to put the ship into a dry dock at that point. It would be very attractive, both from an availability and cost perspective, if no six-year dry-dock visit were needed. However, non-paint reasons such as dry-docking may be necessary. But, as discussed above, the postulated brevity of the dry-docking makes it unclear to us what will happen in the dry dock beyond painting the ship.

A further complexity is that elimination of the six-year CVF dry-docking would imply the initial CLS contract would expire prior to the first mid-life dry-docking. Would the MOD be comfortable re-competing its CLS arrangement without having seen how well the initial contractor did with dry-dock work?

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[8] In fact, most paint-related costs are for the labour, not the paint itself. On the *Illustrious* refit, for instance, £1.1 million was spent on paint, whereas £12.8 million was spent on the labour.

Summary

The MOD faces a variety of challenges in maintaining the CVFs. The decision to shift from three CVS carriers to two CVFs considerably escalates the importance of carrier maintenance. The three-to-two transition also ends the current arrangement in which there is always one carrier in refit. That arrangement had certain advantages, e.g., a ship off which to cannibalise parts and workload stability at the Rosyth refit facility. Managing with much less cannibalisation and workload stability will be difficult. The MOD and its support contractor will also have to maintain the CVFs with vastly less reliance on dry-docking. Under the current conception of CVF maintenance, there will not be time for much more than hull painting during the brief visits the ships do make to a dry dock.

The MOD might gain from designing to commercial standards some systems that the CVF will have in common with cruise ships. Studies for the US Navy suggest that the use of commercial-standard HVAC systems and freshwater distillation systems, together with reduction in the sorting of trash, could save a combined net £400 million in WLCs.

Paint is also a major maintenance expense. If the kind of high-quality paint used in US Navy carriers were also used for the CVF, the scheduled sixth-year dry-docking might be eliminated, which could yield substantial savings. However, the MOD might have other reasons to proceed with the dry-docking.

CHAPTER FIVE

Contractor Logistics Support

In the 2001 Use Study, the MOD notes its policy 'to evaluate the desirability for Contractor Logistic Support (CLS) during Assessment, Demonstration and Manufacture' (Use Study, Section 4.9). However, whereas the Use Study was somewhat noncommittal about CLS, our 2003 conversations with the MOD personnel made it clear they plan to implement some variation of CLS on the CVFs.

Every Royal Navy ship receives some support from contractors, of course. For instance, contractors FSL at Portsmouth and Babcock at Rosyth have integral roles in CVS maintenance.

A distinguishing feature of a CLS approach is that the CLS contractor is compensated based on the level of availability the ship achieves, not on a cost-plus basis. The CLS contractor is then responsible for the myriad decisions underlying keeping a ship operating. For example, a CLS contractor will decide when it is cost-effective to replace a broken piece of equipment versus repairing it and bears the cost in either instance. A CLS contractor might also make trade-off decisions between storing spare parts on a ship versus employing a rapid resupply arrangement. The contractor has strong incentive to efficiently balance costs incurred early against those incurred later, which might include some form of unavailability penalty. Thus, a contractor may choose the greater cost of replacing a part over repairing it, if judged that the risk of unavailability or deferred replacement is too high.

A CLS arrangement involving the ship's designer and/or builder might be particularly desirable because the contractor would then appropriately consider long-run supportability issues in designing and building the vessel. Such an advantage could be lost if the ship were to be maintained by a different contractor.

CLS contracts are typically lengthy. Contract duration is important because the CLS contractor should have incentive to fully consider the long-run implications of its choices. A very short-run CLS contract would probably not work well because the contractor would have incentive to defer any repair or replacement actions that would be costly in the short run but beneficial in the long run.

The potential is that, over the long run, CLS will result in a net benefit that, discounted to present value, will be an improvement over a non-CLS arrangement. Whether this would translate into a savings in WLCs is uncertain. However, CLS may also reduce MOD contract oversight costs. Under CLS, the MOD would just have to monitor ship availability versus having a more prescriptive role under traditional contracting in telling the repair contractor exactly what repair to undertake and, potentially, how to do it.

To assist development of a CVF CLS arrangement, we examined three examples of programmes subject to CLS: The US Air Force's (USAF) C-21A aircraft, and the Royal Navy's survey vessels and offshore patrol vessels (OPVs). We will discuss each arrangement and then conclude the chapter by drawing inferences for the CVF.

Current CLS Arrangements

C-21A Aircraft

The C-21A (Figure 5.1) is the USAF's version of the Learjet 35 passenger aircraft,[1] a long-range executive transport plane. It has a crew of two pilots and can hold eight passengers, with up to about 450

[1] This subsection benefited from a meeting the authors had with the C-21A programme office at Tinker Air Force Base, near Oklahoma City, Oklahoma, April 1, 2003.

Figure 5.1
US Air Force C-21A

SOURCE: www.af.mil/media/photodb/photos/021205-O-9999G-008.jpg.
RAND *MG240-5.1*

kilograms of luggage, and has a flight endurance of about five hours, with intercontinental range.[2]

The USAF accepted its current fleet of 76 C-21As between January 4, 1984, and September 25, 1987. The aircraft cost approximately £2.7 million each in today's terms (adjusting for inflation and the current-exchange rate differential). The USAF primarily uses its C-21As to transport high-ranking military leaders.

When the USAF bought its C-21As, it decided that the aircraft would not be supported through its standard support system. Instead, given the large commercial infrastructure supporting Learjet 35s, it was decided to rely on CLS. The initial 10-year C-21A CLS contract was with a subsidiary of Learjet, the aircraft's original equipment manufacturer (OEM). (The C-21A programme office agreed with the MOD philosophy that the first CLS contract should be with the OEM.) That contract expired in 1994, and a different contractor, Serv-Air, won its renewal. Serv-Air was subsequently acquired by

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[2] See US Air Force fact sheet on the C-21A at www.af.mil/factsheets/factsheet.asp?fsID=88 (last accessed September 2004).

Raytheon, which later spun off its acquisition as Raytheon Aerospace LLC.

The C-21A contract specifies a minimum required aircraft availability level. Required modifications to the aircraft (e.g., installation of a terrain collision avoidance system) are negotiated as 'over and above' work on a case-by-case basis.

It is noteworthy that, with the exception of military-unique identification of friend or foe (IFF) equipment, the C-21A is essentially a commercial product. Raytheon Aerospace is responsible for maintaining the aircraft's commercial components but not the IFF equipment.

Survey Vessels

The Royal Navy has two survey vessels whose responsibility is to assist naval navigation, e.g., to map channels. The key piece of equipment on the ships is a state-of-the-art, commercial survey system.

Under an agreement with Vosper Thornycroft (VT), the vessels were built by Appledore but have been VT's responsibility to maintain.[3] The Royal Navy owns these ships. VT is paid for each day each vessel is available; the ships must each be available at least 334 days per year. The survey vessel contract runs for 25 years with a firm fixed price, except for inflation adjustments. Each survey ship has two VT employees onboard who are also Royal Navy–sponsored reserves.

Offshore Patrol Vessels

The Royal Navy uses three VT OPVs to patrol fishing areas. As with the survey vessels, the Navy has a CLS arrangement with VT. However, the specifics of the contract are somewhat different: VT built the three OPVs itself and, in fact, owns them. The Navy has a five-year, fixed price contract in which it pays VT for usage of the ships. As with the survey vessel contract, VT is paid for each available ship-day. VT is responsible for having each ship available at least 320 days

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[3] This subsection and the next are based on information provided to RAND by Adrian Burt of VT's Integrated Logistics Division.

per year. With the OPV contract, VT also receives a fixed annual management fee.

VT does not feel an undue risk burden in actually owning the OPVs, given that fishery protection is likely to be a continuing Royal Navy requirement. Also, there are a number of other countries, e.g., Canada, engaged in fishery protection, so VT could easily lease or sell, relatively, the ships internationally if need be.

Implications for the CVF

How would CLS work for the CVF? Using the arrangements just described as a baseline, we here discuss the feasibility of adaptation to the CVF. We then discuss several points bearing on the implementation of CLS (or other maintenance contract).

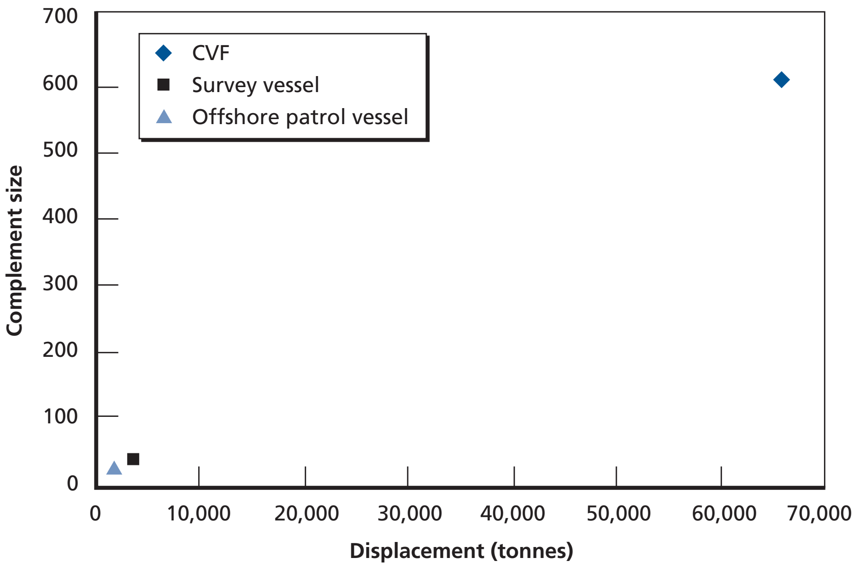
Applicability of the CLS Concept to the CVF

Striking differences exist among the three CLS arrangements reviewed above and what the MOD envisions for the CVFs. First, on a very basic level, the two VT CLS vessels are only a fraction the size of a CVF (see Figure 5.2). Of course, vessel size per se is not important, but it is reasonable to think a CVF will also be vastly more complex than either VT vessel.

Second, the three CLS cases we examined are all, essentially, commercial products or, in the case of the products VT is responsible for, 'commercial ships painted grey', in the words of Adrian Burt, VT's Technical Executive, Integrated Logistics Division. The C-21A, for instance, draws on an established private-sector Learjet support infrastructure. Indeed, the three CLS contracts explicitly have exemptions from their availability requirements in cases for which a missing or damaged piece of government-furnished military equipment prevents the vehicle from operating.

A CVF, of course, will not be a commercial product in military guise. GFE cannot be as neatly excised from the purview of a single party nominally bearing responsibility for the ship's availability.

Figure 5.2
A CVF Compared with VT CLS Vessels (in Thales UK's proposed design)



RAND *MG240-5.2*

Instead, a CVF CLS contractor will almost certainly be dependent on a Defence Logistics Organisation (DLO) provision of some equipment on the ship. A CVF, for instance, cannot operate without a sophisticated military radar system, but the CVF contractor may be dependent on the DLO and/or other contractors to make sure this system works. One can imagine a series of 'seam' problems in which the MOD blames the contractor for the ship not being available but the contractor argues that it was dependent on the DLO for the provision of requisite support. Assuming BAE as the CLS contractor, one could envision ship problems that the MOD believes the company should solve but that BAE feels emanate from flaws in Thales's design.

Seam problems can be addressed, but they put considerable burden on the MOD's contracting officers to create clear lines of demarcation and also to respond agilely to an inevitable unanticipated scenario. These responsibilities will not be an easy nor textbook exercise in contract development and administration.

Another complication is that, in comparison with the future usage pattern of the C-21A, the survey vessels, and the OPVs, the CVF's usage is less predictable. The ships will probably be involved in contingencies or combat, but the magnitude of those crises and their effects on demand for CVF maintenance are highly uncertain.

Finally, no contractor will likely assume responsibility for the entire ship's availability, if only because the penalty fee for not having the ship operating would likely be so daunting. Recall that, in Chapter Two, we reasoned that a more than £500,000 per day penalty would be justifiable. However, without a penalty that adequately reflects the value of the ship's availability to the MOD, the contractor will not be motivated to make the kind of efficient support decisions discussed above. Availability will be undervalued, and long-term investments will be eschewed in favour of fixes that are economical in the short run.

In a ship as complex as an aircraft carrier, there remains the challenge of determining whether the ship is truly 'available'. BAE System's 2002 report (Section 2.5.1) notes that 'it is not clear today to what extent an infrastructure exists that could reliably measure [in service availability] within reasonable timescales'. If availability cannot be easily defined and fairly measured, it cannot feasibly serve as a driver of contractor compensation.

For these reasons, a 'pure' CLS contract (like those covering the C-21A, the survey vessels, and the OPVs) is impossible for the CVF. However, a modified or compartmentalised version of CLS may be appropriate and desirable. For example, the MOD might consider having a habitability contract for which any aspect of ship habitability (e.g., plumbing, heating, air conditioning, food service) would fall under the purview of that contractor. Paying for 'fully habitable days' would seem reasonable and appropriate. One might consider other possible contractual compartmentalisations, e.g., an operable flight deck contract or a propulsion system contract.

Warranties might also be employed as part of, or in lieu of, compartmentalised CLS. Under a warranty, a part's OEM would be responsible for keeping the part operating for a specified period. There are potential seam issues with warranties too. For example, was a part failure a result of adjoining systems malfunctioning or unintended usage of the part? In the US Department of Defense, engine warranties are being supplanted by arrangements like CLS, in part because commercial engine warranties have traditionally been fairly brief. Also, the department's decentralised maintenance makes it difficult to enforce warranties (Peters and Zycher, 2002). Nevertheless, the philosophy of increased contractor responsibility is consistent across CLS and warranties.

The US Navy's F/A-18-E/F Fleet Integrated Readiness Support Team (FIRST) programme is another possible paradigm. As discussed by Blickstein, Camm, and Venzor (2003), the Navy and Boeing have a partnership to support the aircraft. This partnership is not a pure CLS arrangement because there remains Navy-provided depot-level support of the aircraft. There are numerous detailed rules and arrangements delineating the roles, responsibilities, and liabilities of the Navy and Boeing. (It took Boeing and the Navy four years to work these out.) Intriguingly, Boeing is not inoculated from failures in the Navy depot system; it is not clear how well the FIRST programme will perform if there are serious problems in the depots.

We urge that any 'compartmentalised' CLS contract be as explicit as possible as to which responsibilities are the contractor's versus the DLO's or someone else's. There may have to be explicit exemption for combat-related maintenance problems. We would also suggest that CLS probably does not make a lot of sense for very high value and/or legacy weapon systems unless the contract is with the weapon system's OEM. The CVF might therefore end up with a set of CLS contracts, not a single CLS agreement.

The MOD must also be willing to accept a loss of control with any CLS contract. If a contractor, for instance, is responsible for maintaining habitability, the MOD should not be involved in a decision as to whether a broken air conditioner should be repaired or replaced.

The OPV contract most fundamentally shows the loss of traditional control the MOD must accept as part of CLS: The OPVs belong to VT. Clearly, such an approach will not be employed with the CVF. But the MOD must tolerate a loss of some control to harvest the savings that can accrue from CLS-type arrangements.

Contractual and Other Issues in Planning Maintenance

In this subsection, we briefly discuss three issues that bear heavily on the ability to arrange for effective and efficient maintenance over the CVF class's life. The first and third involve the adoption of measures to see that monopoly power is not exerted by one contractor over facilities and data that the MOD pays for. The second relates to the ability to take advantage of whatever maintenance opportunities arise.

Sustaining Access to CVF-Specific Facilities. Dry-docking the CVF is an important and costly issue. There are no dry docks in the United Kingdom today wide enough to accommodate a CVF. Such a dry dock must be constructed or, more likely, an existing dry dock expanded, for the CVF's assembly. Development of this new dry dock will be expensive, and the MOD will doubtlessly be asked to pay for most or all of the project, given how it is solely being done for the benefit of CVFs. (Hopefully, other ships will use this dry dock when it is not utilised by a CVF, but it is clear the size requirements for the dry dock will be CVF-driven.)

After the construction of the CVFs, a dry dock of sufficient size will still be needed, at least occasionally, for maintenance action. Given the idiosyncratic CVF dry-dock size, it seems most reasonable to think CVF mid-life dry-dockings will occur at the same location the CVFs are assembled.

One beneficial step the MOD could take would be to require 'open access' to the CVF dry dock as part of the construction agreement for it. For example, if the CVF dry dock is built at Rosyth, the MOD might secure, if it wishes, an agreement that contractors other than Babcock could use the dry dock for a later docking. In other words, the MOD and its other contractors should not be subject to the whims of a CVF dry-dock monopolist if the MOD is paying for the CVF dry-dock project. Another issue the MOD has to consider is the cost of maintaining the unique facilities and equipment in its operating and support budget.

Symmetric to this dry-dock discussion, the MOD should insist on 'open access' if it pays for any other CVF-specific pieces of equipment as part of CVF construction or initial support. Open access need not be established to ordinary equipment that would be used widely in building or maintaining other ships and that would be part of the typical yard's capital investment programme. But if, for instance, an unusually large crane or some other nonstandard piece of equipment must be acquired to suit the unusual characteristics of the CVF, the MOD should be able to transfer that equipment to a different contractor (assuming the MOD paid for the equipment).

The MOD might also wish to investigate the possibility of building a CVF dry dock at Portsmouth. There would be considerable advantages if the ship could be dry-docked at its home port. We are concerned the MOD has been overly sanguine about the amount of CVF maintenance and upgrade that can be done outside a dry dock.

Ensuring That Maintenance Is Done When the Opportunity Arises. When we talked to personnel involved with CVS maintenance, they suggested there have been problems with 'memory loss'. For example, one of the ship's systems may fail to receive a desirable maintenance action during one docking, but then, during its next maintenance action, that action is again deferred because there is no record of the previous omission. Given the infrequent maintenance events envisioned for the CVF, comparable problems would be particularly costly.

It is entirely possible that the CVFs will enter maintenance outside the calendar currently envisioned. The circumstances for such unexpected maintenance could be prosaic—e.g., the ship accidentally hits a rock and damages the hull. Or the circumstances could be much more tragic, like the October 2000 terrorist attack on the USS *Cole*.

In any case, if a ship does enter maintenance unexpectedly, the MOD and its contractors should be poised to do as many other maintenance actions as possible within the time frame allotted for the causal repair.

There would be considerable challenges in such unplanned maintenance. The MOD would have to have requisite funding available. Also, there would have to be the capability to surge workforce on to the CVF project. However, given the stringency of the planned CVF maintenance schedule, the MOD must fully take advantage of opportunities for maintenance that do arise, even unexpectedly.

Ensuring Access by Competing Contractors to Maintenance Data. In 2019, six months after CVF-1's first docking, the plan is for the first phase of the CVF CLS contract to end. The second CVF will be approximately two years away from its first docking. Although these dates seem today to be comparatively distant, the MOD must take care not to leave itself with a highly noncompetitive situation when its CLS contracts come up for re-competition.

It would clearly be in the MOD's interest to have as many bidders as possible on its new CVF CLS contract. However, a natural informational advantage will lie with the incumbent contractor.

The MOD must reduce the incumbent's informational advantage to the greatest extent possible. All CVF maintenance actions must be documented and cost information tabulated in a common, non-proprietary format. Updated technical documentation and a drawing data pack must be available. As discussed above, arrangements must be secured so that contractors can utilise the CVF dry docks and other CVF-unique equipment on an equal footing basis.

We mentioned that the USAF switched from a Learjet subsidiary to an outside contractor, Serv-Air, when its initial 10-year C-21A CLS contract came up for renewal. C-21A programme office personnel noted that their office had to mediate tensions that arose between Serv-Air and Learjet after Serv-Air took over the contract. Thus, if the MOD awards the CLS contract renewal to a new contractor, the MOD may be called on to serve as an interface between the ship system's OEM and the new contractor.

Summary

We do not think the MOD can have a 'pure' CLS arrangement for the CVFs in which the contractor is responsible for every aspect of making a vessel available and is paid solely for available vessel days. First, the ship is too costly and complicated for a contractor to assume full financial risk for not having the ship operate (recall the more than £500,000 per day value of having an operating carrier). Second, a CVF CLS contractor will doubtlessly be dependent on the DLO and other contractors to supply and maintain some shipboard equipment.

Instead, CLS on the CVF will be a modified version in which considerable responsibilities are left to the DLO and/or weapon system OEMs. Warranties from part OEMs may also be useful in conjunction with, or instead of, CLS. Modified CLS, with or without warranties, might be prone to 'seam' problems in which different participants blame one another for why the ship does not operate correctly. A further seam arises from the MOD's decision to have BAE Systems build a ship with Thales UK's design. While seam problems can be addressed, they make considerable demands for agile response on the part of MOD's contracting officers.

A modified CLS contract also poses practical challenges. For example, if a contractor is to be compensated based on availability of some portion of the ship, there must be a reasonable and agreed-on way to easily measure that availability.

CLS implementation difficulties aside, there is reason to be optimistic about CVF maintenance costs. Because the MOD has expressed in its Use Study considerable ambition for cost reduction through new maintenance paradigms, long-run advantages may accrue. For example, a reader of the CVF maintenance specifications will immediately realise that the MOD regards as unacceptable the disruption caused to the *Invincible* and *Illustrious* by replacement of their gearboxes during refits.

Indeed, many of the most problematic aspects of carrier maintenance may well have been addressed in the choice of ship design. What remains for the MOD is to write a careful contract that considers such details as whether a subsequent CLS contractor will have access to the first contractor's dry dock and maintenance data. Without this, a truly competitive contract renewal is likely to be difficult. Also, the MOD will have to be careful, yet creative, in seeing that maintenance demands close to the seams dividing responsibilities among the various parties are not evaded by all of them.

CHAPTER SIX

Estimating the CVF Complement

As pointed out in Chapter One, the onboard complement is anticipated to be a major contributor to CVF whole-life costs, comprising more than a quarter of the total. Small reductions in the personnel complement can produce significant reductions in WLC. In the next three chapters, we seek ways to bring about such reductions. We begin in this chapter with a review of the way that complement size and composition are estimated. We then proceed in Chapter Seven to describe a number of attempts on other naval platforms to reduce the complement. Finally, in Chapter Eight, drawing from the case studies in Chapter Seven, we identify and evaluate a number of complement-reducing measures.

To understand how complementing is done, we conducted interviews with and gathered documents from IPT members, Thales UK representatives,[1] and Royal Navy complementing experts. We evaluated complementing data to better understand the contractor's estimates and assumptions as well as the complementing processes and policies that determine the major sources of workload.

We begin this chapter with a review of some trends and relations bearing on complementing that will be helpful in the remainder of

[1] BAE Systems has also performed complement projection work. This chapter relates more to the Thales analysis because it was Thales's design that was taken forward at the end of the competitive stage. Both Thales and BAE, as part of the CVF Alliance, are working together on complementing activities in stage three and beyond. At the same time, the Royal Navy will have oversight, so the Navy's complementing section will also play a role.

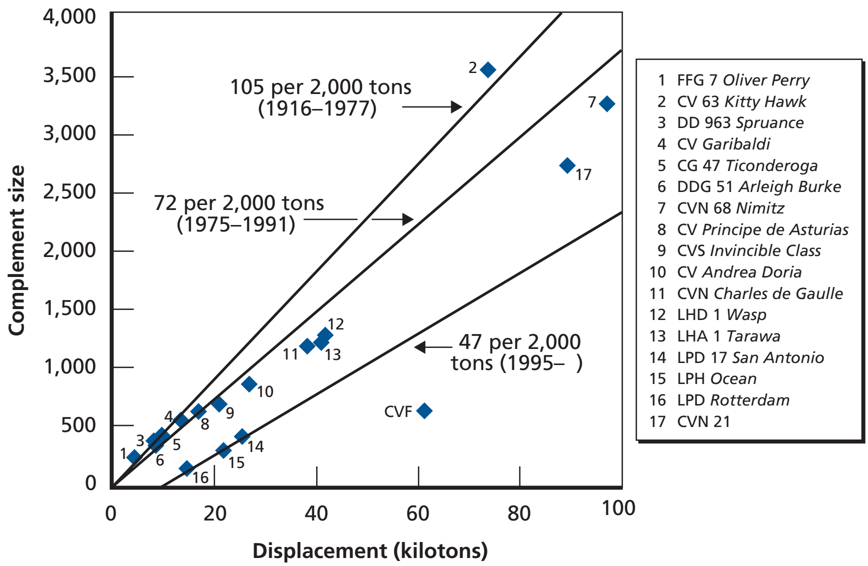
the discussion. We then review some aspects of complementing in the US Navy, the traditional approach in the Royal Navy, and Thales UK's method for the CVF. We compare these methods on various dimensions and then suggest possible paths for improvement, with emphasis on targeting of manpower drivers and other important complement influences.

Is Thales UK's CVF Complement Estimate Optimistic?

To put our tasks into context, we met with the competing prime contractors (CPCs) to understand their estimates and approach and interviewed Royal Navy complementing and training experts. We also evaluated the Thales UK complementing report of October 2002 (Thales Naval, 2002a) to further discern the underlying estimates and assumptions. As we examined the report, we understood that there was pressure from MOD to reduce the CVF complement in order to save WLCs. A contractor bidding competitively on the CVF would therefore have incentive to reduce the manpower estimate to win the contract. In fact, Thales's 2002 complementing report calls for a 605-person complement for the 60,000-ton CVF; that may be compared with the *Invincible*-class's 680-person complement for a 21,000-ton ship (both these complement numbers exclude the air group). We thus urge the MOD to exercise care in viewing the winning CVF contractor's bid as the baseline. Historical cases have indicated that unexpected issues arise that will challenge the initial manning estimates offered by the contractor. Such issues will call for creativity and insight on the MOD's and the contractor's parts. Notwithstanding the contractor's incentives, we covered all possibilities by considering whether the contractors pushed far enough in trying to keep the complement low, as well as whether they pushed too far.

To shed light on this issue, we compared Thales UK's proposed CVF displacement and complement size to other British, French, NATO, and US carriers and assault ships, based on data in *Jane's Fighting Ships, 2000–2001* (see Figure 6.1). The regression lines in

Figure 6.1
Thales UK's 2002 Design CVF Complement Is Below Historical and Recent Trends



RAND *MG240-6.1*

the graph show a best-fit estimate of the empirical relationship between displacement and complement size for all the ships listed except the CVF. A different relationship is estimated for each of three eras (each of the regression lines explains at least 90 percent of the variance). The fact that the CVF point lies so markedly below any of the regression lines underscores the ambitiousness of the planned CVF complement size.

In 1916, the US Navy set a standard for complementing of 100 enlisted personnel and five officers per 2,000 tons of displacement (see top regression line in figure). We call this standard 'personnel by the pound' (or kilo). Note that the five officers make up 5 percent of the overall complement. As we shall see later, this standard appears to still be the norm. Not much changed through the 1970s, even for a ship as large as USS *Kitty Hawk* (CV-63). From 1975 through the mid-1990s (Italy's *Andrea Doria* being the exception), the average complement size across the selected ships dropped to about 72 personnel per 2,000 tons. The light, middle regression line is fitted through the classes shown in the middle of the legend, including the *Invincible* class.

It is noteworthy that the CVF complement falls well below this line. In other words, the proposed CVF complement is quite small, relative to its displacement. Note, for instance, that the CVF is projected to have a smaller complement than the *Invincible* class, despite the fact that it is to be almost three times as large. Recent US nuclear aircraft carriers falling close to this line displace 95,000 tons and carry 90 to 110 aircraft. They have a complement of approximately 3,200 ship's company personnel. The Thales CVF displaces over 60,000 tones. As mentioned above, Thales's CVF complement for ship's company is approximately 605 personnel.

It may be more appropriate, however, to compare the proposed Thales CVF complement to that on ships of more modern construction by the Dutch, the US Navy, and the Royal Navy. They have significantly lowered the bar to about 47 per 2,000 tons on average. At a complement of 605, the CVF is at 20 per 2,000 tons. A question to address is whether the CVF fits with this newer construction or fits better with the *Andrea Doria* and the *Charles de Gaulle*. If the latter, then the CVF is undermanned by a factor of nearly 4 and should have a complement of over 2,000. If the former, the CVF complement is still only about half what might be expected on the basis of recent complementing history. This analysis suggests that contractor complement estimates should be viewed with caution. But the analysis can only be suggestive. The regression line for recent complements is based on only a few points and, even if precise, does not preclude the possibility of further reductions. Perhaps the CVF will be the first in a new group of small-complement ships.

Other Considerations in Reducing the CVF Complement

A ship's complement cannot be determined without considering the jobs people perform and the skills they have. Onboard a ship, personnel perform several functions. Reducing the workload does not necessarily reduce complement requirements. Removing or reducing one function may not result in eliminating the need for the person.

Typically, a manpower billet[2] will span multiple activities or types of work during different evolutions[3]. For example, an individual may be assigned to the bridge during normal watch-keeping functions, but when the ship is conducting an underway replenishment operation, the same individual may perform deck duties in support of the replenishment. These duties are outlined in a 'quarter bill', which details what position an individual will perform during different evolutions (e.g., navigation detail, underway replenishment, underway watch-standing, fire stations).

In addition to duties performed during quarter bill assignments, an individual also must perform so-called functional duties. Functional workloads include equipment operations and maintenance, watch-standing requirements, own-unit-support (food services, medical, administrative, etc.), facilities upkeep, and maintenance and battle-damage control.

Therefore, removing or making one portion of an individual's task more efficient will not necessarily reduce the need for the individual to perform additional functions for different evolutions. In addition, different workloads may be accomplished by different groups (ship complement, air wing, contractors, etc.). In the complementing process, the allocation of functions across different work groups must be considered.

Finally, the type of person, or occupational specialty, is important. Different ratings and occupations have different costs associated with them. Optimising the crew would call for a compromise

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[2] A billet is a position, or 'slot', for an individual.

[3] Evolutions are events that require different stations or equipment to be manned—e.g., underway replenishment detail and flight quarters for launching/recovery of aircraft.

between the desire to have work done by the least-expensive capable rating and the need to retain specialists onboard.

Comparing Complementing Practices

Critical to the understanding of potential methods for reducing manpower is an understanding of manpower requirements and how they are derived. The Royal Navy uses a heuristic process to determine complement. The US Navy attempts to determine workload and changes in workload resulting from changes in technology, policy, and processes. Thales UK has also followed this approach.

US Navy

The US Navy uses five primary workload categories: operational manning or watch-standing (OM), own-unit support (OUS), preventive maintenance (PM), corrective maintenance (CM), and facilities maintenance (FM, which includes painting and cleaning). The workload is assessed based on wartime scenarios and onboard equipment (and its associated maintenance requirements). The assumption is that, by developing manpower for the most demanding scenarios, there will be enough to provide for less-demanding scenarios. The time needed for OUS (administrative, medical, food service, shopkeeping) is based on staffing standards for various functions. PM is based on manufacturer documentation and expected maintenance actions. CM workload is estimated as a function of PM workload using 'rules of thumb' that have been developed over time. FM workload is based on industrial standards using metrics such as square footage, hours per square foot, and frequency of tasks. Service diversion and training are additional, secondary workloads, which then become the inputs into determining the engineered or derived workload.

Once workload is determined, the US Navy calculates the number of billets needed by estimating the standard workweek for personnel. Workweeks for personnel assigned to ships are based on operational requirements under projected wartime conditions (US Department of the Navy, 2002).

The above process provides a wartime 'requirement' for ship manpower. Currently, the US Navy 'authorises' ship manpower at approximately 90 percent of the requirement.[4] The lower authorisation figure is based on funding constraints and the assumption that peacetime workload is less than wartime workload[5] and that the peacetime crew will be augmented, typically with selected reservists, during time of war. However, for numerous reasons, the actual number of people 'assigned' to the ship (i.e., the number of sailors on the ship at any one time) is often less than the number authorised.[6] Therefore, in the US Navy there are three measures of a ship's complement: the requirement, the authorisation, and the assignment.

Changes in operations, technology, or policies can reduce workload and potentially manpower. The US Navy is actively pursuing operations and policy changes through Smart Ship initiatives to reduce the manpower-intensive operations currently employed on its ships. In addition, technology insertions that save associated manpower are being pursued. These initiatives are detailed in the case studies looked at in the next chapter.

Royal Navy

Primarily, the knowledge of how to man a ship in the Royal Navy is unwritten and maintained in the minds of individuals responsible for manning, some of whom we interviewed.[7] Written manning direc-

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[4] Nuclear-related manpower slots are typically manned at 100 percent of the requirement. Full manning is also assumed for optimal-manning billets authorised in the US Navy's OME (see Chapter Seven).

[5] However, the peacetime workweek is shorter than the wartime workweek (81 hours), so that partially offsets the peacetime billet exaggeration that would otherwise result from basing the billet count on a wartime scenario.

[6] The number of sailors assigned to a ship may be less than the number authorised because of training delays in providing the needed skills, medical problems, or family emergencies.

[7] In the course of our research, RAND team members met with a number of Royal Navy representatives to gain further understanding of the complementing process. We met with representatives of the Navy's Complementing Section, CVF IPT Complementing, IPT cost

tives are sparse and outdated. We used them mainly for informational purposes rather than as a basis for evaluation.

The Naval Manpower Planning Manual (BR4017), published in 1989, was the last directive for manpower planning. It is considered so obsolete that it is rarely used. A more modern version of the document is currently being written but is not a priority because those who are working manning issues are already knowledgeable on the subject.

The directive has four main parts: manpower planning, complementing, structure planning, and training planning. *Manpower* planning consists of organisational structure, requirements, and costing. *Complementing* consists of general sea and shore complementing. *Structure* planning refers to officer and rating mix, estimates of attrition, etc. *Training* planning addresses general plans for all phases of training and considers the demand for training, the supply capacity, forecasting training throughput, and measuring results.

There is an extensive organisational chart of the 22 individual organisations responsible for some aspect of manpower planning. It is unclear whether all these organisations actively participate in manpower planning today.

The manpower requirement is established by aggregating

- the trained requirement, which is the number of personnel required by rank/rate and branch that enables a unit to effectively operate
- loss of manpower due to further career or specialised training of those who are already trained
- margins, which are established to provide manpower coverage for times when individuals are not available in peacetime for leave or various other reasons
- an 'untrained allowance', which is provided to make up for those who are untrained but in the force.

team/programme forecasting group, a Thales UK complementing representative, and a member of the Training Policy Group.

There is a 10 percent board margin, which is still in use today, a 7 percent advancement margin, and a 5 percent training margin. The manpower requirement is not always met; it is constrained by a ‘ceiling’ imposed by the budget.

The complementing process starts with the quarter bill, which shows the manpower needed for the ship in each ‘principal state’, e.g., action stations, defence stations, cruising, harbour. As a platform class becomes clearly enough designed, the Director of Naval Manpower Planning produces a quarter bill for each ship.[8] The basis for determining the quarter bill is an identification of tasks and the effort required to achieve those tasks in each department of the ship. This identification is made by the prime contractor and IPT. Then an evaluation of ‘whole-ship activities’ such as communal duties is performed.

There are three types of billets directed in BR4017. Short-term billets are allowed for specific requirements of a finite period. General billets are those intended for a longer period that can be filled by any rating from any branch. A special billet is one that is extended to someone with a special skill required for more than a short period.

The state-specific quarter bills are inputs to characterising the ship’s complement, which also depends on its ‘role’. Roles are related to the life cycle of the ship, and ships change roles from time to time. Ships have a normal running role in addition to such roles as standby preservation for operations, reduced-man refit, and new construction. Action and defence states typically drive the size of the crew for normal running. A scheme of complement (SOC) is crafted to tell how much manpower and of what type the ship will have for the different roles.

All roles have requirements for similar types of persons in the SOC but differ in the time phasing that shows when each person is supposed to join. For example, in the build role, people will join on a time-phased plan as construction is completed. In the refit role, only

[8] Once the quarter bill is eventually issued to the fleet, it is used only as a guide. The actual stationing of the ship’s crew is the responsibility of the commanding officer.

a basic core of expertise might be retained, but people will phase back in as the refit is completed.

Minimum numbers of each rate/rank have been established by department for each ship class that was in existence in 1989, the rule being that once the first of class complement is developed, then each successive ship would follow the same complement patterns. However, to use the same factors for calculating complement for first of class today may lead to over- or under-complementing. For example, rules such as 'one writer can keep a maximum of 250 pay entitlement records' or '13 cooks per 350 sailors' do not take technological developments into consideration.

Officer structure planning is based on a document established in 1956 by the Committee on Officer Structure and Training. Since then, the percentage of lieutenant commanders being promoted to commander has been varied to sustain a pyramid-shaped promotion structure. Statistical models have been built to calculate other promotion factors such as the number of recruits needed to support the force structure. Although the margins and other equations used to calculate manpower numbers in BR4017 might be outdated, many of the underlying methodologies and principles are still used today by the United Kingdom and also by the United States.

The Royal Navy's Complementing Section has 10 personnel. Their major functions are to control every SOC and to advise on how to do complementing. Every new or changed SOC is input into a Navy Manpower Management Information System, which contains both job and person information and which is used for planning, deploying, and for future requirements.

In the United Kingdom, there are two new initiatives that affect manpower planning: Tomorrow's Personnel Management System (TOPMAST) and the Naval Optimised Manning Integration Systems Engineering Tool Set (NOMISETS). The main provisions of TOPMAST are the harmony rules whereby a sailor can be away from port only 60 percent of the time or no more than 660 days over a rolling three-year period. NOMISETS[9] is an approach created by QinetiQ to calculate and validate manpower numbers.

Thales UK

Thales UK took a zero-based approach to complementing. That is, it did not start with a base number, e.g., the CVS-class complement, to add or subtract from to reach its initial complement. Instead, the company's complementing process followed three steps:[10]

- **Validate the tasks to be done.** The CVF must be complemented for capability in all its assigned missions and tasks (not just for average daily workload). It was not clear how this was accomplished. It may have been through discussions with subject-matter experts, designers, CVS visits, and/or policy reviews.
- **Apply BR4017 factors and allowances.** It was not clear whether those were changed to account for different working conditions and productivity constraints or assumptions. Thales then converted workload estimates into billets (or tasks into billets).
- **Compute the minimum number of billets needed to execute tasks, including allowances and taking harmony rules into account.** Workload is parcelled out by department, division, and rating. Staffing tables are used to allocate numbers in each pay grade; the system generates more junior requirements as the group size increases.

The Thales UK complementing plan lists billets needed for envisioned missions with the systems expected to be onboard. The plan should become more precise as design goes from 35 percent (maturity at the time of this study) to 60+ percent at Main Gate. It should change, for example, if the proportion of legacy equipment changes. It should also be responsive to other trends likely to influ-

[9] For more information about NOMISETS, see Boardman et al. (2002).

[10] This section is drawn from discussions with Thales complementing representatives and a review of the materials provided by the company.

ence complement needs through 2012. For example, it is likely that the Royal Navy will put more emphasis on choosing appropriate technology and adapting crew skills accordingly. Labour productivity is on the rise and growing consistently, driven by investments in capital equipment, managerial innovations, and an increasingly skilled and knowledgeable workforce. We do not know if Thales's factors and allowances currently account for these items.

Thales UK validated complement generation by testing capability against the usage scenarios based on the generic missions identified in the System Requirements Document to confirm that the proposed complement can achieve those missions.

How Complementing Systems Vary

Our evaluation of cross-national complementing processes for differing platforms revealed that they vary in many respects (see Table 6.1[11]): whether they use human systems integration (HSI), whether the core method is based on staffing or workload, whether there is a functional or task analysis performed and a manpower modelling tool employed, whether the goal is reducing WLC or trying to optimise that against acquisition costs, and what manpower-related policy initiatives might be in force. These aspects of complementing are discussed below. Throughout the following cases, it should be kept in mind that, within each navy, a different standard is further used based on the type of person—military or civilian mariner—who will be manning the ship.

It has been widely observed that using an HSI approach can result in a different complement than not using one. *Human systems integration* (as defined by the Human Systems Information Analysis Center[12]) is a science that

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[11] The platforms are drawn from the case studies described in the next chapter; the nature of the platforms is described there and is not of great relevance here.

[12] On the agency's Web site at http://iac.dtic.mil/hsiac/HSI.htm.

Table 6.1
Complementing Is Approached in Multiple Ways

	Uses HSI	Core Method	Functional or Task Analysis	Uses Manpower Modelling Tool	Goal	Initiatives Affecting Manpower
MSC/Royal Fleet Auxiliary	No	Staffing	No	No	Civilian manning standard	National standards
Smart Ship	No	Workload	Yes	No	Reduce WLC	Smart programme
LPD-17	Yes	Workload	Yes	Yes	Reduce WLC	Smart programme
DD(X)	Yes	Workload	Yes	Yes	Optimise	Smart programme
US carriers	Some	Workload	Yes	Yes	Reduce WLC	Smart programme
Dutch	Yes	Goal-based	—	—	Reduce WLC	Budgeted cost
Commercial	—	Staffing	—	—	Minimise costs	National regulations
Royal Navy	Yes	Staffing	Yes	Yes	Correct, efficient	TOPMAST
Thales UK	Yes	Top-down	Yes	Yes	Optimise	TOPMAST

NOTE: The Smart Ship, LPD-17, and DD(X) are US Navy programmes; see next chapter.

> optimizes the human part of the total system equation by integrating human factors engineering (HFE); manpower, personnel, training (MPT); health hazards; safety factors; medical factors; personnel (or human) survivability factors; and habitability considerations into the system acquisition process ….

HSI has also been defined as a philosophy by which you 'machine the man, not man the machine'.[13]

Human systems could imply the addition of new technologies or changes in design of the work environment to improve physical work conditions or to facilitate the accomplishment of a particular job. Because it is easier to add technologies or make design changes in the beginning of ship design and construction, HSI is more widely employed on new platforms. However, the philosophy's utility is still great enough to be employed as a means to reduce manpower on older ships as well. In our analysis, most cases employed HSI.

An integral part of determining a ship's complement is assigning workload to personnel. There are two main approaches to doing this: One uses an 'engineered workload' calculation; the other uses a staffing algorithm. An engineered workload approach assumes that each task requires a specific amount of time and persons to perform it. The total number of hours and workload are aggregated and the number of persons required to satisfy the workload is calculated based on the amount of time a person can work and the amount of workload. The staffing algorithm approach is less systematically analytic and relies more on heuristics such as 'for every 100 crew, we need one chef'.[14]

Most large organisations that have a complicated structure for staffing opt to use some kind of computational model to assist in determining who is needed and where, as well as how much the com-

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[13] Philipp Wolff, RNN Human Factors Group Leader, provided these comments at the Thirteenth International Ship Control Systems Symposium, Orlando, Florida, April 7–9, 2003.

[14] We have classified Thales UK's approach separately in the table. Thales evaluated the overall missions that the ship must perform. It then examined the equipment, maintenance, and trained operators necessary to support these missions and added personnel necessary to meet the top-level mission requirements.

plement will cost. Each of the world navies evaluated had its own complement generation and cost models. RAND team members evaluated the US and UK models and concluded that the costs of complementing the same ship would differ depending on which model was used. In addition, two navies with the same requirements would get different complements depending on the tool. These discrepancies are apart from cultural and resource differences that are not picked up in the models. The point is that, ceteris paribus, different models could result in different complement sizes and costs. This could also be investigated within the Royal Navy. If the Thales UK Complement Generation Model and the Complement Generation Tool provided to the CPCs as part of NOMISETS were compared, different complements might result. (This should be noted and investigated.)

When a new class of ship is being built, there are many conflicting goals that must be balanced for an optimal design. Normally, a principal goal is reducing WLCs, for which a reduced crew may be important; other goals might include reduced acquisition costs and increased performance and survivability. Generally, one or two of the goals come to the forefront and drive the design and complement of the ship. For example, reducing WLC might require increased acquisition costs for investments in technology and training. If the programme cannot afford the up-front costs, the latter would have to be balanced against WLC and the complement may be larger than if the goal was reduced WLC alone.

At a much higher level than that of the programme goals are the overarching policy initiatives affecting manpower or design of the ship, such as the Royal Navy's TOPMAST initiatives. For the commercial sector and the US Military Sealift Command (MSC), it is national standards that govern, and they are considerably different from the military staffing standards. There are certain programmes that are set up with the intention of changing current policies or bending current traditions and practices, like Smart Ship, Smart Carrier, and the Optimal Manning Experiment (OME).

In summary, no two manpower reduction initiatives are likely to be identical. The variation in the combination of characteristics and the extent of implementation of each will also result in variant reductions.

Towards More-Effective Complementing

The Royal Navy's complementing process takes technology as a given and uses old assumptions about hours of work and mix of trades and rates. It does not involve computing billets from expected workloads, and there is no direct workweek concept. Possible policy motivations are not taken into account: It is not a process to reduce costs, increase crew productivity, improve work efficiency, reduce manning, or improve harmony. It does not produce any recommendations for reorganising work or for adding technology, materials, or equipment. The current Royal Navy complementing process *is* a review and assessment by an honest broker. If the process is to result in a functioning ship at a cost consistent with precedents, the broker must be experienced in the process and with the Royal Navy. Most manpower planning heuristics, rules of thumb, and other such knowledge of 'how-to' complement seem to be unwritten. The few complementing tools that are used require expert judgment for determining final complement based on their output. With no systematic evaluation of the complement-reducing potential of evolving technologies and work processes, decisions in the current complementing system may be overly affected by culture and by outdated policies and practices.

Furthermore, there is currently a large emphasis on growing the right people and keeping a pyramid structure to do this, even if it is inefficient. Having fewer people doing more tasks will require significant changes to current Navy training and manpower structures as well as require greater retention, which may be unrealistic.

In the remainder of this chapter, we set out some complement-reduction principles that the Royal Navy might find useful in reviewing ongoing complement-reduction efforts by the contractors. The most obvious principle is to target manpower-intensive functions and departments. Therefore, we begin with a summary of some different approaches to doing so.

Identifying High-Value Manpower Reduction Targets

When starting to make manpower reductions, the CVF CPCs (like the US Navy on its ships) targeted the tasks or workload that requires the most labour. These manpower-intensive tasks, which may be performed regularly or cyclically, are referred to as 'manpower drivers'. Each CPC listed manpower drivers. Table 6.2 compares those with the ones put forth by the US Navy for US carriers. (Only the BAE list is prioritised.)

Table 6.2
Carrier Manpower Drivers Listed by Different Organisations

BAE Systems	Thales UK	US Carriers
TOPMAST	Damage control	Antisubmarine warfare flight quarters
Damage control	Food services	Condition I (GQ/damage control)
ME watch-keeping	Weapon handling	Corrective maintenance
RAS & storing		Flight quarters
ME maintenance		Food services
Aircraft movement		Housekeeping/cleanliness
Ops watch-keeping		Inspections
Bridge watch-keeping		Laundry services
Husbandry		Medical/dental services
Administration		Operational manning–underway watch-stations
Hotel services		Personnel and pay records
		Personnel muster
		Preservation
		Preventive maintenance
		Special sea and anchor detail
		Stock and material control
		Stores loading and handling
		Training
		Underway replenishment
		Weapons handling and loading

The list established by BAE Systems and especially that for US carriers are lengthy. Thales UK concentrated on a more limited set of major manpower drivers: damage control, food services, and weapons handling.

Note that all the BAE Systems' manpower drivers were also considered as major manpower drivers on US carriers in one form or another, as were the major drivers considered by Thales UK. Interestingly, while Thales UK listed weapons handling as a major manpower driver, BAE did not.

Another way to find inviting targets for manpower reduction is by department. The complement that was presented in the Thales UK report indicated a total of 605 personnel were to be assigned to the CVF's company. Table 6.3 indicates the personnel assigned to each department as a percentage of the entire ship's complement. The *Ark Royal* was utilised as the base case, and the Royal Navy and Thales complementing estimates were evaluated against the *Ark Royal*. The Royal Navy CVF estimate refers to a planning scheme of complement[15] derived from the manpower planning system. Clearly, the Royal Navy CVF complement follows very closely the *Ark Royal* complementing percentages, by department, and the total is not much different either. Culture and tradition may have had an effect on these numbers. The Thales complementing report had a sharp percentage reduction in the Warfare Department, a small reduction in the Marine Engineering Department, relatively higher increases in Weapons Engineering and the Air Department, and a small increase in other ship's company personnel.

Other Factors Influencing Manpower

It is important to note that manpower drivers as defined above and listed by BAE Systems, Thales UK, and the US Navy are all workload

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[15] RAND was provided a Royal Navy CVF complement entitled, 'Print of the Planning Complement on 23 January 03'. It was the first estimate of the CVF complement modelled on the CVS; it did not include the complement necessary to support TOPMAST harmony rules.

Table 6.3
Some Departments Might Be Targeted for Change

Ship's Department	*Ark Royal*	Royal Navy CVF	Thales UK
Warfare	34%	30%	20%
Marine engineering	22%	24%	20%
Weapon engineering	4%	5%	9%
Air engineering	8%	9%	9%
Supply	19%	19%	20%
Medical/dental	2%	2%	1%
Air	8%	8%	15%
Other	3%	3%	6%
Total Complement	678	653	605

related, as is the departmental analysis. Such drivers are not solely responsible for the size and composition of the complement. Below, we discuss several important points related to other drivers of manpower:

- Goals are primary manpower drivers.
- Functions can come and go.
- Tradition and culture have an effect.
- Legacy systems can constrain manpower reductions.
- Up-front costs typically carry more 'weight' than downstream costs.
- Risk acceptance matters.

Goals Are Primary Manpower Drivers. The goal or direction provided for the complementing process is a primary manpower driver. During the course of our research on complementing of various platforms, we have learned that different platform goals affect complement size and composition. The goals vary among

- minimising cost (whole-life or acquisition)
- minimising crew
- optimising crew
- increased survivability and operability.

The goal of *minimised whole-life costs* almost always leads to minimised crew because the crew is such a large proportion of WLC. However, minimising costs does not necessarily mean reduced crews. It may lead to replacing expensive people (senior rates) with technology and supplementing with a larger, less-expensive crew. The goal of *minimised acquisition costs* may lead to less investment up front that could potentially save money in the long run, including technology insertions used to reduce the crew.

The goal of *minimising the crew* may not result in lower costs. For example, one would not expect a smaller crew to be more expensive, but it could be if more senior, experienced (and more costly) crewmembers make up the bulk of it. Conversely, a less-costly crew could be achieved through a larger complement if more junior (and less-costly) crewmembers make up the bulk of it. When the goal is to have fewer people, certain missions or tasks *may* be compromised to achieve the smaller crew. It has been noted that sometimes rash efforts to reduce manpower backfire. In some cases, insertion of technology for more junior rates was made, but these rates ended up having to stay onboard because of their multiple duties.

An *optimised crew* generally refers to the right mix of technology and complement to maintain a certain level of capability at a minimum cost. The optimised crew requires a delicate balance of man versus machine and is not always easy to determine.

For such reasons, the goals and constraints of the CVF programme should be carefully evaluated. Questions that should be asked are: Will the CVF manpower be the driving force of the Royal Navy personnel system? Might an optimised complement be suboptimal for the Navy's personnel system? Will there be structured occupations that perform assignments only onboard or in support of the CVF?

Functions Can Come and Go. Reliance on precedent and historically developed rules of thumb has a drawback. Functions now performed on CVS carriers might not be on CVFs. A US Navy initiative is relevant here. The Navy has identified various shipboard functions performed today and where and how they should be completed in future warships to optimise the use of a ship's complement. Navy ships of the future are expected to perform in multiple roles and possess increased war-fighting capabilities. However, this increased capability is to be achieved through warships that are manned with relatively smaller, more highly trained professional crewmembers. A 1999 US Naval Inspector General report (1999) suggested that reducing crew size should not be the objective; rather, the reductions will be the result of necessary initiatives and investments in technology. The initiatives and investments should be geared towards improving the reliability and maintainability of the ship's equipment and systems, and when combined with enabling policy and procedural changes, the effect will be to maximise the utilisation of every crewmember. In addition, ships at sea should shed those functions that do not directly contribute to operating, training, or sustaining themselves. The combined effect of these changes will reduce a ship's complement and increase capability.

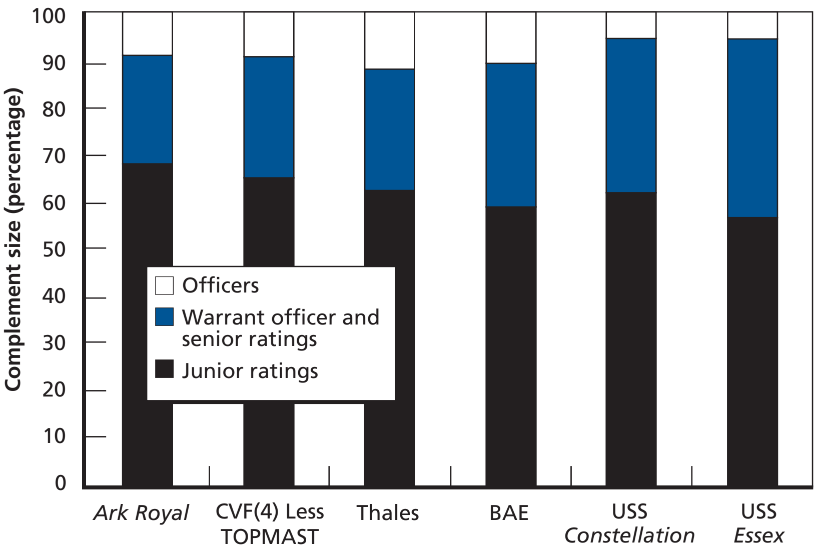
Supporting this effort, the report suggested that certain shipboard functions (most routine maintenance and most collateral functions) could be eliminated from ships; other necessary functions (such as legal and logistics functions) should be moved ashore; and still others should stay aboard, either with optimisation or with fundamental reengineering (see Table 6.4). These are functions needed to support a future optimally manned ship. The report concluded that the costs of ownership must assume new importance in the ship acquisition decisionmaking process.

Tradition and Culture Have an Effect. One rather costly tradition is the Royal Navy's large shipboard officer complement. As mentioned earlier, the CVF will follow Royal Navy tradition in using more officers as a percentage of total complement than the US Navy (see Figure 6.2). Across multiple US Navy ship classes, the percentage of officer content averages around 5 percent (it is 10 percent in an attack submarine). We believe the difference can be accounted for in the denominator. That is, the Royal Navy and US Navy tend to have comparable numbers of positions for officers on ships, but the Royal Navy generally has fewer enlisted personnel, which leads to a higher officer percentage.

Table 6.4
Selected Shipboard Functions, by Future Disposition

Eliminate	Move Ashore	Reengineer Onboard	Improve Onboard
Most routine maintenance	Mission planning	Watch-standing	Damage control
Collateral functions	Watch qualification training	Special evolutions	Weather deck auxiliary functions
	Painting and preservation availabilities	Medical and dental	Embarked detachment support
	Upgrades and alterations	Casualty maintenance	Receiving and stowage systems
	Logistics	Cleaning	Food service operations
	Collateral duty	Inspections (external)	Laundry
	Disbursing	Ship's store and vending	Hazardous waste disposal
	Postal services	Team/battle group training	Proficiency training (onboard)
	Personnel records	Internal LAN management	LANs
	Legal services	Physical fitness training	
	Religious services		
	Morale, welfare, and recreation services		

Figure 6.2
UK and US Complements Differ in the Percentage of Officers Assigned



RAND *MG240-6.2*

Other traditions and culture potentially limit manpower reductions. For example, stewards have traditionally been assigned to the officer mess, and officers have been accustomed to a certain level of service (food service, stateroom upkeep, etc.) from the stewards assigned. If the number of stewards were reduced, the level of service and the privileges normally offered to officers through the steward assignment would be correspondingly reduced. Although we have seen this occurrence on other ships, the tradition and culture paradigm must be changed[16] on Royal Navy ships to achieve manpower savings.

Legacy Systems Can Constrain Manpower Reductions. The ship's complement is dependent on the equipment that will be installed. The CVF was in initial stages of design during our evaluation of the ship's complement. However, we were told that the CVF will be built with a significant percentage of legacy equipment. Will the CVF follow the manning prescriptions inherited with the legacy equipment? Remaining questions that could not be addressed by our team because of the immaturity of design include the following:

- Will the remaining non-legacy design 'freedom' be enough to have a dramatic impact on the CVF complement?
- What will these design changes be?
- Will acquisition dollars be available to invest in technology?

Up-Front Costs Typically Carry More 'Weight' Than Downstream Costs. If the goal is to reduce life-cycle costs by minimising the crew, it could require up-front investments in technology that make acquisition costs higher. In such a case, there is the potential for the technology not to be purchased, because of limited up-front funding, resulting in higher WLCs. Raising the up-front cost can be challenging because, although acquisition accounts for only about 30 percent of the WLC of a ship, it is concentrated over a relatively short period. The result (see Figure 6.3, from a US Navy cost database) is a

[16] The impact of these changes, if implemented, will have unpredictable effects on officer morale, retention, and recruitment.

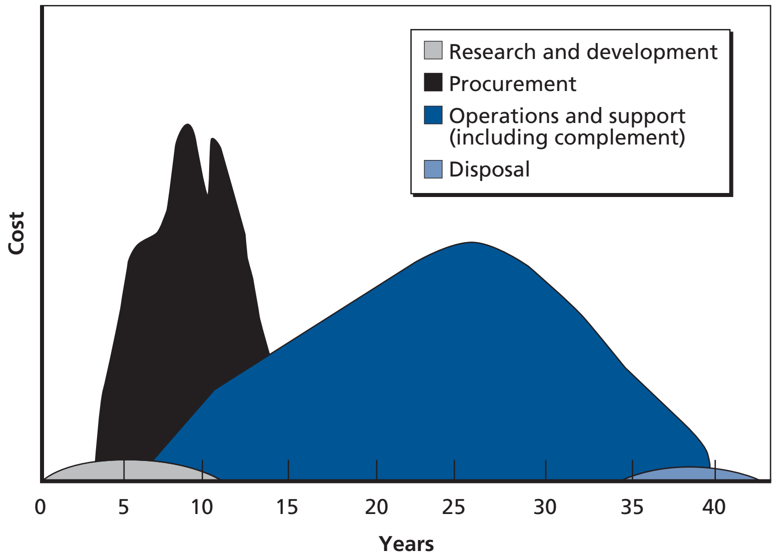
peak in required funding that exceeds what is spent to operate and support the ship in any given year.

Risk Acceptance Matters. Greater reliance on technology versus manpower is a change from the status quo—and risky. It has been an often-used luxury and historical advantage to solve unexpected problems onboard by having extra personnel to spare. As new platforms are developed with new technology, as well as changes to current policies and procedures, operational decisionmakers charged with maintaining the safety and security of the ship may be assuming more risk with a reduced crew onboard. The risk assumed is unknown and may not be quantifiable. However, it is safe to assume that, when an operational commander is faced with a risk, e.g., through damage control efforts to combat fire or flooding, a reduced crew will mean additional risk. An increased reliance on technology to address faults and control casualties should reduce the manpower required to deal with such faults, but the reliability of the new systems must be sufficient to mitigate operational risks.

The Royal Netherlands Navy (RNN) has sharply reduced the crewmembers in its new Air Defence Command Frigate. The necessary drawback to operating a ship with a smaller crew is that they cannot perform all tasks at once as they could previously. Therefore, they prioritise their missions and perform them in accordance with the precedence. This practice results in the requirement to perform some evolutions in series vice parallel. The crew limitations require that the ship plan ahead to accommodate their inability to perform some missions simultaneously.

With a smaller complement, every crewmember counts. When complements are reduced, such as on US ships in the OME (which we will discuss in detail in the next chapter), the personnel who remain become cross-trained so that they may perform multiple roles. As each crewmember becomes more highly trained and performs multiple roles, his or her importance in accomplishing the ship's mission increases. Crew fatigue becomes an increasingly important factor in maintaining a ship's readiness to perform its mission, so it must be monitored and controlled.

Figure 6.3
Up-Front Funds for Technology Investment Are 'Costly'[17]



SOURCE: COMET.
RAND *MG240-6.3*

Summary

The Royal Navy's complementing process takes technology as a given and uses inherited assumptions about hours of work and the mix of trades and rates. Expected workloads are not used to compute a complement requirement. Possible policy motivations are not taken into account: It is not a process to reduce costs, increase crew productivity, or reduce manning, and it does not produce any recommendations for reorganising work or for adding technology, materials, or equipment. The current Royal Navy complementing process *is* a review and assessment by an honest, experienced broker. Most manpower-

[17] The ship life-cycle cost profile chart was obtained from the Navy Center for Cost Analysis Web site at www.ncca.navy.mil/images/lcc.gif (last accessed September 2004).

planning heuristics, rules of thumb, and other such knowledge of 'how-to' complement seem to be unwritten. With no systematic evaluation of the complement-reducing potential of evolving technologies and work processes, decisions in the current complementing system may be overly affected by culture and by outdated policies and practices. Indeed, the Royal Navy's target complement for the CVF differs little in size or in allocation of personnel across departments from that for the current carriers, even though the ship will be twice as big.

Thales UK, in contrast, appears to have taken a zero-based approach to complementing. It has estimated the work to be done and computed the number of manpower slots necessary to accomplish it. Allowances were made for personnel in training, on leave, etc. We do not know whether Thales's complement estimate accounts for technology-, management-, and education-driven increases in labour productivity that might be expected in the coming years. The result of Thales's complementing process was a distribution of labour that differed substantially from the Royal Navy's breakdown for the CVF. The company cut more than a third from the Royal Navy's Warfare Department while increasing Weapon Engineering and Air. It should be kept in mind, however, that a contractor that has been bidding competitively on the CVF has had an incentive to reduce the manpower estimate to win the contract. We urge the MOD to exercise care in viewing Thales's complementing bid as the baseline.

As further complementing work is done, the following points should be kept in mind:

- A principal, persisting goal must be observed. Minimising WLCs, minimising crew size, and optimising the crew across capability and cost will each result in a different complement.
- The workload should not be regarded as immutable. Functions can be eliminated, moved ashore, or kept onboard but made less manpower-intensive.
- Officers are expensive; their percentages are higher in the Royal Navy than in the US Navy; and they enjoy expensive perks.

- It is anticipated that a significant percentage of CVF systems will be inherited from the current carrier class. Such systems might bring inefficient manning with them, limiting opportunities for complement reduction.
- Ambitious plans to cut manpower by investing in technology can be impeded by constraints on the up-front funding required to acquire the technology.
- Operational commanders may be reluctant to accept smaller complements because they would reduce the margin for error in situations threatening ship safety.

CHAPTER SEVEN

Complement-Reducing Initiatives on Other Platforms

The great expense of sustaining a complement has inspired many navies to institute efforts to reduce the number of personnel assigned to their warships. To provide a basis for identifying manpower reduction options potentially relevant to the CVF, we evaluated several specific cases to determine how manpower reductions have been achieved. We evaluated US Navy programmes, Smart Ship, Smart Carrier, and the DD(X) programme; the Royal Netherlands Navy and commercial cruise-ship operations; among others. We performed this phase of the research by conducting interviews, attending maritime technology conferences,[1] and reading and researching documents and reports. In Chapter Eight, we will discuss the manpower reduction options identified and evaluated through analysis of these cases.

We did not limit the research to carriers, but reviewed manpower reduction efforts on other platforms where the lessons learned appeared relevant. We recognise that the platforms evaluated generally have completely different missions and capabilities from those of the CVF, and we acknowledge that the cultural variations between countries could result in different manning profiles for the same ship. However, similar technologies, policies, and procedures have been effective in reducing or optimising manpower across various plat-

[1] 13th International Ship Control Systems Symposium in Orlando, Florida, USA, 7–9 April 2003, and Human Systems Integration Symposium, Vienna, Virginia, USA, 23–25 June 2003.

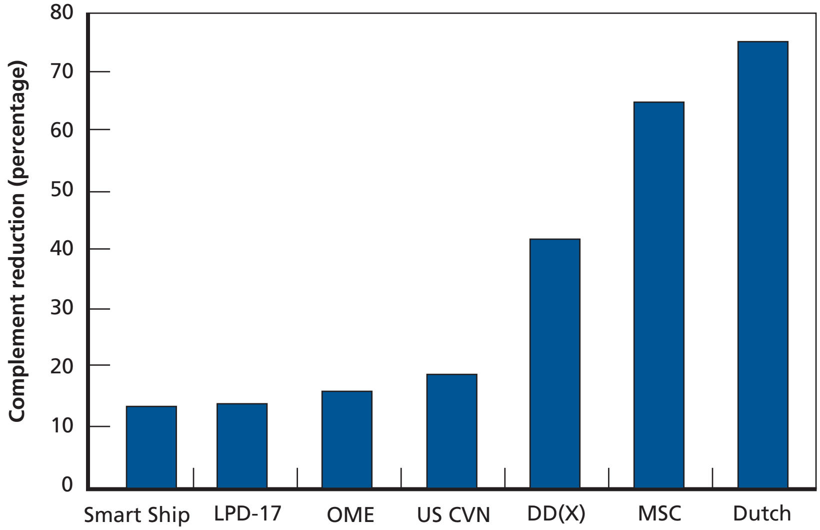
forms. To take advantage of this, we use a case-based reasoning approach that governs the adaptation of solutions to one problem for use in solving another. By searching for similarities between the CVF and the other platforms, we could identify measures proven useful elsewhere that might be expected to work on the CVF as well, although the amplitude of the effect might well be different. For example, employing the concept of shore-based experts could be used to reduce manpower on a number of platforms. It is the *quantity* of billets saved that would vary by platform. The amplitude of the effect would vary not only because the CVF differs in scale and scope of activities from other platforms but because different approaches to policy changes, mission requirements, and risk acceptance might be taken on the CVF.

We pay particular attention to the US Navy, which has several efforts under way to reduce the number of personnel on various classes of ships. The CVN-77 programme office has examined the potential of using cruise-ship practices and equipment, and the future carrier (CVN-21) programme office has identified a number of potential technologies that might reduce manpower requirements. This effort follows the Smart Ship programme that sought to reduce manpower on *Aegis*-class ships by 10 to 15 percent. There have also been a number of efforts that evaluate and challenge current Navy policies and procedures that impede manpower reductions.

The options we examine are associated with the US Military Sealift Command, US aircraft carriers, the US Smart Ship programme, the OME, and the DD(X) programme. We also studied the US Navy's new LPD-17 class, the RNN's practices, and the commercial ship industry.

These cases have all achieved reductions in their complement (see Figure 7.1) through a combination of technology and policy and procedural changes. The baseline for the savings indicated in Figure 7.1 was derived either from the ship affected—before a technology, policy, or procedural change was made—or from the class of ship that the ship affected was designed to replace. The Smart Ship savings represent a change from baseline ship CG-47 to USS *Yorktown* CG-48

Figure 7.1
Complement Reductions of Selected Case Studies



RAND *MG240-7.1*

(the 'Smart Ship'). The LPD-17 represents the change in manning from the LPD-4 class. The change for the US Navy's OME represents the decrease in manpower in USS *Milius*, a DDG-51 class ship, below the baseline DDG-51. Even greater reductions in complement are being planned for USS *Milius* and other ships through implementation of the OME. 'US CVN' designates a *Nimitz*-class private analysis conducted to review policy, procedural, or technology insertion to reduce manpower. The savings indicated represent what could be achieved if the private study recommendations were followed. DD(X) represents savings below the costs of the baseline DDG-51 class. The MSC represents the manpower savings that were achieved by conversion of an active duty manned AOE-6 to a civilian mariner manned T-AOE-6. The Dutch manpower reductions compare the 50-personnel complement (as relayed to us during discussions with RNN representatives) to the 200-man ships they are replacing. We now discuss each of these cases in some detail, with the exception of the commercial cruise-ship industry, which has already been discussed in Chapter Four.

Transfer of US Ships to the Military Sealift Command

The MSC operates combat logistic force ships for the US Navy. These ships are manned by civilian mariners and typically have an active duty US Navy flight crew and operations department. Starting in the early 1990s, the Chief of Naval Operations approved the transfer of the AFS-1 and AE-26 class ships to the MSC. This decision was based on the capability to achieve long-term cost savings by manning the ships with civilian crews. The US Navy's ongoing reduction in uniformed end strength also factored into these decisions. More recently, the AOE-6 class began conversion to the MSC (where they become redesignated as T-AOE-6). Like the Royal Fleet auxiliary ships, the T-AOE-6 ships operate as 'station ships', delivering stores, food supplies, and fuel to Navy ships.

The T-AOE-6 class has three primary mission areas:[2]

- **Mobility**—to operate at sustained carrier battle group (CVBG) force speeds, thereby providing the CVBG with the flexibility to conduct combat operations.
- **Command, control, and communications**—the ability to serve as Battle Group Logistics Coordinator during combat operations.
- **Logistics**—to support the CVBG logistically.

The ships are capable of providing simultaneous underway replenishment of conventional ordnance and dry and liquid cargo from seven stations. In addition, the ships will be capable of simulta-

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[2] Information on the T-AOE-6 was derived from a draft *Military Sealift Command (MSC) Transfer and Fleet Introduction Manual (TFIM) for AOE-6 (SUPPLY) Class Ships*, provided to project researchers by MSC representatives.

neously providing ammunition, fleet freight, personnel, mail, stores, and other items via vertical replenishment (helicopter transfer).

The AOE-6 class was designed for a large US Navy crew. The MSC crewing requirements are significantly smaller than even the lowest Navy crewing requirements. The following examples are of work items that increase operational efficiency, among other benefits:

- main machinery room watertight door
- bolted equipment removal plate
- oily water separator installation
- self-contained breathing apparatus (SCBA) installation
- ClearView screens
- navigation aid (NAVAID) relocation
- MK2 surface search radar and electronic chart display and information system (ECDIS) installation
- gyro compass modifications
- Global Marine Distress Safety System (GMDSS) installation.

The transfer of combat logistic force AOE-6 to the MSC resulted in significant manpower savings. Table 7.1 indicates the manning complement, by department, for the US Navy AOE-6 class ship manned by active duty officers and enlisted personnel. The second pair of data columns reflects the manning of the same AOE-6, when it is transferred to the MSC, and the third pair of columns represents the manning reduction in going from an active duty manned to a civilian mariner manned T-AOE-6.

The MSC manning is based on the historical experience of operating MSC ships for 50 years.[3] The MSC begins complementing prior to conversion from a Navy to an MSC asset, when a ship-check is conducted. MSC representatives assess what the Coast Guard minimum manning requirements would be for the vessel's deck watch and

[3] Much of this material is from our discussion with Mr. King Marandino, human resource specialist, Military Sealift Command, Washington, D.C., USA, May 13, 2003.

Table 7.1
Complement Reduction, by Department, in US Navy–MSC AOE Transfers

Department	USN AOE-6		MSC T-AOE-6		USN–MSC Manning Difference	
	Licensed/ Officers	Unlicensed/ Enlisted	Licensed/ Officers	Unlicensed/ Enlisted	Licensed/ Officers	Unlicensed/ Enlisted
Weapons/operations	3	37	0	0	3	37
Deck	4	214	8	72	–4	142
Communications	3	28	1	14	2	14
Electronic repair	0	8	0	5	0	3
Purser	3	17	1	1	2	16
Medical	2	7	1	0	1	7
Engineering	5	150	11	29	–6	121
Deck machine repair	2	12	1	5	1	7
Supply	5	34	4	7	1	27
Food preparation	1	17	1	9	0	8
Food service	0	20	0	33	0	–13
Laundry	0	11	0	1	0	10
Total	28	555	28	176	0	379

SOURCE: Center for Naval Analyses (2002).
NOTE: Negative numbers indicate manning increases.

engineering functions. For example, an MSC ship bridge is typically manned by four personnel: a mate, a seaman on the helm, a seaman as a lookout, and an operations specialist for miscellaneous duties. In addition, special functions require attention to their manpower requirements. For instance, underway replenishment ships need additional manning for performing their replenishment mission. The manning for underway and vertical replenishment stations and for the flight deck is based on historical standards.

MSC ships could operate with fewer personnel because, when their crewmembers report aboard, they are fully functional and qualified for the positions that they will be performing. In contrast, on Navy ships, one-third of the personnel are trainees. On-the-job training occurs on MSC ships—in particular, for new crewmembers who have not operated the underway replenishment equipment—but most are qualified when they report aboard. In addition, the MSC hires professionals to do the sweeping, swabbing, and cleaning. Further, the MSC is not concerned with the amount of time a person is at sea. Personnel are eligible for rotation off the ship after four months at sea, but most stay longer to build up their shore leave accounts. MSC personnel may transfer off the ship and take shore leave when their relief reports onboard. The ship's manning remains relatively constant. Another complement-reducing factor is that the MSC takes the commercial approach to damage control with two repair lockers. US ships would normally have three repair lockers.

In summary, MSC manning is based on experience and a civilian standard for manning ships that has been tried and proven.

The MSC personnel we interviewed made specific recommendations for manpower reduction that should be considered when designing the CVF:

- Use the commercial model for locating the galley. By having the galley centralised and designing it such that the enlisted dining facility and the chief petty officer's mess and wardroom directly attach to it, efficiencies in food service will be gained.
- Plan and rotate standard meals. This process would allow the use of prepackaged palletised food loads, which the personnel called

'unitised' loads. In a unitised load, the food service officer would know and plan for his or her stores on-load requirements.

- Order soda in syrup form vice cans and dispense it from the mess decks. Cans are recyclable, cannot be disposed of at sea, and present a large collection, storage, and pest-control problem. If a ship with a crew size of 605 consumes two sodas per individual per day, the number of cans that must be collected, held onboard, and disposed exceeds 1,200 per day. If a ship remains at sea for extended periods, this collection process can become a manpower and space drain on the ship. MSC representatives indicated that if a ship were to use syrup dispensed on the mess decks, money spent for collection efforts would be reduced dramatically.
- Design storerooms for easy insertion and removal of palletised loads via forklifts. In addition, they recommended that elevators vice package conveyors be used to load stores. They added that the breaking down of pallets of stores (for all ships) is a manpower-intensive task and a driver of manpower and that the effective organisation of stores on-load and stowing is key.
- Use such technology as remote monitoring systems, automatic closure of watertight doors, efficiency of plant design, and changed ergonomics.
- Use a condition-based maintenance approach.
- Have the capability for the ship to do its own organisational maintenance. Some MSC ships also do their own intermediate-level maintenance. This capability eliminates the requirement for shore-based support of some intermediate-level maintenance, even during availabilities in port. MSC ship scheduled maintenance periods do not exceed 75 days.
- Require everyone to do their own laundry, eliminating the requirement for ship's servicemembers to perform this function. Although this change may reduce the quality of life at sea for sailors, who must do their own laundry during their 'off time', it is an accepted standard and reduces manpower.

- Have the afloat personnel management centre handle personnel records. MSC ships have automated pay with no administrative office.

To summarise, manning for an MSC ship is determined by a ship-check of a Navy asset prior to transfer to the MSC. The manning required is based on the experience of the ship-checker as he compares the ship equipment layout with similar ships or manning requirements used in other MSC assets. The MSC relies on highly trained, multifunctional professional civil service mariners to operate combat logistic force ships. The successes achieved of reduced manning in MSC ships can be attributed to extensive training and experience gained by crewmembers prior to their reporting aboard (US Naval Inspector General, 1999). In addition, weapons have been removed when ships transfer to the MSC, which eliminates the ship's weapons department personnel. Further, an MSC asset is utilised differently from a Navy ship. A Navy crew is available 24 hours a day to perform underway replenishment duties. MSC assets typically perform replenishments during the daytime, and crewmembers receive overtime pay for underway replenishments performed outside normal working hours.

US Carriers

The US Navy has been constructing the last two ships of the *Nimitz* class of aircraft carriers. The USS *Ronald Reagan* (CVN-76) was commissioned in summer 2003, and the USS *George H.W. Bush* (CVN-77) is currently being constructed at Northrop Grumman's Newport News Shipyard in Virginia and is scheduled for delivery to the Navy in 2009. In addition to the *Nimitz*-class construction, the Navy is in the process of designing the next generation of aircraft carriers (designated CVN-21). According to Birkler et al. (1998),

> The CVN-21 will be the first new U.S. aircraft carrier design since the Nimitz was built in the 1960s. The current plan is to

> have the first ship in the CVN-21 class available to replace the *USS Enterprise* by its scheduled end-of-fuel date in approximately 2013.

In an effort to increase the performance of future aircraft carriers or reduce their WLCs, several initiatives have been undertaken. In fact, reducing the WLC is a major objective of the Aircraft Carrier Program Executive Office. To evaluate how to reduce total operating costs for US carriers, the CV/CVN programme office is examining a number of technologies, operation policies, and practices. The CV/CVN programme office adopted a 'Transition to the Future' strategy for the design and construction of the last ship in the *Nimitz* class (CVN-77). The basic goal of the strategy was to identify technologies that would reduce the construction cost, the operations and maintenance costs, or the ship manpower requirements. CVN-77 will also serve as a test platform or transition ship for incorporating such technologies in the CVN-21 class, as well as offer the potential for retrofitting the technologies to earlier ships in the *Nimitz* class to reduce their WLC (Birkler et al., 1998).

Not all the efforts to reduce WLCs will result in a reduced crew. Furthermore, not all actions reducing manpower, such as streamlining maintenance practices, will achieve the same reductions on all ships.

The Transition to the Future strategy was an evolutionary one. Some elements were to be implemented on ships in service; some were to be ready in the short term for ships under construction; and others were to apply to the CVN-21 class. Table 7.2 was developed from a number of sources, including the Aircraft Carrier Program Executive Office. It shows the potential technology development efforts in an evolutionary manner. This list has changed, and not all the improvements will affect manpower.

At a minimum, currently available measures embodied in the Smart Carrier programme should be relevant to the CVF. The Smart Carrier programme's goal was not directly or solely to reduce man-

Table 7.2
US Navy Carrier Technology Development, by Time Frame

Now (Smart Carrier)	Short Term (CVN-77 and refits)	Long Term (CVN-21)
Workload reduction and sailor quality-of-life improvements	Full integration of combat systems	New propulsion plant
Smart Card	Smart Deck	New functional arrangement
Integrated condition assessment system	Good service improvements	State-of-the-art flight deck
Advanced vent/filter cleaning system	Medical complex improvements	Automation in engineering
Wireless communication	Main switchboard upgrade	Automation in damage control
Digital physical security upgrade	Embarked aircraft tracking	Automation in combat systems
Low-maintenance materials	Remote damage control capabilities	
Reduced condition III watch-standing	Automation of damage control	
Advanced damage control system	Remote sensors and video monitoring for damage assessment	
JP-5 fuel management automation	Reliability-centred maintenance	
Network infrastructure upgrade	Alternative energy catapults	
Core/flex	Multifunctional embedded antennas	
Integrated bridge	Crews wash their own clothes	
Maintenance-free materials	Barcode and scanner (UPC) used for loading and unloading	
Remote sensors and actuators	Improved (corrosion-resistant) material coatings	
List control system	Integrated bridge	
	Consolidate medical and dental departments	
	Automated supply storage and retrieval process	
	Automated weapons storage and retrieval process	
	Cashless ship	
	Electrical components replacing auxiliary steam equipment	
	Card readers and swipe cards	
	Video cameras to reduce watch	
	Remote monitoring of critical systems	

power but rather to (1) reduce workload, (2) improve sailor quality of life, and (3) reduce total ownership costs. The Smart Carrier initiative began with the goal of reducing workload by 15 percent. Some of the reduction in workload would contribute to an improved quality of life for sailors. The other part of the reduction would result in fewer billets and thus lower operating costs. The initial approach was to target five main areas for possible reductions: information technology, automation and controls, personnel support, maintenance and preservation, and policy and procedures. Proposed advances spanned a wide range of technologies, including sensors and automated condition monitoring, communications, decision support systems, weapons handling automation, supply tracking automation, distance learning, on-line shore-based support, automated damage control, automated bridge information, navigation, control, and logistics.

The first fully outfitted Smart Carrier was the USS *Carl Vinson* (CVN-70). Smart Carrier team members told us they did not want to superfluously add technology onboard, but rather provide a means to integrate technology into the other systems currently onboard plus provide lessons learned from past implementations and help with the rewrite of various instructions. The Smart Carrier representatives indicated that the most important item on the carrier is having a local area network (LAN), which is the backbone that can collect and distribute digitised data throughout the ship. This network would collect and distribute key information from automatic sensors, damage control consoles, wireless communications, closed-circuit television, distance-learning or remote specialists, etc. In addition, other systems resulting from the implementation of LAN are the following:

- **Aviation fuel system** (JP-5), which relies on the hull, mechanical, and engineering LAN and 'provides control functions related to the on-load, storage, and movement of over 3.2 million gallons of aviation fuel in support of embarked air wing' (Tangora and Mariani, 2003).
- **Integrated Condition Assessment System (ICAS)**, which provides up-to-date information about critical systems functionality and supports condition-based maintenance practices.

- **Machinery condition analysis**—another tool for supporting condition-based maintenance—provides information on rotating machineries vibration.
- **Advanced damage control system.**
- **Damage Control Inventory Management and Stowage System,** for tracking damage control equipment.
- **Firemain information system,** for data on the firemain, such as pressure. It is connected to LAN for damage control centre status reports.

The ample resources describing means for reducing or optimising manpower onboard US carriers provided several options for consideration on the CVF (reported together with those from other sources in Chapter Eight).

The US Navy's Smart Ship

The Smart Ship experiment aboard the guided missile cruiser USS *Yorktown* (CG-48) has reduced workload and manpower requirements while enhancing combat readiness and improving the crew's quality of life. Smart Ship improvements occurred through combination of procedural changes (e.g., core/flex manning, training) and technology insertion (e.g., various commercial off-the-shelf [COTS] systems).

Significant reductions were achieved through the Core/Flex Manning concept. Under the core/flex concept, underway watchstations stand down in reduced threat environments. Because the numbers of watch-standers are reduced, those not on watches have increased time available to accomplish the ship's workload. The workload remaining was reengineered and distributed evenly among crewmembers, which allowed for long periods of sustainable operations. As increased numbers of personnel become 'day workers', their time can be better coordinated and scheduled for training and workload requirements. The 'flex' occurs when the remaining core watchteams are augmented as the situation dictates.

In addition, the Smart Ship instituted an increased training capability. A dedicated training department was created with the rationale that reduced manning required a better-trained crew. New crewmembers received comprehensive indoctrination upon reporting aboard by members of the training department, and the training was continually available.

Technologies used on Smart Ship were primarily COTS hardware and software products. These products were a suite of systems run on commercially available personal computers via the LAN. The following technologies were key:

- **Machinery Control System** (MCS)—consists of software loaded on LAN consoles controlling the main propulsion and electric plant diesel engines, all switchboard functions, 400Hz distribution, shore power, and selected auxiliaries; includes the fuel control system, previously a stand-alone system. MCS replaced the individual control consoles located in each engine operating station.
- **ICAS**—designed to provide complete machinery condition assessment, diagnostics, and maintenance management capabilities for a broad range of shipboard machinery interfaced to the US Navy's logistics management system.
- **Damage and ballast control system**—consists of several software-based LAN-resident systems: damage control sensor/systems integration; firemain and ventilation control and display; ballast system control and display; and on-line damage control trainer. This system replaced a previously installed firemain/ventilation control console, a ballast control console, and numerous interior communications alarms.
- **Integrated bridge system**—converts legacy navigational information from sources such as the Global Positioning System, speed log, gyro, windbird, and depth sounder into digital data formats and provides them throughout the ship via the LAN.

The USS *Yorktown* tested these and other technologies and procedures with great success:[4]

- Operated with integrated bridge, damage control, and engineering systems, which automated many of the routine daily tasks, freeing sailors to concentrate on their war-fighting skills.
- Achieved a 15 percent reduction in maintenance workload.
- Raised the potential for an estimated $1.75 million per year shipboard manpower savings.
- Effected an additional estimated $2.76 million per year reduction in WLCs, including associated shore manpower reductions and shipboard repair savings.

In conclusion, the USS *Yorktown* (CG-48) achieved its results through the use of cost-effective commercial technology and policy and procedural changes that free crewmembers from repetitive tasks and enhance their ability to focus on war-fighting and professional skills. The Smart Ship achieved incremental manning reductions. To achieve greater or revolutionary reductions, complete platform and systems integrated design must be achieved. A lesson learned through the Smart Ship programme is that optimised manning is complex and the relationships between tasks and manpower assigned must be considered and integrated.

The US Navy's Optimal Manning Experiment

The purpose of the OME is to reduce crew size without affecting performance. The USS *Mobile Bay* (CG-53) and USS *Milius* (DDG-69) are participating, and both have achieved significant manpower reductions. *Mobile Bay* has reduced its number of billets authorised

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[4] Information available from the US Navy's Office of Information at www.chinfo.navy.mil/navpalib/ships/cruisers/yorktown/smrtship.html (last accessed September 2004).

from 321 to 287, while *Milius* has gone from 290 to 237 (Brown, 2003b). The ships have accomplished these reductions through new technologies, procedures, and policies.

The *Mobile Bay* manpower reductions were achieved largely by the cross-training of personnel in order that they could perform the requirements for different positions. Aboard *Milius*, the installation of a new self-service mess line allowed the ship to reduce the number of food service attendants. Increased use of video cameras for remote monitoring also decreased the 24-hour manning of certain watches, and distance support software will give sailors an increased capability to access technicians ashore. Instead of requiring an expert for every system on the ship, the ship uses personnel with general skills to discuss troubleshooting with experts ashore.

The largest policy modification also involves transferring some billets ashore. The ships will have some of their preventive maintenance done in port by specialised teams. The USS *Milius* and USS *Mobile Bay* are both homeported in San Diego and have sent parts of their crews to a maintenance organisation ashore. When the ships return from sea, these personnel come aboard to maintain equipment, reducing the requirement for ship's company to perform maintenance and freeing them to perform operational functions and training.

On *Milius*, some procedural changes have also helped in reducing billets. For example, the positions of boatswain's mate of the watch, quartermaster of the watch, and signalman of the watch have been consolidated into a single position called the 'bridge specialist'. Electronics technicians and information systems technicians are learning each other's jobs, and the ship is adopting a more flexible, rapid-response approach to damage control, using one robust repair locker instead of three to fight a main-space fire.

As a result of this manning reduction project, the OME reduced the number of billets authorised aboard *Milius* by a net 53 (enlisted personnel only). The US Navy is planning to implement the OME to other guided missile destroyers (DDGs) fleetwide.

LPD-17 and Other Amphibious Ships

While the Smart Ship programme was already under way, a companion programme called Smart Gator was initiated to analyse how Smart Ship principles could be employed in amphibious ships. The initiative was named the Gator 17 project, after the upcoming LPD-17 class (though it was not restricted to that class), and had four main goals: to decrease the ship's workload, reduce its manning, improve the crew's quality of life, and increase combat readiness.

Rushmore (LSD-47) completed Phase I of its installations in January 1998. They included the following:

- a fibre-optic LAN linking all divisions and departments by computer
- internal communications systems, called Hydra II, that eliminated the need for sound-powered phone talkers in many evolutions
- a 'real time' damage control system (to replace interior communications alarms), the user-friendly plotting features of which have allowed the ship to do away with laminated damage control plates and grease pencils
- two new control systems: Integrated Bridge System (consists of an Automated Radar Plotting Aid and the ECDIS) and a modern ship steering stand that controls the ship's steering via fibre optics ('steering by light')
- An MCS, as on the Smart Ship.

Phase II of the GATOR 17 installation commenced in October 1998. Key projects for this phase included

> installation of pollution prevention systems, such as an ultra filtration membrane system that so finely filters oil products out of waste water that the resulting effluent can be pumped overboard, and a corrosion control facility that allows ship's force to sandblast and powder-coat valves, watertight doors, and other fittings without assistance from outside contractors.

The LPD-17 (*San Antonio* class) is the latest class of amphibious force ship for the US Navy. It is being procured to replace the older LPD-4 class. The mission of the San Antonio class is to embark, transport, and land the US Marine Corps's Advanced Amphibious Assault Vehicles (AAAVs), air-cushioned landing craft (LCAC), and MV-22 Osprey tilt rotor aircraft to trouble spots around the world.[5] The primary focus of its design was on reliability, survivability, and warfare capabilities. A second primary design objective was to reduce operational costs and improve the ship's capability to incorporate advances in technology over its life cycle. It is important to note here that the programme office 'stressed the importance of full operational readiness and the need to validate reductions before removing manning' (Koopman and Golding, 1999).

The research team met with LPD-17 manning authorities, and our conversations revealed that manpower optimisation (incorporating human and machine integration and ergonomic designs and technology to improve human performance) began early in the design phase with a 'design for ownership' approach to procurement. The LPD-17 design team used a three-dimensional model for showing potential users what the ship would look like when completed. The potential users were then able to provide input as to how the design should be changed to make day-to-day operations more efficient. There were 1,200 design changes proposed, and 300 of them were implemented. There was also an emphasis early in the design phase to make technology insertion and upgrades easier than they had been so that manpower savings or operational capabilities could be achieved in the future.

LPD-17 was the first class of ship to be commissioned under a new US acquisition policy that required consideration of total operating costs, which includes original procurement, maintenance, and operating costs. A goal of an operations-and-support cost reduction of $4 billion was set forth for the entire class, and it was decided that this cutback would require, among other things, a reduction in man-

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[5] Information found at www.naval-technology.com/projects/lpd17/ (last accessed September 2004).

power of 20 percent. There were originally 450 billets in the Cost and Operational Effectiveness Analysis, which were reduced to 382 in the Preliminary Ship Manpower Document, but are still 22 more than the 20 percent reduction goal (Koopman and Golding, 1999). The current crew size is 361, which is expected to be reduced after certain technologies are proven.[6]

Many items were considered when evaluating manpower for the LPD-17 programme. A large part of the manpower on the LPD was for moving equipment on and off the ship, so a side ramp that would more easily marry up with a pier providing easy drive-on and -off capability was installed. Elevators were strategically located to help expedite the on-load/off-load process. Design changes were made to reduce queuing in the galley, and other changes in food service were made. The bridge and combat information centre were redesigned for better ergonomics and human factors support. More onboard training systems were installed. LPD-17 representatives noted that wireless communications and the ship's new wide area network contributed significantly to efficiencies that led to the reduction in manpower.

Not all the efforts to reduce manpower were achieved by employing technologies. A combination of changes in practices and procedures as well as technology insertion contributed to the reduced numbers. Forty-three billets were cut from LPD-17's complement as a result of changes in operational watch-standing requirements. Replacing equipment to reduce maintenance by removing large, bulky, maintenance-intensive equipment in favour of smaller, faster, and more-efficient computers was another practice employed. Some changes required crew increases, e.g., the addition of a training department, which includes five to seven people. LPD-17 personnel continually stressed to us, however, that any number of reductions could not easily be attributed to a particular change. It is the sum of improvements in design, addition of technology, and change in prac-

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[6] This information was provided by a Naval Sea Systems Command LPD-17 programme manager for human systems.

tices or policies together that allow for reductions in manpower. The personnel indicated that any numbers attributed to a particular change had been very difficult to arrive at and probably did not represent the true ultimate value of the impact of making that change.

Beyond the technologies and initiatives mentioned above, there were several other initiatives in the Smart Ship programme that had implications for LPD-17 (NSSC, 1997). They included

- changes to the Condition III watch
- electronic data interchange, which reduced various administrative operations
- installation of EZ-Pup I, a commercial fire-hose handling device
- ICAS terminals and stand-alone workstations
- replacement of chilled-water and Firemain Zebra valves with local remote-control capability and COTS remote actuators (which provided the ability to close the valves manually, locally with a remote controller, or remotely from a damage control station)
- automated log-keeping, including automated logging of key engineering parameters by installed equipment, significantly reducing the watch-standers' logging requirements.

Other improvements included installation of marine engine flushing, which reduced required manpower and maintenance; intelligent electronic power resource management; and other enhancements to electrical or electronic power management.

The LPD-17 programme took advantage of 'Smart Technologies' and optimised-manning initiatives to enhance operations, reduce workload, and achieve significant savings in operating and support costs. Table 7.3, provided by LPD-17 manning authorities, displays the main technologies and areas of improvement that were believed to have the most impact on enhancing operations and reducing workload and costs.

Table 7.3
Measures to Enhance Operations and Reduce Workload and Costs on LPD-17

Smart Technology	Other Improvements
Advanced food service	AAAV gun
Engineering control system	AEM/S mast
Fibre-optic cable plant	Corrosion control changes
Fire/smoke sensing systems	High solids paints
Integrated bridge	Maintenance reductions
Integrated condition and assessment	Optimised manning (adjusted design)
Integrated product data environment	Phased maintenance concept
Ship wide area net	Porcelain tile in wet spaces
Smart Track in C4I (command, control, communications, computers, and intelligence) spaces	SCBA versus OBAs
	Self-cleaning lube oil/sea-water strainer
Total ship training system	Stratica tile
Waste stream management	Synthetic well deck planking
Wireless communications	Titanium piping
	Twin-screw reefer compressor
	Watertight door changes

The Royal Netherlands Navy

The Dutch are well known for their innovations in determining crew requirements. They typically have lower manning than comparable ships in other navies. The new Air Defence Command Frigate (ADCF) is to be manned with a base crew of 45 to 50 crewmembers, expanding to 100 if needed. The ADCF was originally designed with accommodations for 227 personnel.[7]

Compared with those of the Royal Navy and US Navy, the budget of the RNN is quite small and reductions in manpower are necessary to achieve budgetary constraints. However, the RNN does not have strictly a top-down approach to manning. The ADCF's Human Factors and Ship Automation Group was given a ceiling that could not be exceeded, but only after given flexibility to come up with a number independently. The number provided as a ceiling for the ADCF was near to the same number derived by the Human Fac-

[7] www.amiinter.com/samples/netherlands/NL1301.html (last accessed November 2004).

tors Group before receiving the requirement. Once the ceiling is established, it is up to the group to design the best possible crew at the given number. Essential posts such as navigation and the combat information centre (CIC) were manned first. The rest of the ship's complement was then designed for flexible execution of activities such as damage control and cooking and cleaning that do not have to be continuously performed.

The primary philosophy for reducing crews is optimisation of what Human Factors and Ship Automation Group personnel referred to as 'ambition level': 'The ambition level describes which ship functions can be realised to which level and which ship functions can be performed simultaneously' (Wolfe, 2003). The ambition level concept brings to bear an interesting manning philosophy: to 'maximise ambition level given a fixed cost ceiling' (Wolfe, 2003) or minimise costs at a fixed ambition level. Sacrificing ambition to reduce costs means sequencing work to reduce the crew size, mainly through reducing peak workload levels, which reflect activities that require a large number of crewmembers but occur infrequently, such as underway replenishment. Thus, when a ship is involved in such an activity, few other activities can be carried out. High ambition incorporates the ability to deal with emergencies through massed crew response, so giving up ambition to lower crew size increases risk. The ambition level concept is thus flexible enough to bring risk into play as a factor that must be considered in crew reduction decisions. The risk associated with the reduced crews reflects the missions of the particular ship and its likelihood of involvement in combat.

Reducing crew through sequencing tasks also applies to more-routine functions such as cooking and cleaning—tasks that contribute importantly to mean workload. Reductions in both peak workload and mean workload are affected mostly by policy and procedural change, followed by technological implementations. Some of the policy and procedural changes currently being employed to reduce mean workload (or base personnel) are the following:

- **Reduction of preventive maintenance and moving work from ship to shore.** The general operating procedure of the ADCF was that the small or base crew would handle primary ship functions for safety and self-defence. Much of the preventive maintenance will now be performed by shore personnel, and most routine maintenance will be done ashore.

- **Shore-based experts.** The RNN emphasises use of shore-based experts for consultation and troubleshooting vice retaining experts onboard.
  - Use of mechanisation, such as line-handling devices, to reduce nautical workload on deck.
  - Introduction of more generally educated personnel for flexibility. This requires broader changes, because the prevailing RNN training, education, and promotion structures were tailored to existing ship requirements. More generally, integrating a newly designed crew with the existing fleet personnel structure presents difficulties. Such organisational issues could limit the crew reduction potential.
  - A damage control philosophy in which initial responses are made by advanced built-in systems, with which the crew then follows up. This is a case in which a policy decision enables technological advance. Personnel not required on the bridge, on the CIC, or for engineering are all involved in damage control but perform other duties such as cooking and cleaning when not responding to damage.
- **Unmanned ship control centre.** Again, this transformation is basically a technological advance, but a procedural change was required to remove the manning. Onboard US ships, CIC watch-standers perform many of the same functions as bridge personnel, such as navigation and tracking of surface shipping, to back up the bridge. An unmanned ship control centre eliminates these redundant operations.
  - Modularised crew. This model is basically the same as the US core/flex concept. Additional crew ‘modules’ can be added to the ship as its mission demands.

The Dutch Navy also produced manpower savings through design and technological changes. The unmanned CIC could be combined with the bridge, and further ship automation could be pursued through the use of electric-drive systems.

Conversations with personnel from the RNN revealed that their navy had many unique practices, policies, and procedures that helped expedite manpower reductions. For example, the system for approval of new technologies seems to be less rigorous than those of the United States or United Kingdom. Change is very welcome and does not receive much resistance. Manpower reductions are supported by nearly all in the organisation.

It should not be surprising then that the RNN is often at the cutting edge of automation. The 2002 Ship Control Systems Symposium highlighted the following Dutch innovations:

- **Reliable autonomous systems** (Logtmeijer and Westermeijer, 2003). These systems are designed to reduce the number of tasks and amount of information presented to operators. Automated tasks include deactivation of damaged system components, isolation of damaged paths, activation of alternative paths when damage occurs to one, and matching supply and demand of systems. The level of automation varies for each.
- **Self-configurable distributed control networks** (Janssen and Maris, 2003). Such networks make decisions autonomously, independent of a human operator, based on the information it gathers about its environment. In case of a calamity, it reconfigures itself.
- **Risk-based decision aid for damage control** (Gillis, Keijer, and Meesters, 2003). These systems are designed to help decision-makers evaluate risk and choose action for damage control. They require real-time collection of data on critical systems and components, integrated with software and decision tools for display to the operator.

An evaluation of the proposed technologies reveals that the Dutch consider more-risky technologies according to the US National Aeronautics and Space Administration's (NASA's) developed 'Level of Readiness' measures. Some of the technologies that involve artificial intelligence, for example, are between levels 1 and 3 (short of validation), while others such as the reliable autonomous systems rely on technologies that are between levels 4 and 7 (validation to prototype stages).[8]

DD(X)

The US Navy's DD(X) programme is a future surface combatant that will use a new acquisition strategy as well as new technological advances to maximise its capabilities with a reduced complement. The major changes in the DD(X) acquisition strategy stem from a goal to use developing technologies and upgrade them for use in multiple flights of the ship. A family of ships, including the future cruiser, will employ DD(X) technology. The following technologies are being engineered for utilisation on the DD(X):[9]

- advanced gun system
- integrated power system
- dual-band radar suite
- total ship computing environment
- peripheral vertical launching system
- integrated deckhouse and apertures
- autonomic fire suppression system
- integrated undersea warfare system.

To reduce total ownership cost, the DD(X) programme will feature optimal manning, which will be based on comprehensive human-systems integration and human-factors engineering. The initial manning goal for the DD(X), formerly called the DD-21 programme, was for a crew of 95. This target has now increased to 125

[8] Technology readiness level definitions are available online from Global Security.org at www.globalsecurity.org/military/intro/trl.htm (last accessed September 2004).

[9] Information taken from www.peos.crane.navy.mil/ddx/default.htm (last accessed October 2004).

crewmembers, with a maximum complement of 175 personnel (Brown, 2003a). The need to remain affordable and achieve high operational effectiveness requires a systematic approach to minimise total ownership costs throughout the ship's life. The approach to optimising DD(X) crew includes consideration of crewmember needs and abilities up-front, in the systems and ship design, before construction begins.

A recent US General Accounting Office report (GAO, 2003) discusses how the crewing of the DD(X) will differ from older, legacy ships. Older ships employ onboard systems developed independently of each other, with watch-standers supporting each system. Very little integration and/or cross-training of watch-standers was applied. Legacy systems are thus 'stovepiped'; that is, they are separately developed, maintained, and require specific training for operation. Stovepiping results in many specialists and watch-standers being required onboard, which increases a ship's complement.

The GAO report also indicates that the DD(X) plans call for 20 watch-stations, requiring 60 billets—a significant reduction from the DDG-51 destroyer, which has 61 watch-stations requiring 163 billets. To support this reduced manning, plans for the DD(X) include a new operational crewing concept, human-centred design and reasoning systems, advances in ship cleaning and preservation, a new maintenance strategy, an automated damage control system, and 'reach-back' technologies and distance support. To support this new concept of manning, the DD(X) will eliminate barriers existing in older ship classes where there are separate watch-stations for specific legacy systems and little cross-training. Crewmembers will be cross-trained over several functional areas, with the net goal of having a more versatile, senior, and experienced force manning these warships. A maintenance strategy of replace vice repair, engineered improved reliability of equipment, and condition-based maintenance will reduce the requirement for maintenance and repair specialists onboard. The DD(X) will integrate whole-ship sensors, weapons, and databases and eliminate the need for specialisation of different personnel in different systems. Such an approach will increase the flexibility of each watch-stander.

To ensure that the DD(X) programme's optimal manning goals and total ownership cost reductions can be met, the Navy will address the need for changes in manning and training policies to allow these warships and systems to be manned differently, by more trained, experienced, and versatile crewmembers, to take full advantage of the planned and emerging technological improvements. Human systems engineers are engaging with operators in the fleet and bringing them into the design and engineering process early so that they will trust the automation that will be installed in these future warships. Experienced and professional DD(X) crewmembers will be required to report onboard fully trained and qualified for their duties, because a reduced complement increases the importance of each individual.

Summary

To provide a basis for identifying manpower reduction options potentially relevant to the CVF, we reviewed several of the many efforts by various navies to reduce complements:[10]

- **Transfer of US ships to the Military Sealift Command.** As sealift ships have been shifted from US Navy manning to MSC manning—largely with civilians—billets have dropped dramatically. Crew reductions are possible because crewmembers are fully trained before reporting aboard and replenishment of stores, for example, is done during normal working hours.
- **US carriers.** Of particular interest is the Smart Carrier programme, a series of innovations implemented chiefly during *Nimitz*-class refits. The most important of these innovations was the establishment of an LAN for distributing data on the status of various systems throughout the ship.
- **The US Navy's Smart Ship.** In an experiment aboard the guided-missile cruiser USS *Yorktown,* significant complement

[10] The case of the commercial cruise ship, mentioned in Chapter Four, is also pertinent here.

reductions were achieved with a core/flex manning concept. Underway watches were not stood in reduced-threat environments, making more manpower available for other duties but still permitting the watches to be manned where required.

- **The US Navy's Optimal Manning Experiment.** Innovations on the destroyer USS *Milius* and the cruiser USS *Mobile Bay* permitted reductions in crew size without affecting performance. The transfer ashore of preventive-maintenance teams was the biggest factor in complement reduction. As in the Smart Ship programme, it was important that the smaller crew be cross-trained.
- **The LPD-17 and other amphibious ships.** Smart Gator applies Smart Ship principles to amphibious ships. For example, ship system operators were brought into the design process to suggest efficiency improvements.
- **The Royal Netherlands Navy.** The Dutch are constrained by tighter manpower ceilings than apply in the United Kingdom and thus accept somewhat higher risks while spreading out most predictable tasks to permit accomplishment by small crews. The RNN is also on the cutting edge of automation.
- **DD(X).** This set of technologies will be used on future US surface combatants. A good deal is being staked on elimination of 'legacy manning' associated with systems inherited from earlier platforms.

The more incremental initiatives—OME and the Smart Carrier, Ship, and Gator programmes—either have shown or are intended to show complement reductions on the order of 15 to 20 percent. Much higher reductions are hoped for in the case of DD(X) and certain Dutch ships.

CHAPTER EIGHT

Identifying and Evaluating Complement-Reduction Options

The set of cases described in Chapter Seven provide a wide array of ways and means to reduce or optimise manpower. We identified a potential reduction technique as an option for the CVF if it was

- proven to reduce costs for its employer,
- proven to reduce workload or manpower for its employer,
- proven to improve efficiency to a point where complement reduction could occur, or
- widely employed across multiple platforms.

We felt it important to include a criterion such as the last because options that have been widely employed indicate a demonstration of gained efficiencies. The options meeting the criteria included technological insertions, policy or procedural changes, design changes, or a combination of these.

Our research and examination of cases led us to identify 130 options whose implementation aboard the CVF was of sufficient technical and operational feasibility to make them candidates for further evaluation. Our evaluation of these options consisted of qualitative judgments regarding their potential impact on cost and on manpower, the level of 'readiness' or maturity of technology options, and the level of operational risk incurred. This phase of the research was completed through interviews, researching documents and reports, and assessing the technologies, policies, and procedures presented.

In this chapter, we identify and describe the 57 options we judged as having manpower reduction potential consistent with their cost, risk, and level of maturity. We list them by shipboard department (plus one category for shipwide options).[1] Within the description, we include the results of our qualitative evaluation (of the 57, some appeared more attractive than others). We present tables summarising the prevalence of the options across the case studies and conclude with a summary discussion and table, together with some thoughts on where CVF complement reduction might go from here.

Three of the dimensions of our evaluation warrant some discussion before we address the options. First, we defined operational risk as any change that compromises the safety and security of the ship. There were three levels of risk:

- *Low risk* meant that failure of the technology presents little or no risk to the safety and security of the ship.
- *Medium risk* meant that failure of the technology temporarily or more severely compromises the safety or security of the ship but does not alone result in a catastrophic or unrecoverable casualty.
- *High risk* meant that failure of the technology results in more seriously reduced safety or survivability or compromises the safety and security of the ship or crew.

Second, we derived the technical level of readiness from NASA standards put forth for evaluating technical risk (see Table 8.1). We converted the NASA standards into a set of four ratings (see Table 8.2).

Finally, in reading about our brief, qualitative judgments of the complement-reduction potential of the various options, it should be kept in mind that complement reduction is a complex and iterative process. Each crewmember will have different responsibilities during

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[1] For a tabular presentation of options and evaluation results, see the Appendix.

Table 8.1
NASA Technical Levels of Readiness

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and 'flight qualified' through test
TRL 9	Actual system 'flight proven' through successful mission operations

Table 8.2
RAND Technical Levels of Readiness for CVF Evaluation

TRL 1	The technology is still conceptual (corresponds to NASA TRL of 1–3).
TRL 2	The technology is being explored in a lab setting (corresponds to NASA 4–5).
TRL 3	The technology exists as a prototype (corresponds to NASA 6–7).
TRL 4	An operational system exists (corresponds to NASA 8–9).

the CVF's varying levels of readiness and in the different evolutions that occur onboard. The introduction of a technology or a design, policy, or procedural change may eliminate the requirement for a crewmember for an 'evolution' on the quarter bill. However, the quarter bill must then be reexamined to determine whether the crewmember's other position requirements can be performed by remaining crewmembers. This process must be followed as each manpower reduction option is introduced. Only after a crewmember's responsibilities for all evolutions on the quarter bill are eliminated or absorbed by other crewmembers can a crew reduction occur.

Caution must be exercised with crew reductions to ensure that additional responsibilities absorbed by remaining crewmembers are within their capabilities. Quarter bill responsibilities and performance often require specific training and qualifications. As crew reductions are considered, increased training time and qualifications for the core crew remaining may result. It is thus the combined effect of incremental changes and the ability to redistribute a crewmember's total quarter bill responsibilities that determine the ability to reduce the ship's complement. These factors must be addressed, not only in developing an initial complement but also throughout a ship's life as changes occur.

Damage Control Options

We list complement-reduction options associated with damage control in Table 8.3. These options have a wide range of risk, and because of the nature of the casualties the technology is designed to support, the risks can be high if the technology's components fail. Some of the damage control technologies are experimental, and not all technologies are currently available. These options offer a significant opportunity for reduced manning, because damage control is a primary manpower driver.

Current US carriers have up to 1,100 personnel in the damage control organisation, which is greater than the proposed total complement of the CVF. It has been suggested that through the use of modern communications systems, improved readily available commercial damage control equipment, doctrine revision, and organisational streamlining, damage control manning on US carriers could be reduced by approximately 700 personnel. It is clear that damage control advances in technology, policies, and procedures could result in significant manpower reductions on US carriers, and potentially for the CVF.

Self-contained breathing apparatus is the new fire-fighting breathing device that replaces the oxygen breathing apparatus (OBA). The older OBA is cumbersome and more difficult to don and operate, whereas the SCBA is easier to don, wear, and operate. The operational risk for the SCBAs is less than that of the current OBAs because of their ease of use and reliability. The SCBA has been in use in commercial industry and fire departments. SCBA technology is

Table 8.3
Damage Control Options

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Self-contained breathing apparatus	X	X	X	X			
Remote sensing of spaces		X	X	X	X	X	X
Flex-response damage control team				X			
Automatic alternative-path identification when system fails						X	
Automatic damaged-path isolation from network						X	X
Automatic deactivation of damaged system elements						X	X
Automated damage control	X	X	X	X		X	X

NOTE: The X's in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

currently available and being installed widely across US Navy platforms. Use of the SCBA has received positive response from sailors. However, the greater ease of use of this equipment may not affect the number of personnel required to suit up to fight fires. The technology has not been proven to substantially reduce complements.

Remote sensing of spaces refers to a series of liquid level, smoke, heat, pressure, and noise sensors that can be used to replace manning of spaces aboard ship. Remote sensing of spaces is performed on commercial ships, the LPD-17, the Smart Ship, US carriers, and Dutch ships and is planned for use on the DD(X). Use of remote sensors reduces the requirement for manned spaces and sounding and security watches. Because of their widespread use, we consider remote sensors to be a high-reliability, low-risk option. Remote sensors can reduce watch-standing requirements, which can lead to a smaller complement. The cost of sensors should be low compared with the manpower savings that will result from their use.

A **flexible response damage control team** reflects a policy change being employed by US Navy Smart Ship platforms. Under this concept, a ship has fast reaction teams whose responsibility is to react to and resolve casualties (fires, flooding, etc.) that occur onboard. In the past, when a fire occurred, ships have gone to general quarters and set material condition Zebra, which entails the entire crew setting impenetrable boundaries throughout the entire ship. A flexible response damage control team tailors the effort required to the situation at hand and surges the necessary response commensurate with the casualty. In addition, under the Navy's OME, the ship's main engineering repair locker (repair locker 5) was boosted in size, while the forward repair locker (repair locker 2) and aft repair locker (repair locker 3) were reduced in size. Repair locker 5 handles the main engineering casualties, and repair lockers 2 and 3 provide backup. Increasing the size of locker 5 provided a greater pool of assets where the main casualties have the greatest occurrence. A flexible response damage control team reflects a policy change and should be low risk. This policy's tailored approach to damage control can help reduce a ship's complement. The cost of the policy change is deemed to be minimal.

Autonomous systems. This technology is under development by the Dutch RNN. Intelligent systems communicate with the environment via a computer network and automatically reconfigure equipment to a default or safe state without operator intervention (Logtmeijer and Westermeijer, 2003). In certain situations, operators are faced with many urgent decisions and tasks, and in the future, information overload may become even greater with reduced crewing. Reliable autonomous systems will effectively reduce operator tasking and information burden and make workload more manageable. Autonomous systems include three functions:

- automatic alternative-path identification
- automatic damaged-path isolation from network
- automatic deactivation of damaged system elements.

One example (Logtmeijer and Westermeijer, 2003) is that of an autonomous system response to a ruptured chilled-water pipe. In the event of such a casualty under a manually operated system, an operator would deactivate the parts of the damaged system, isolate the damage from the rest of the system, reroute the water to vital users, and monitor the system to balance load within the parameters of the equipment. An autonomous system would include sensors and remotely operated valves with which it would monitor system pressures and operating parameters and reconfigure equipment without operator intervention if a rupture occurred.

Autonomous systems are still in the conceptual stage and being considered for use in the RNN and the US Navy's DD(X) destroyer. We consider the risk of this system to be medium because it is currently an unproven technology with unknown reliability. Autonomous systems do support a reduced complement, although the complement reduction resulting from its use is currently unknown. Evaluation of references did not provide enough information to determine the cost of such a system.

Automated or advanced damage control is a system of displays, workstations, consoles, or computers located throughout a ship that is interconnected with the ship's LAN. A real-time dynamic display indicates information received from sensors (heat, smoke, tank levels, etc.) or input from operators to provide all stations with a common view of a casualty. Space information necessary to contain the casualty can be displayed for coordinating casualty control. Such information might include how to electrically isolate the space and what the main engineering-space fire-fighting protocols are. The concept of automated damage control includes

- the ability to operate fire pumps from any damage control system station
- a fire and smoke sensor system
- automated closure of Zebra valves for chilled-water, firemain, and ventilation systems
- ability to control a series of point-source fine-spray mist fire suppression systems at key points throughout the ship
- remote activation of fire-fighting agents, e.g., aqueous film-forming foam, halon, and carbon dioxide
- automated firemain break detection and isolation
- automated boundary cooling and space dewatering.

Elements of automated damage control are used on the LPD-17, and some forms of it can be found on commercial ships, the Smart Ship, and Dutch ships and is planned for use on the DD(X). The risk of using automated damage control is high, since failure of this technology can lead to inherent danger to the safety and security of the ship. That is, failure of a display or failure of remote operation of a valve could potentially cause harm to the ship and its personnel as well as to the casualty control efforts. The technology is available now, however, and automated damage control can reduce the requirement for manpower. By remotely operating damage control equipment, a reliable system may reduce the requirements for manpower assigned to damage control parties.

Marine Engineering Options

The marine engineering options we identified (Table 8.4) were all low-risk, operationally ready systems. The costs and complement impacts varied, as discussed below.

Unmanned machinery spaces. The policy of having unmanned machinery spaces is a commercial practice that has been implemented in the Smart Ship, the OME, and by the Dutch RNN and is also likely to be employed on the DD(X). It has been in the US Navy's common practice to man a machinery room, even though the machinery in a space can be remotely activated. The policy of employing unmanned machinery spaces is facilitated by technologies such as remote sensors and closed-circuit television (CCTV), which could be used to determine engineering casualties or unsafe conditions in the space. When combined with remote sensors, the risk of maintaining unmanned machinery spaces is low—and the sensors are available now. Maintaining unmanned machinery spaces likely results in a reduced complement because of the reduction in watch-standing requirements.

Titanium saltwater piping is now being considered for use onboard US warships. This piping is immune to corrosive attack by saltwater or marine atmospheres and is also resistant to cavitation. The complement-relevant benefit is that, because of the superior corrosion resistance, much less corrective maintenance is required than for currently used copper-nickel alloys.

Reverse osmosis. Ships have traditionally used distilling plants for turning saltwater into freshwater, where the saltwater is flashed into steam and the freshwater condensate is collected. Reverse osmosis purifies the water by removing salts, small particles, and other impurities through filtration. A private commercial study indicated that if the Navy were to adopt a reverse-osmosis freshwater system, a large savings (less development costs) could be achieved (see also Chapter Four). Reverse osmosis is used on the LPD-17, but the impact on the complement is likely to be small.

Table 8.4
Marine Engineering Options

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Unmanned machinery spaces	X		X	X		X	
Titanium saltwater piping		X		X			
Reverse-osmosis freshwater system		X					
Preventive maintenance by a shore establishment				X			
List control system		X			X		
Integrated condition assessment system		X		X			
Commercial heating and ventilating systems			X				
Automated fuel control			X	X	X		X
All-electric auxiliaries		X			X		X

NOTE: The X’s in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

Preventive maintenance by a shore establishment. The US Navy's Smart Ship and OME both move sailors off the ship and into a Readiness Support Group shore station, where they become assets to the ship when the ship returns to port. Readiness Support Group sailors embark the ship to perform corrective and preventive maintenance to the ship's equipment and systems. The main benefit of the shore establishment's performing preventive maintenance is that it frees up those who are assigned to the ship to undergo critical training in support of war-fighting mission requirements. The effect on costs is unclear: The costs of performing the maintenance appear simply to be shifted off the ship and onto the shore. That is, the maintenance is still being completed but by different people.

List control systems monitor list control tanks using tank level indicators. These systems allow for remote monitoring vice manual sounding of the tanks. The list control system provides centralised monitoring, control, and operation of pumps and motorised valves that serve the list control tanks. List control systems are used on the LPD-17 and are being planned for installation on US aircraft carriers.[2] The systems' primary benefit is a reduced workload for watchstanders. The impact on a ship's complement should be relatively small, and the cost low.

The **Integrated Condition Assessment System** is an automated machinery condition monitoring and assessment technology that enables condition-based maintenance and log generation, particularly for the ship's mobility systems (Sturtevant et al., 2003). It interfaces with the ship's databases to provide configuration and logistics information to the operator. Various US Navy platforms use ICAS. The benefits of ICAS include reduction in equipment casualties, maintenance, and fuel consumption. Costs are likely to be moderate, and any associated complement reduction would probably be low.

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[2] Information on list control systems was presented by Michael F. Tangora, NAVSEA, at the 13th International Ship Control Systems Symposium in Orlando, Florida, on 7–9 April 2003. His (and James Mariani's) conference paper, entitled 'US Carriers Exploiting Technology to Pilot Toward 2010 and Beyond', contains further information on these systems.

All-electric auxiliaries replace steam-powered auxiliaries for heating, hot water, and cooking. Steam auxiliaries are manpower-intensive because steam piping is difficult to maintain. All-electric utilities are in use by the LPD-17 and will be installed on new US helicopter/dock landing ships (LHDs). A private commercial study indicated that backfitting existing US carriers with electric auxiliaries would reduce the maintenance load and weight of the ship. This technology would have an appreciable complement impact, but its effect on other costs is uncertain.

As shown in Chapter Four, using freshwater **vacuum sewage collection** technology can reduce sewage system maintenance and manpower by 90 percent and overall sewage, grey water, and food waste volume to 70 percent of the level from conventional gravity drain systems. Costs of disposal would thus significantly decrease. The vacuum system also uses smaller-diameter copper-nickel and stainless steel piping and tubing, resulting in some material cost savings. Thus, after taking up-front investment into account, the vacuum system could reduce WLCs as well. Furthermore, weight and space savings would be realised. Although maintenance would require no more than one billet, the complement reduction involved would be low.

Medical and Dental Options

Several efficiencies can be gained in the medical and dental departments. A private study of US aircraft carriers recommended that instead of performing routine dental care onboard (while a ship is in port), sailors could be sent to a shore facility for treatment. The study indicated that pooling of dental assets in an ashore facility was a more efficient method of distributing the dentists' workload and better met the routine dental requirements of the crew. The same study also recommended the consolidation of medical and dental facilities, which could lead to efficiencies in handling of infectious material and administrative record-keeping. The implementation of these two recommendations would lead to a reduced workload and lower cost.

Supply Department Options

We show in Table 8.5 the distribution of supply department options across the various case studies. All options are associated with low risk, and any technologies required are embodied in currently operational systems. Most options require low investment and support costs, but there are exceptions we note below.

Use of elevators vice package conveyors allows for a whole pallet of supplies to be driven onto the ship and into an elevator for easier storage and retrieval. This system requires less manpower to load and unload than the traditional conveyor systems. Elevators are also less dangerous than package conveyors and allow easier transfer of goods from one ship level to the next. Elevator systems are employed by the MSC and the LPD-17, which both have missions heavily focused on loading and unloading cargo. For any ship that requires a large amount of manpower for loading and unloading stores, using elevators should result in appreciable manpower savings. The cost will vary depending on ship design, number of elevators, and other factors. There is no additional operational risk—the elevators actually improve safety. Complement impact could be appreciable.

Smart Cards allow for improved efficiency to the point of manpower reduction. A Smart Card is a credit-card-sized and -shaped piece of plastic that contains information about the individual (his or her finances, personal information, etc). Crewmembers use the card to make purchases onboard and in port at locations that have Smart Card readers. The card's usage reduces the need to keep cash onboard and at various locations around the world. Onboard, a sailor swipes or uses the card to enter certain locations, get food from the galley, or buy something from a vending machine or store, which eliminates the need for dedicated persons to manage the cash flow and sale of goods. The MSC, LPD-17, Smart Ship/OME, and US carriers all employ Smart Card technology. Costs would be minimal provided some kind of information system is in place, but complement impact would also be low.

Table 8.5
Supply Department Options

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Use of elevators vice package conveyors	X	X					
Smart Card/cashless ship/automated vending	X	X		X	X		
Optimising layout: location of galley and storerooms	X	X			X		
Administrative functions and personnel to shore	X	X		X	X		
Self-service stamp machine	X			X			
Self-service postal meter	X			X			
Info technologies to reduce log/admin workload	X	X		X	X		
Contract storeroom loadout		X			X	X	
Automated inventory and material handling system					X		
Advanced food service	X	X		X	X		X

NOTE: The X's in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

Optimising the location and layout of galleys and storerooms, e.g., by locating galleys close to one another, would allow sharing of certain resources, including personnel. Piping, garbage disposal, and various other functions could be combined to reduce husbandry. Optimising the location of storerooms could minimise crew workload by reducing travel and search time for items. Currently, the MSC, LPD-17, and US carriers are employing Smart designs in an effort to improve efficiency and reduce workload for sailors. Costs could be modest if this approach is adopted at the design stage, and complement impact could be appreciable.

Moving administrative functions and personnel to shore is a policy measure that can result in small crew reductions. If many ships participate and share shore facilities, personnel, and resources, then economies of scale can afford cost savings. Certain technologies may be required to support transfer of information from ship to shore, but those technologies already exist and are in use presently. Currently, the MSC, LPD-17, Smart Ship/OME, and US carriers all employ this manpower reduction method.

Self-service stamp machines and postal meters are simple pieces of equipment that eliminate the need for a dedicated body to sell stamps and provide postal functions. Both pieces of equipment are used by MSC and the Smart Ship/OME. The subsequent complement reductions would be minor.

Information technology to reduce logistic and other administrative workload. The ability to have electronic access to and maintenance of pay/personnel records ashore is just one of the many information technologies employed to reduce logistic, administrative, and executive workload. Automated log-keeping through the use of Smart Cards, personal digital assistants, and Smart sensors allows for a slightly reduced crew and can be used to gain supply chain efficiencies. It also allows for ships to move payroll clerks onshore. Cost should be minimal provided the information system backbone is in place. Information technologies to reduce log-keeping and administrative workloads are used by the MSC, LPD-17, Smart Ship/OME, and US carriers.

Contracting of storeroom loadout is a policy measure permitting a private company to be hired for loading or unloading stores. On- and off-loading ships are manpower-intensive tasks that can take place before overseas movement as well as while deployed forward. US auxiliaries frequently employ stevedores at foreign ports to on-load stores. The LPD-17, US carriers, and the RNN either use or are evaluating use of this practice. The complement impact would manifest itself as a steep reduction in working parties necessary to load stores and supplies. Whether a contractor is used to load stores would depend heavily on the hired company, and a careful evaluation made at that time; however, the workload savings and subsequent manpower savings could be appreciable.

Automated inventory and material handling systems could result in substantial manpower savings. An automated inventory and material handling system would pick up supplies, evaluate what they are, decide where they go, and put them away. Conversely, they would read input about what is needed, determine where it is located, and retrieve it. All the while, the system would be keeping a database of what is in inventory and how much is in inventory and could send orders for new material when inventory fell to a certain level. These systems would incorporate elevators and conveyors, UPC scanners, and radio frequency bar codes, and intelligent information systems and robotics. Costs could be moderate, but so could manpower savings. The technology is currently used widely in manufacturing. It is at the prototype stage for military applications and is currently being evaluated for new US carriers.

Advanced food services include a number of technologies and practices to save manpower or improve efficiency. Some of the methods employed are flash-freezing and -heating techniques for meals, as used on cruise ships; use of soda syrup vice cans, which saves space and trash; and using standardised menus, which makes ordering supplies easier and generates less waste. However, food service improvements need not be terribly innovative to save manpower; even automated dishwashers and Teflon pans would represent advances on military ships. Advanced food services are being employed by the MSC, LPD-17, Smart Ship/OME, and US carriers and are being considered for the DD(X). There is little or no operational risk related to these innovations; all are easy to employ, available, and relatively inexpensive. The manpower savings and efficiencies gained far outweigh the risks and costs.

Warfare Department Options

In Table 8.6, we show the distribution of warfare department options across case study platforms. All are currently operational systems involving low risk. Costs for most should be low (exceptions are noted in the discussion), but complement impacts for all should also be low.

Multimodal consoles. Multimodal displays such as the Q-70 installed on the LPD-17 allow a watch-stander to monitor more than one watch-station at each console and, in addition, allow the use of decision support systems to facilitate situational awareness. The technology has not been proven to reduce a ship's complement substantially. Reductions that do occur are achieved through improved man-machine interfaces, so watch-standers are more efficient and fewer are required. The technology is being installed widely across US Navy platforms. In addition, the consoles are easily upgradeable because of COTS technology and design.

Advanced Enclosed Mast System. The Advanced Enclosed Mast/Sensor (AEM/S) system encloses existing radars and provides reduced signature and other operational benefits. By enclosing major antennas and other sensitive equipment, the AEM/S system protects these elements from inclement weather. This reduces maintenance, as well as providing significantly reduced radar signature.[3] The reduced maintenance results in lower WLCs. The mast system is currently being employed on the LPD-17 and is being considered for installation on the DD(X). The operational risks are lower than with previ-

[3] Information taken from www.fas.org/man/dod-101/sys/ship/aems.htm (last accessed September 2004).

Table 8.6
Warfare Department Options

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Multimodal consoles	X						X
Enclosed mast system	X						X
Integrated bridge system	X	X	X	X		X	
Combined signalman and quartermaster rates				X	X		
Automated log-keeping		X					

NOTE: The X's in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

ous mast systems. The small manpower savings result from reduced mast and radar maintenance, and operational and tactical improvements are key drivers of implementing this technology.

Integrated bridge system. The integrated bridge (see Figure 8.1) is a suite of aids that help the bridge navigation team steer the ship safely. The bridge watch-team must integrate various sources of information to navigate and maintain the safety and security of the ship and its crew. These systems provide computer-based navigation, planning and monitoring, automated radar plotting, and automated ship control. Integrated ship technologies are commercially available and have been proven effective and efficient, by improving situational awareness and reducing operational risks. The MSC, the LPD-17, commercial industry, the Smart Ship/OME programme, and the RNN, among others, employ the systems. Because the efficiency and

Figure 8.1
Integrated Bridge

SOURCE: Tokimec Inc.
RAND *MG240-8.1*

effectiveness of bridge watch-standers are improved, their number can be reduced, although the overall impact on crew reduction is minimal.

Combining signalman and quartermaster rates. A quartermaster is responsible for charting a ship's current position and advising the officer of the deck on the safe navigation of the ship. A signalman is in charge of visual communications, i.e., via flashing lights and semaphores, and is part of the bridge watch-standing team. By combining the rates, a ship can effectively reduce the bridge watch-standers by one person per team. The combined rate would then be responsible for safely navigating the ship as well as maintaining responsibility for visual communications. The costs of this policy change are relatively low and would consist of cross-training signalmen and the quartermasters to fulfil both responsibilities. Onboard training tutorials are available, but some off-ship training might be required.

Deck/Air/Weapons Engineering Departments

The Deck and Air departments have traditionally been responsible for manpower-intensive activities. The options presented below focus on saving manpower in the special evolutions of loading stores, retrieving an anchor, and handling weapons. Whether saving manpower on these special evolutions reduces the complement depends on whether the other functions performed by the sailors on the special evolutions can be allocated to their shipmates.

Use of conveyor to load stores from shore to ship can result in reduced workload for the ship's crew and, depending on how often and to what extent stores are moved, could result in substantial crew reductions. Conveyors effectively move supplies from the shore to the ship and are less manpower-intensive than using crewmembers to do it. Currently, the MSC, LPD-17, and US carriers employ conveyors in this manner. There is little technical risk, no operational risk, and conveyors are available now.

Anchor chain wash down is achieved through a device installed on a ship's hawse pipe. The installation delivers pressurised water to remove sediment and organic material from the chain and anchor as they are retrieved. This installation could save a little manpower by eliminating the requirement to provide additional personnel to man a fire hose during a 'sea and anchor' detail evolution. There is little to no operational risk with this installation, the technology is simple and available, and the cost is low. The device is currently used on the LPD-17.

Automated weapons handling. The Naval Storage and Retrieval System (NAVSTORS[4]), now under development, will be a fully automated system that handles cargo and weapons in the holds of magazines. Weapons strike down (movement of ordnance to a weapons magazine) and strike up (movement from a weapons magazine to an aircraft) is a manpower-intensive, time-consuming activity, conducted largely through the use of bulky, manually moved ammunition-handling equipment. The current practice of strike down and strike up of ordnance is accomplished through the use of hand trucks, forklifts, and weapons elevators.

During hostilities, the variability of targets presented requires a responsive, flexible system to load various ordnance on aircraft to meet mission requirements. The speed of strike-up operations using manually moved ordnance could limit aircraft sortie generation rates.

An automated weapons handling system can reduce the manual labour required for the stowage and retrieval of ordnance. Further, it can increase the speed of the process, maximise the stowage area for weapons of different sizes and shapes, and provide the capability to select a requested payload contained in the magazine and automatically move it to service elevators.[5] These advantages have utility to an operational commander.

Literature review and interviews with US Navy officials reveal that automated weapons handling is a promising option for man-

[4] A description and goals of NAVSTORS is available at www.dawnbreaker.com.

[5] The benefits of NAVSTORS are detailed at www.dawnbreaker.com.

power reduction. Experts are still evaluating the risks and costs, which will depend on the platform and the situation. Automated weapons handling is currently being considered for employment on future US carriers.

Liaisons with CVF designers indicate a debate over whether or not there should be investment in an automated weapons handling device. The germane issues to consider include, for example, that the main mission of the CVF is to put ordnance on target in support of the operational commander. An automated weapons handling device can expedite and improve the CVF's capability to perform this function. The frequency of events in which an automated weapons handling system would be utilised, the man-hours saved, and the system's reliability would all affect the return on investing in the system.

Shipwide Options

Many shipwide options contributed to manpower reductions, which we present in Tables 8.7 and 8.8 (pp. 148–149). Because the quarter bill prescribes various shipwide responsibilities during watch-standing and special evolutions, shipwide options have the potential for capturing significant manpower savings, although, of course, the magnitude varies with the option. Risks for all options are low; costs are generally low (exceptions are noted below); and all are ready for implementation now.

Use of remote specialists via video technology. Communications and video technology have greatly increased the ability of a ship at sea to 'reach back' and obtain expert advice from ashore. Video of an equipment problem can be transmitted ashore to experts who can advise the ship's company on troubleshooting and repair. Although requiring some inherent general skills onboard for operation and maintenance of systems, video technology permits onshore experts who can be consulted on an as-needed basis. This is not to say that ship's company can always fix problematic equipment by merely consulting experts; the equipment may be irreparable. However, a reach-back capability provides another resource to assist in effecting repairs. The MSC, LPD-17, and Smart Ship all use video technology.

The **use of very-high-frequency (VHF) handheld radios** provides a dramatic reduction in the requirement for sound-powered-phone operators for US Navy ship internal communications. VHF radios (walkie-talkies) represent a COTS technology that improves the speed of communications for command, control, and direction necessary in the daily operations of a ship. The US Navy has for special evolutions required several nets including engineering and manoeuvring circuits to be manned with sound-powered-phone operators to relay commands to control stations. VHF handhelds allow instantaneous communications between command authorities and eliminate the need for several phone operators during special evolutions. VHF handheld radios were used in all cases examined. Using such radios reduces the number of personnel required for special evolutions and therefore should have a high impact on reducing a ship's complement.

The application of **anticorrosive coatings** can have a significant effect on the workload of Deck department personnel, as well as those in other departments. A significant amount of effort is required to maintain a ship because it operates in a corrosive environment. A large contingent of junior rates are normally assigned to a ship's deck division to 'chip and paint', which is a manpower-intensive and recurring operation to maintain vertical and horizontal surfaces. Improvements in anticorrosive coatings can increase the time between maintenance cycles (for chipping and painting). Further, the deck of an aircraft carrier is painted with nonskid material that must be prepared and recoated at periodic intervals. Advances in anticorrosive coatings can increase the mean time between maintenance cycles for that material also, reduce workload, and potentially reduce the number of personnel assigned to perform this maintenance. Contracting painting requirements could also reduce this shipboard manpower-intensive task. Anticorrosive coatings are used in all cases examined (except by the MSC) and are a low-risk, high-impact option for optimising manpower.

Table 8.7
Shipwide Options (part 1)

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Use of remote specialists via video technology	X	X		X			
VHF handheld radios	X	X	X	X	X		X
Anticorrosive coatings		X	X	X	X		X
Total ship training system		X		X			
Sensor-directed condition-based maintenance	X			X	X		X
Replace, not repair							X
Reliability-centred maintenance	X	X		X			X
Private preservation work			X	X			X
Multiple crews	X						
Low-maintenance deck materials			X	X	X	X	X

NOTE: The X's in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

Table 8.8
Shipwide Options (part 2)

	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
HSI design		X			X	X	X
Embedded training		X		X	X		X
Core/flex concept		X		X		X	X
Consolidated watches	X	X	X	X	X		X
Civilian crew to augment ship's crew	X						
CCTV for shipwide surveillance and monitoring		X	X	X	X		X
Broad skills, cross-trained workforce	X		X	X		X	X
Automated log-keeping				X			
Networked internal communications		X		X	X		X

NOTE: The X's in this table indicate our research and observations of leverage points being used on each platform. It is possible that some leverage points are used but not indicated.

Total ship training system. A smaller, optimised crew means that well-rounded crewmembers onboard must have knowledge at their fingertips to accomplish the mission. A total ship training system would be capable of being activated and used 'anywhere, any time, on demand' to address a wide range of tasks related to a variety of operational contingencies (Advanced Surface Training R&D Team, no date). The LPD-17 and the US Navy Smart Ship/OME use such a system. The impact of a total ship training system on a ship's complement is unknown, but the training system is supportive of a reduced complement by helping maintain performance and restrain risk. Costing information was unavailable.

(Sensor-directed) condition-based maintenance is a philosophy positing that, vice using a scheduled maintenance plan, a system or piece of equipment should be monitored for changes in condition, at which time maintenance should be performed. The objective of condition-based maintenance is to accurately detect the current state of mechanical systems and accurately predict systems' remaining useful lives. Under this concept, crewmembers perform maintenance only when needed to prevent operational deficiencies or failures, which serves to eliminate periodic maintenance while reducing the likelihood of machinery failures. A piece of equipment can be monitored in two ways: by human measurement whereby a person frequently visits and takes measure of conditions or by a sensor or other technology that will record and report the measurements on a regular basis. Clearly, using a person to take measurements could be more expensive than using a sensor or other technology. A sensor-directed condition-based maintenance philosophy has been employed by the MSC, Smart Ship/OME, and US carriers and is under consideration for the DD(X). This wide use testifies to the philosophy's ability to greatly reduce unnecessary maintenance and therefore save manpower. The direct savings in manpower resulting from the reduced maintenance will vary depending on the extent of the application of the philosophy and the combination of other manpower-reducing technologies employed. The sensor and network technology required to employ such a philosophy exists and is relatively inexpensive (compared with the WLCs of a human). Because the operational and technical risks are low, the cost is low, and the benefits are intermediate, such maintenance is a good option.

'Replace vice repair' is a maintenance philosophy that proposes to keep spares onboard that can be used to replace an item in need of repair. This backup allows for the broken part to be sent to a centralised shore repair facility, eliminating the need to have a wide variety of maintenance and repair skills onboard. This option is being explored for the DD(X) programme. The practice could only be cost-effective if it is adopted widely enough so that the economies of scale of having the shore facility could be achieved. The cost and manpower savings of this strategy would depend heavily on the extent of its adoption and the number and variety of spares kept onboard, as well as the skill levels of onboard personnel. It requires no special technologies per se.

Reliability-centred maintenance is a larger umbrella maintenance philosophy that encompasses condition-based maintenance and any other maintenance philosophy that suggests a policy of using extensive and detailed information about the history and current state of the equipment to make decisions about maintenance or repair. The knowledge required of a system or systems and its components includes the mean time to repair and failure rates. The benefits are seen in greater efficiency of use of resources, including human resources. The MSC, LPD-17, and Smart Ship/OME employ this philosophy, and it is being considered for the DD(X).

Privatising preservation work is effective as a means to reduce core complement by hiring civilian or some other private workforce to perform required tasks. It is most effective in reducing manpower under certain conditions, mostly for peak cyclical work that is very manpower-intensive and requires dedicated workers in port. A good example may be painting of the ship. The complement savings would vary depending on which function is privatised, but there is generally a manpower savings to some degree. The criticality of the task to the safety of the ship and to national security would have to be evaluated and assessed. Commercial ships have used this practice, the Smart Ship/OME employed it, and it is being investigated for the DD(X).

Multiple crewing is a concept in which ships remain deployed forward and crews are rotated to the ships. This concept maximises the use of the capital asset (the ship) by keeping it on station. It is a concept in use by civilian mariners aboard MSC ships, and the US Navy is also experimenting with it. It does not appear that rotating crews vice ships to forward deployed stations will save manpower. However, maintaining extra on-station time for each ship can increase mission readiness by achieving greater use of each ship in support of mission requirements. The increased on-station time may offset the increased cost for multiple crews. The operational risk of rotating multiple crews to forward deployed ships may be significant if the configuration of the ship on which individuals train is different from that of the ship they deploy on. Multiple crewing is a policy change that is directed by higher authority and is being used now.

Installing low-maintenance deck materials refers to the employment of advanced materials that are anticorrosive, require little to no cleaning or are self-cleaning, or have any other characteristic that allows for reduced maintenance. Historically, swabbing the deck has been manpower-intensive. Reducing the maintenance and cleaning required on deck should reduce workload substantially and may result in reduced manning. Commercial ships, the Smart Ship/OME, US carriers, the RNN, and DD(X) all employ low-maintenance deck materials for this reason. It is a low-cost option, with zero risk and clear benefits, making it a good choice for implementation.

Human systems integration (Table 8.8) is widely touted as the only way to achieve optimal manning and has now become a requirement for approval in the US acquisition process. For a description of it, see Chapter Seven. HSI does not necessarily reduce the complement but should make it more optimal. The cost would depend on design changes, choice of technologies, and various other factors. It is more likely that HSI will reduce operational risk, not increase it. The technologies involved are easily employed on new platforms. HSI was employed on the LPD-17 during its design as well as on US carriers; it is used throughout the life of a ship in the RNN.

Embedded training refers to an array of equipment, facilities, and trainers moved onto a ship so that training can take place onboard, either in port or while underway. The idea is that by allowing the sailors to train anytime, anywhere, they will be more available because of greater flexibility. For example, a sailor may need to obtain a 20-hour certification. Without embedded trainers, he or she must leave the ship for a five-day period. If the training were available onboard, the sailor could accomplish the training faster and still stay onboard to perform other duties. The costs will vary widely depending on a number of factors. The benefits will be seen largely in areas outside of manpower reduction and more in the area of manpower optimisation and fleetwide efficiencies. Embedded training is currently used on all the US platforms evaluated.

The **core/flex concept** is a policy change that was experimented with onboard the US Navy's Smart Ship, where the vast majority of personnel perform day-work activities, which makes them more productive, and only core teams of personnel stand watch. As the situation dictates, the core watch-standers augment or flex their team with additional personnel to respond to various threat conditions or special evolutions. This low-cost, high-impact policy change can reduce watch-standing requirements and thus manpower.

In **consolidating watches**, watch-stations or duties are combined, resulting in fewer of them. This consolidation is a very effective way of reducing manpower but requires detailed knowledge of the particular ship's systems and functions. Once the knowledge is gathered, an assessment can be made of watch workloads, risk acceptance, and other items, and a high-level decision can be made about where watches could be consolidated. The MSC, the LPD-17, commercial ships, the Smart Ship/OME, US carriers, and the DD(X) use this method to reduce manpower. The operational risk associated with the consolidation of watches is dependent on the individual ship, its missions, and its crew. Use of certain technologies helps to enable consolidated watches, but there is little to no associated technical risk involved. There is minimal to no cost to employ this method, and it could be done very quickly.

Utilising a **civilian crew to augment the ship's crew** is a method that has been considered for certain functions onboard the CVF, such as food service. Often, active duty crewmembers are tasked to perform collateral duties such as food service. These personnel must be trained and only take on these responsibilities for a short period.[6] The advantages in using a civilian crew for some functions are that they man to a civilian standard. Civilian crewmembers can be used to augment a ship's crew to perform nonwarfare responsibilities and can take on such responsibilities more efficiently and cheaply. This low-risk, low-cost, high-impact policy is followed on MSC ships to optimise a ship's complement.

Closed-circuit television for shipwide surveillance and monitoring involves the employment of video cameras, information systems, and television monitors to relay visual images of current situations and activities at various locations onboard. The employment of this network of technologies results in potential reductions in the requirement for watch-standers, damage control personnel, and others. It can also serve to improve communications and increase efficiency of onboard operations. Currently, the LPD-17, the commercial shipping industry, the Smart Ship/OME experiment, and US carriers employ the technology, and it is being considered for the DD(X). Employing the technology will allow for a potential reduction in manpower and (assuming some network infrastructure) would have a minimal cost. The operational risk of employing such technology will vary depending on its specific use and what manpower reductions occur because of it.

Broad skills/cross-trained workforce is a way to avoid the costs of having specialised skills. Specialised skills require specialised training and limit what persons can do onboard. Specialisation is required to a certain level, but having one electrician for a certain piece of engine equipment and another for a different piece of engine equipment can be expensive. The idea is to have one electrician who can work on any piece of engine equipment. This may or may not reduce

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[6] The US Navy has a rotation policy whereby junior personnel perform food service and cleaning responsibilities in a ship's galley and mess decks.

training costs, but having fewer people is cheaper than having more people. Having persons with a wide variety of skills also provides for more flexibility when assigning persons to a ship. The risks are situation dependent but appear to be minimal. The changes would take time to employ because the new training philosophy would have to be established and put into action. The benefits are large enough that the MSC, commercial industry, the Smart Ship/OME, and the RNN currently employ this technique to reduce manpower, and it is being considered by the US Navy for use on the DD(X).

Automated log-keeping is a time-saving policy/procedural change that takes advantage of automated log-keeping devices currently employed on ships. For example, a quartermaster used to have to record every speed change in a ship's deck log, but in recent years a data recorder in marine engineering has automatically recorded the event. Recognition of electronic event recording and a realistic evaluation of the need for deck log entry reduced this log-keeping requirement. Other time-saving innovations to reduce redundancies such as this throughout the ship are being explored in the US Navy's Smart Ship/OME. This procedural change reduces the log-keeping workload on watch-standers at little cost.

Networked internal communications may be one of the most important leverage points for reducing manpower because it enables a number of other efforts to reduce manpower. It is responsible for transmitting data from automated sensors, CCTV, multimodal consoles, an integrated bridge, and the like. Referred to as the SWAN (ship wide area network) by the US Navy, it is employed on many platforms, including all US platforms evaluated here. The largest benefit of the network is improved efficiency that leads to reduced manpower. If the right security measures are taken, the risks can be relatively low. The cost varies by ship, but COTS technologies make these systems relatively inexpensive.

Synthesis

Using the case studies presented in Chapter Seven as a basis, we have identified 57 technically and operationally feasible complement-reduction options of potential relevance to the CVF. Most of those are listed in Table 8.9 by cost impact and complement impact.[7] Other issues such as risk and technological level of readiness are noted.

Many of the options require trade-offs between desirable attributes. For example, because weapons handling will be one of the most manpower-intensive operations on the CVF, we judged automating this function to have a high impact on the ship's complement, i.e., a reduced manpower requirement. However, it is also likely to be a costly innovation—and has not yet reached the prototype stage of development—so its availability for the CVF is not assured. Conversely, many options are inexpensive and ready to implement now but have relatively small manpower impacts (lower right-hand cell in the table).

Establishing a flexible-response damage control team would be a low-cost policy change that should have a relatively high impact on the CVF complement because damage control is also a manpower-intensive operation. Nevertheless, there is some risk to ship safety in relying on a leaner manning concept for a team with such a critical function.

Not all options require balancing pluses and minuses. Some options available now have a medium or high impact on reducing manpower and a low cost, which would incur little risk (see the remaining options listed in the top two cells in the last column of Table 8.9). Of the 12 options meeting those criteria, six are shipwide, which should not be surprising given the broad complement implica-

[7] We were not able to estimate the complement or cost impact for seven options, so those are omitted. The two self-service postal options are combined into one entry in Table 8.9. Thus, there are 49 entries.

Table 8.9
Many Reduction Options Have Low Cost Impact

Complement Impact	Cost Impact: High	Cost Impact: Medium	Cost Impact: Low
High	(Install automated weapons handling)	(Automated damage control[a])	*Flexible-response damage control*[a] *Unmanned machinery spaces* *Consolidate watches* *Core/flex concept* *Civilian crew to supplant* *Broad skills, cross-trained workforce* Use of conveyors for loading stores
Medium		Commercial heating and ventilating Vacuum sewage system *Replace, not repair* *HSI design* Networked internal communications Use of elevators vice conveyors Optimal layout, location of galley, storerooms (Automated inventory, material handling)	Remote sensing of spaces *Preventative maintenance by shore components* Sensor-directed condition-based maintenance CCTV for shipwide monitoring *Contract storeroom loadout* Advanced food service
Low		Reverse-osmosis freshwater system Titanium saltwater piping Integrated condition assessment system Commercial metal and glass processing hardware Multimodal consoles Enclosed mast system	Automated fuel control Incinerators Self-contained breathing apparatus List control system *Consolidate medical/dental* *Routine dental ashore* Use remote specialists Anticorrosive coatings *Reliability-centred maintenance* *Privatise preservation work* Automated log-keeping Smart Card/cashless ship *Move administrative personnel to shore* Self-service postal Information technology to reduce administrative work/log workload Integrated bridge system *Combine signalman and quartermaster* Install low-maintenance deck materials Anchor chain washdown

[a] Medium or high risk (otherwise low).
( ) = No operational system yet (prototype or earlier stage).
Italics = policy, procedural, or design measure (vice technological).

tions of shipwide options. Three of the options involve alternative ways of employing manpower: consolidated watches, the core/flex concept, and substitution of civilians for the ship's crewmembers. For example, the core/flex concept, pioneered by the US Navy's Smart Ship programme, resulted in a greatly reduced number of watch-standers and made a greater number of the ship's company 'day workers'. As such, the company could more effectively train on and maintain their equipment, as well as flexibly augment the watch-team as conditions required.[8]

It is noteworthy that seven of the 12 most attractive options are for such policy or procedural measures (e.g., maintaining unmanned machinery spaces) rather than technological insertions, which are typically more costly. In fact, of all the options on our list, policy and procedural options would be responsible for the largest reductions in manpower.[9] Realising the full impact of some of these procedural measures, however, requires supporting-technology upgrades. The converse is even more often the case: The benefits of technology insertions will often not be fully realised if accompanying policy or procedural changes are not made. For example, the installation of an integrated bridge can support reduced bridge watch-standers—if reduced watch-standing is authorised. The IPT should carefully evaluate policy and procedural changes to capture manpower savings. These changes may mitigate technological, design, and fiscal challenges that may arise in achieving further manpower reductions.

There are other reasons why the evaluations summarised in Table 8.9 should be interpreted with some caution. In some cases, the cost depends heavily on the platform, on whether COTS technologies are used, on how much training is provided, and so on. The absolute effect on the crew is also variable for some of the options:

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[8] Even such broadly desirable options can have their subtle drawbacks. The US Navy has been giving increased responsibility to enlisted watch-standers on the bridge (such as the officer of the deck) and in engineering (engineering officer of the watch). These watches have traditionally been stood by officers. Because enlisted watch-standers are less costly, this approach saves money, but it blurs divisions of authority and responsibility typically maintained between officers and enlisted personnel and runs counter to culture and tradition.

[9] This conclusion was derived from literature and conversations with manpower experts.

The larger the crew, the more potential for reductions. Finally, if an option has the potential of removing crewmembers, whether that potential is realised depends on the ability of the remaining crew to absorb the affected crewmembers' workload that is not associated with the option.

While the 12 most broadly desirable options should obviously get the most attention, there are also some promising options at a somewhat higher cost (central cell in table). For example, if the ship is designed with a single centralised galley and dining facilities are placed adjacent to it, the Royal Navy will realise gains in cost, space, weight, and manpower. The installation of elevators for transfer of palletised stores between decks can eliminate the need for large working parties to support stores on-load. Neither should the list of low-impact options at low cost be ignored. Small decrements in the complement can add up.

There are thus many complement-reduction options tested or planned for testing on other platforms that might contribute to attempts to meet the CVF's target complement. We cannot say at this time which of these options should be employed on the CVF, i.e., which would return a complement-reduction benefit commensurate with any additional costs incurred through its adoption. The ship's design is not yet mature enough for such an estimate, and we do not have specific enough data on the design or on manning plans in their current state. We cannot say whether adoption of these options would help CVF designers approach, meet, or even exceed the complement-reduction target. We do not know on what assumptions the target rests and whether those assumptions already include the adoption of some or many of the options identified here. Table 8.9, however, should provide a useful checklist for later review.

Reasons for Optimism About Complement Reduction

Given the great increase in ship size over the CVS class, the CVF complement target of 605 is aggressive, even revolutionary. Given the dearth of hard data, we cannot be confident that that goal is feasible, but there are reasons for optimism that the IPT's aggressive approach will succeed:

- There is strong fiscal motivation for the United Kingdom, as with other countries, to reduce the WLCs of its ships. Since manpower costs are the largest component of a ship's operating and support costs, reducing crew will produce great savings over a 35- to 40-year ship life.
- The Royal Navy and the CVF CPCs have made reducing the complement an important goal of ship design and planning efforts. HSI initiatives being implemented should support the achievement of that goal. Coordination between the complementing and design group is ongoing.
- Because the CVF design is not yet complete, there remains room for further design improvements to incorporate complement-reduction measures, particularly those relying on technology. And even a mature design could still benefit from policy and procedural changes, as has been demonstrated with the case studies examined.
- Operating and personnel policies will continue to evolve and support reduced crewing through sailor multifunctionality. Ideally, any sailor could perform any function on the ship. That is not likely, but increased flexibility to use more broadly trained sailors for multiple functions can be gained by grouping like skills, as the Royal Navy is doing by combining 33 ratings into 17. A senior, more experienced, and more interchangeable crew could lead to manpower savings. It does not appear, though, that such a crew will be an immediate high priority, but fiscal realities and technological changes are pushing the Royal Navy in that direction.
- Finally, technology is evolving and will be increasingly relied on. The reluctance to change from older methods of performing manpower-intensive work will eventually give way to the competitive advantages that technology brings. As the reliability of a technology is proven, the confidence of the Royal Navy and the CVF's company will follow. As this occurs, increased reliance on technology will likely result. In the end, the increased use of technology will result in manpower savings.

Challenges Remaining

If the target complement reduction is to be achieved or exceeded, it is also important that the challenges to doing so be clearly understood so they can be met. We see four principal challenges.

First, CPC design and Royal Navy manning authorities conveyed to us that the CVF would be engineered with a significant percentage of legacy equipment. Therefore, even if additional technology insertions or policy and procedural changes were implemented, only minor changes might result in the CVF complement. That said, outfitting the CVF with legacy equipment does not necessarily mean that the ship has to be complemented with a legacy-sized crew. The US Navy's OME provided evidence that policy and procedural changes can downsize a crew without significant equipment change. It must be kept in mind, however, that the OME was conducted on a cruiser and a destroyer, ships differing greatly in size, mission, and capability from the CVF.

Second, while policy and procedural changes can be powerful, they are also the most difficult and time consuming to make. Although there are few hard or direct costs associated with these changes, the cost of the time of the individuals it takes to put changes into action could be substantial. Institutional inertia may have to be overcome if a commitment is to be made to expend that kind of time and effort, especially if the change in question challenges the prevailing culture.

Third, as is the case for costs in general, initial complement projections for new classes of ships have historically proven to be optimistic. The complement tends to increase during design, when optimistic generalities from the concept stage must meet the specific realities of a ship coming into shape, although the true reason for in-design complement creep is unknown. Further, missions often change for ships in service, and that usually translates into more manpower, not less.

Finally, it is unclear to what extent operational commanders will be prepared to accept the additional risk inherent in a smaller complement. Commanders now enjoy the luxury of a large crew when faced with challenging operational issues. A reduced crew size has the potential for limiting the missions a ship may perform and the tasks and functions that may be undertaken simultaneously. Complementing planners for the CVF must consider the effect of complement-reducing measures on the operational commander. This will not be easy. Manning a large ship like the CVF with only 605 officers and sailors takes the Royal Navy into uncharted waters. This complement size presents many unknowns that will be clarified as the ship goes into service. However, the following questions might serve to structure the problem:

- How does each complement-reducing measure limit the commander's options?
- What happens if the technology fails? Is there a backup system to replace it? Is it reliable? Are personnel trained on the backup system?
- What is the total risk that an operational commander assumes in running a ship with an optimum complement?[10]
- What happens if a ship experiences major fires or flooding or battle damage? Is the crew trained and of sufficient size to recover from the casualties and carry on to fight?

The Way Forward

When we began this analysis, we had hoped to provide a strategic roadmap offering guidance as to how to get from a recommended list of options to implementation of those options. Given that the design was still in the assessment phase, such a road map is not feasible at this point. However, we conclude by offering some general observations as to how to proceed—in the face of uncertainty—to better define complement-reduction options and push them closer to realisation.

Manning Tradition and Personnel Policy. First, our research indicates that some Royal Navy manning requirements survive because of custom and tradition. The cultural, traditional, and

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[10] An *optimum complement* can be defined as that which has sufficient, but not excessive, appropriately qualified manpower to achieve the user requirements (Thales Naval, 2002a).

doctrinal paradigm of heavy manning must be challenged to achieve manpower reductions. A manning profile based on a set of inherited, unchallenged heuristics will not likely produce an optimal complement.

At the same time, it is important to consider the effects of personnel changes beyond the ship. Personnel policies have been formed using a pyramidal structure of manpower. In this structure, a large base of personnel enters the workforce and through promotion and attrition, either moves up or out. The CVF IPT must consider what would happen to other components of the Navy if a different manning system were employed on the CVF. Can the CVF complement depart from the Royal Navy personnel model, or should the two be consistent? Will the CVF's optimal complement be a new model for manpower policies, or will the complement need to depart from the optimum because prevailing manpower policies are judged the most cost-effective for the Royal Navy overall?

Complement Reduction During Design. The emphasis so far placed on complement reduction as a priority in design should continue. After a ship has been designed, it becomes more difficult and thus costly to gain efficiencies through technology insertion. Of course, manpower-reducing technologies are not restricted to large, complex shipwide systems; at times, they might be as simple as a software enhancement.

To take advantage of more ambitious technology insertions, however, a flexible CVF design allowing for easy insertion could be beneficial. The use of upgradeable COTS equipment will assist in reducing obsolescence, will be less disruptive than backfitting, and will help keep the CVF on the leading edge of technological innovation. Such utilisation can be maximised if the MOD continuously evaluates technological innovations available in construction for private-sector clients and their integration with other CVF systems. Of course, technology insertion will be dependent on the availability of up-front investment funds. As long as such funds are uncertain, it will always be necessary to keep a backfit option in reserve.

In the near term and during the design stage, we recommend continued, even expanded, use of HSI, which could lead to greater efficiencies in design. A useful example to follow is the LPD-17 HSI programme, through which operators (sailors) were brought into the design process. They evaluated the design being considered and provided more than 1,200 recommendations to the LPD-17 design team on how equipment could or should be designed and located to aid the ease of operation, maintenance, and support.

Targets and Synergies. In deciding which technologies and which policy and procedural changes to push for, the MOD should look first to big targets, e.g., those that reduce or eliminate personnel required to support manpower-intensive shipwide evolutions (with due consideration of assumed risks). These evolutions include weapons handling, damage control, and stores on-loads. Investments in technology that reduce these and other major manpower drivers, when combined with supporting policy and procedural changes, can have the largest impact in reducing manpower requirements across the CVF's quarter bill.

The Alliance should retain an appreciation for the synergies and secondary effects attending manpower-reducing measures it considers. As personnel requirements for the major manpower drivers are reduced, remaining quarter bill personnel requirements should be reevaluated. The Alliance can also gain by following an integrated approach by selecting design or technology options that are not fiscally challenging and combining them with policy and procedural changes to capture the full potential savings from the investment.

Crew and Equipment. The limits of the crew and of the ship and equipment must be firmly established and understood. Battle damage scenarios that include damage to automated systems should be evaluated to analyse the full response of the crew using newly installed technology as well as backup systems.

A workforce that has developed broad skills and has been cross-trained opens up many options for the CVF's complement. A senior, experienced force presents a best-case option because it can perform many functions on the ship. As systems become more complicated, training requirements for operators and maintainers tend to increase. Technologies that can be used to support a broadly trained workforce include systems being designed so as not to require subject-matter experts to operate, maintain, and troubleshoot. In addition, embedded and logical training systems that allow ease of operation, maintenance, and troubleshooting are needed. Embedded training systems keep personnel onboard and allow them to train on the system that they will operate. An optimised complement requires increased skills and versatility on the part of all crewmembers. Focused efforts in the design and procurement of systems that support ease of training, operation, and maintenance will be a worthy investment.

As mentioned above, the CVF is being designed with a significant percentage of legacy equipment. In the past, legacy equipment has been 'stovepiped' to some degree, i.e., developed and supported in isolation, which has led to the need for 'legacy manning', or manning by personnel specialising in that equipment alone. Reducing the manning associated with legacy equipment requires that stovepiping of legacy equipment be reduced, which will support ease of operation, training, maintenance, and other support functions.

In conclusion, most options set forth herein (technology, policy and procedural, or design) are available for implementation now, are of low operational risk, show promise for reducing or optimising manpower, and are of a relatively low cost. What is required, however, is implementation.

Summary

We identified 57 feasible complement-reduction options of potential relevance to the CVF. Of those, we judged 12 to require low investment and upkeep costs, to incur low risk to the ship in the event of failure, to be ready for implementation now, and to have moderate to high potential for complement reduction. The 12 are as follows:

- Leaving machinery spaces unmanned, a policy change facilitated by technologies such as remote sensing of spaces (see below)
- Consolidating watches, i.e., combining watch-stations or duties so that fewer watch-standers are needed
- Employing a core/flex manning concept

- Using civilians to augment the ship's crew for nonwarfare responsibilities such as food service
- Emphasising broad skills and a cross-trained workforce, so that a smaller crew could perform the same number of activities
- Using conveyors to aid crewmembers in loading stores from the shore to the ship
- Implementing remote sensing of spaces to monitor liquid levels, smoke, heat, pressure, and noise
- Moving preventive-maintenance personnel ashore and having them perform their duties when the ship is in port
- Relying on sensor-directed, condition-based maintenance, so that maintenance is undertaken only when sensors indicate that equipment status is approaching the problematic
- Installing CCTV cameras and monitors to relay visual images of current situations and activities at various locations onboard
- Contracting storeroom loadout, i.e., hiring a private company in port to load and unload stores
- Making food services more efficient by employing flash-freezing and -heating, standardised menus, etc.

We judged the first six of these to be particularly promising. Those not listed here should also be seriously considered, although they involve higher costs or lower manpower impacts and, in a few cases, greater risks or lower technological maturity.

Some of the options we have identified may already be assumed in the target complement estimate devised for the CVF. We did not have enough information to determine that and thus do not know whether the target is optimistic or conservative. There are reasons, though, to believe that the target will be reached:

- There is strong fiscal motivation to realise savings.
- Complement reduction is a key CVF design goal.
- The immaturity of the design may allow for further savings.
- Operating and personnel policies will continue evolving towards sailor multifunctionality.

- As new technologies prove their worth, old manpower-intensive approaches to tasks will fall away.

Initial complement targets have historically proved to be optimistic, however, and progress towards the complement-reduction goal could be complicated by some remaining challenges. The latter reasons include the legacy equipment problem and the possible reluctance of operational commanders to accept dramatically reduced crews. Also, many complement-reducing options are not technological but procedural, and efforts to implement such changes can encounter institutional resistance.

We conclude by offering some general observations as to how to proceed—in the face of uncertainty—to better define complement-reduction options and push them closer to realisation:

- It is important to consider the implications of a revolutionary CVF complement for the Royal Navy personnel structure.
- The emphasis on complement reduction and HSI needs to continue during CVF design. Designers should also seek to build in the flexibility to make future manpower reductions, e.g., through the use of easily upgradeable COTS systems.
- Designers and complement planners should focus on manpower-intensive activities for possible reductions while looking for possible synergies or secondary effects such reductions might have on the complement.
- A premium should be placed on designing or selecting systems that do not require highly specialised personnel to operate and on embedding training opportunities onboard.

APPENDIX

Evaluation of Candidate Options, by Department

Table A.1
Evaluation of Candidate Options, by Department

Department/ Candidate Options	Risk	TLOR[a]	Benefit	Comple-ment Impact	Cost Impact	MSC	LPD-17	Commer-cial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Damage Control												
Use of self-contained breathing apparatus	Low	4	Great efficiency	L	L	X	X	X	X			
Remote sensing of spaces	Low	4	Reduced workload	M	L		X	X	X	X	X	X
Flex response damage control team	Medium	Policy	Reduced workload	H	L				X			
Automatically finding an alternative path when system has a failure	Medium	1	Reduced comple-ment	U	H						X	
Automatic isolation of damaged paths from the rest of the distribution network	Medium	1	Reduced comple-ment	U	H						X	X
Automatic deactivation of damaged system compo-nents	Medium	1	Reduced comple-ment	U	U						X	X
Automated damage con-trol	High	1–4	Reduced comple-ment	H	M		X	X	X	X	X	X
Marine Engineering												
Unmanned machinery spaces	Low	Policy	Reduced comple-ment	H	L			X	X		X	
Titanium saltwater piping	Low	4	Reduced mainte-nance	L	M		X		X			
Reverse-osmosis fresh-water system	Low	4	Reduced cost	L	M		X					

Table A.1—Continued

Department/ Candidate Options	Risk	TLOR[a]	Benefit	Comple-ment Impact	Cost Impact	MSC	LPD-17	Commer-cial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Preventive maintenance by shore establishment	Low	Policy	Reduced workload	M	L				X			
List control system	Low	4	Reduced workload	L	L		X			X		
Integrated condition assessment system	Low	4	Reduced workload	L	M		X		X			
Commercial heating and ventilating systems	Low	4	Reduced complement Reduced cost	M	M			X				
Automated fuel control	Low	4	Reduced workload	L	L			X	X	X		X
All electric auxiliaries	Low	4	Greater efficiency Reduced mainte-nance	M	U		X			X		X
Sewage												
Vacuum sewage system	Low	4	Greater efficiency	M	M			X				
Incinerators	Low	4	Greater efficiency	L	L			X	X			
Commercial metal and glass processing hardware	Low	4	Greater efficiency	L	M			X				
Medical/Dental												
Routine dental ashore	Low	Policy	Reduced workload	L	L					X		
Consolidate medical/ dental	Low	Policy	Reduced comple-ment	L	L					X		
Shipwide												
Use remote specialists via video technology	Low	4	Reduced comple-ment	L	L	X	X		X			
Use of VHF handheld radios	Low	4	Greater efficiency	L	L	X	X	X	X	X		X

Table A.1—Continued

Department/ Candidate Options	Risk	TLOR[a]	Benefit	Complement Impact	Cost Impact	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Use of anticorrosive coatings	Low	4	Reduced maintenance	L	L		X	X	X	X		X
Total ship training system	Low	4	Greater complement availability	U	U		X		X			
Sensor-directed condition-based maintenance	Low	4	Reduced maintenance	M	L	X			X	X		X
Replace, not repair	Low	Policy	Reduced maintenance onboard	M	M							X
Reliability-centred maintenance	Low	Policy	Reduced maintenance	L	L	X	X		X			X
Privatise preservation work	Low	Policy	Reduced in-port workload	L	L			X	X			X
Multiple crews	Low	Policy	Optimised platform use	U	M	X						
Install low maintenance deck materials	Low	4	Reduced maintenance	L	L			X	X	X	X	X
HIS design	Low	Policy	Reduced complement	M	M		X			X	X	X
Embedded training	Low	4	Greater complement availability	U	U		X		X	X		X
Core/flex concept	Low	Policy	Reduced complement	H	L		X		X		X	X
Consolidate watches	Low	Policy	Reduced complement	H	L	X	X	X	X	X		X
Civilian crew to supplant ship's crew	Low	Policy	Reduced complement	H	L	X						
CCTV for shipwide surveillance and monitoring	Low	4	Reduced complement	M	L		X	X	X	X		X

Table A.1—Continued

Department/ Candidate Options	Risk	TLOR[a]	Benefit	Comple- ment Impact	Cost Impact	MSC	LPD-17	Commer- cial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Broad skills, cross-trained workforce	Low	Policy	Reduced comple- ment	H	L	X		X	X		X	X
Automated log-keeping	Low	4	Reduced comple- ment	L	L							
Networked internal com- munications	Low	4	Greater efficiency	M	M		X		X	X		X
Supply/Admin												
Use of elevators vice package conveyors	Low	4	Reduced workload	M	M	X	X					
Smart Card cashless ship/ automated vending	Low	4	Reduced comple- ment	L	L	X	X		X	X		
Optimising layout, loca- tion of galley, and store- rooms	Low	4	Reduced comple- ment	M	M	X	X			X		
Administrative functions and personnel to shore	Low	Policy	Reduced comple- ment	L	L	X	X		X	X		
Self-service stamp machine	Low	4	Reduced comple- ment	L	L	X			X			
Self-service postal meter	Low	4	Reduced comple- ment	L	L	X			X			
Information technologies to reduce log/admin work- load	Low	4	Reduced comple- ment	L	L	X	X		X	X		
Contract storeroom load- out	Low	Policy	Reduced workload	M	L		X			X	X	
Automated inventory and material handling systems	Low	4	Reduced workload	M	M					X		

Table A.1—Continued

Department/ Candidate Options	Risk	TLOR[a]	Benefit	Complement Impact	Cost Impact	MSC	LPD-17	Commercial	Smart Ship/ OME	US Carriers	RNN	DD(X)
Warfare												
Multimodal consoles	Low	4	Reduced complement	L	M		X					X
Enclosed mast system	Low	4	Improved performance Reduced maintenance	L	M		X					X
Integrated bridge system	Low	4	Reduced complement	L	L	X	X	X	X		X	
Combined signalman and quartermaster rates	Low	Policy	Reduced complement	L	L				X	X		
Automated log-keeping	Low	4	Reduced complement	L	L		X					
Deck/Air												
Use of a conveyor to load stores from main deck to the stores deck	Low	4	Reduced workload	H	L	X	X			X		
Anchor chain washdown	Low	4	Reduced workload	L	L		X					
Weapons Engineering												
Installed automated weapons handling	Low	2	Reduced complement	H	H					X		

[a]Technical Level of Readiness.

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