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ACQUISITION RESEARCH SPONSORED REPORT SERIES

The Impact of Maintenance Free Operating Period Approach to Acquisition Approaches, System Sustainment, and Costs

7 January 2013

by

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PEO IWS

Naval Postgraduate Schools

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Abstract

Current acquisitions, logistics, and system sustainment practices in the U.S. Navy are not fully capitalizing on commercial-sector best practices. In addition, the Navy does not have a consistent approach to system maintenance and sustainment. Could the maintenance free operating period (MFOP) approach be a game changer? This paper evaluates the potential impact of MFOP principles on processes, procedures, and costs in acquisition planning. It investigates MFOP and reviews the results of a 2005 submarine pilot program and the 2009 surface ship demonstration involving the concept.

Keywords: Maintenance free operating period, MFOP, acquisition planning, open architecture, business model, integrated logistics support

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About the Authors

Thomas J. Housel is a professor of information sciences at the Naval Postgraduate School. Housel specializes in valuing intellectual capital, knowledge management, telecommunications, information technology, value-based business process re-engineering, and knowledge value measurement in profit and non-profit organizations. His current research focuses on the use of knowledge value added (KVA) and real options models in identifying, valuing, maintaining, and exercising options in military decision-making. His work on measuring the value of intellectual capital has been featured in a *Fortune* cover story (October 3, 1994) and *Investor's Business Daily*, numerous books, professional periodicals, and academic journals (most recently in the *Journal of Intellectual Capital*, 2005).

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I. Introduction

The U.S. Navy has been transforming traditional business practices through the adoption of open architecture (OA) and commercial off-the-shelf (COTS) technologies. Billions of dollars in software and hardware development expenditures, along with subsequent maintenance costs, are at stake with the migration to an OA business model. The adoption of an enterprise-wide business model and product line strategy that leverages “open” computer design principles and architectures to deliver cost-effective, innovative, and rapid/spiral acquisition capabilities has resulted in a number of significant benefits to the Navy.

The OA business model, however, has not permeated into current acquisition approaches and system sustainment practices. Moreover, the naval enterprise does not employ a consistent approach to system maintenance and sustainment. Could the maintenance free operating period (MFOP) approach be a game changer in the acquisitions, logistics, and system sustainment processes? Could the MFOP help achieve significant cost reductions while providing dramatic operational improvement?

MFOP is defined as a period of operation during which an aircraft is able to carry out its assigned missions without the need for any maintenance except pre-defined flight servicing and role change activities. It is a period with no required, emergency, or unexpected maintenance. Following each MFOP is a maintenance recovery period (MRP) in which maintenance is done to ensure that the system is recovered to complete the next MFOP cycle. The MFOP concept could be applied in system maintenance, logistics, acquisitions, and sustainment practices.

A research team from the Naval Postgraduate School (NPS) investigated the MFOP concept and analyzed the initial 2005 submarine MFOP pilot and the subsequent 2009 surface ship demonstration. The goal of this project was to assist the Navy in understanding the potential impact of MFOP principles on processes, procedures, and costs in acquisition planning. The scope of the research was to compare the efficacy of the MFOP and traditional integrated logistics support (ILS) life-cycle methods and to potentially quantify relative cost performance from the two demonstrations. However, there were several limitations to this study. First, secondary research methodologies were primarily used and data on the MFOP projects was to be supplied by the sponsor.

In this paper, we present the results of the project. The paper begins with background information on the acquisitions process in the U.S. Section III provides an introduction to integrated logistics support. In Section IV, we then highlight some of the significant challenges for the Department of Defense (DoD) and the Department of the Navy (DoN) such as reduced budgets, escalating shipbuilding costs, and soaring life-cycle costs. In Section V, we discuss Naval Open Architecture and its successor, open systems architecture. In Section VI, we introduce the concept of the MFOP. In this section, we discuss the introduction of the MFOP in the late 1990s, potential applications, potential benefits, and applications of the MFOP in several projects. In Section VII, we discuss the MFOP pilot and demonstration by the DoN that exceeded initial expectations. In Section VIII, we summarize some of the MFOP models that have been developed over the years. In this section, we also summarize some of the diverse efforts to quantify and develop MFOP models. Project conclusions are in the final section.

II. Defense Acquisitions

The United States has the largest national defense budget in the world. In 2007, the defense budget was $660 billion and equivalent to the next 45 highest spending nations combined (Gray, 2009, p. 212). Figure 1 shows the national defense expenditures in 14 countries.

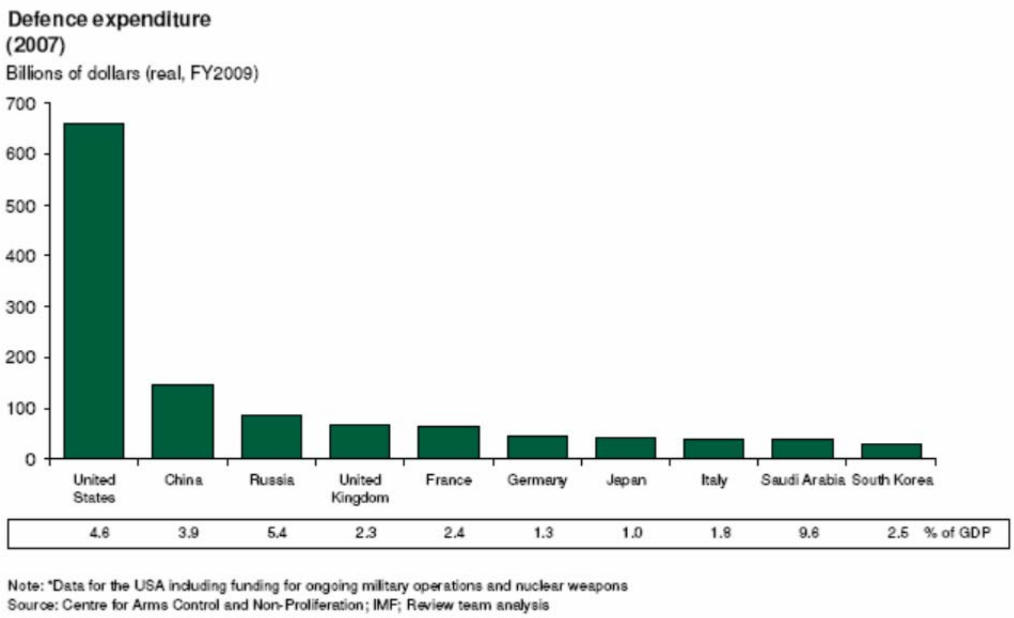

Figure 1. Defense Expenditure for the Top Fourteen Countries (2007)
(Gray, 2009, p. 213)

U.S. expenditures on defense represented 4.6% of national gross domestic product (GDP), followed by South Korea, France, and the UK, as shown in Figure 2.

Country	Military expenditure (2007*)		Equipment expenditure (2007*)	
	$bn*	% of GDP	$bn**	% of Defence spending
UK	66	2.3%	15^	23%
USA	66	4.6%	171	26%
France	63	2.4%	14	21%
Germany	44	1.3%	6	15%
Japan	43	1.0%	7	17%
South Korea^^^	28	2.5%	9	33%
Canada	16	1.1%	2	15%
Australia	15	1.5%	3	18%

Figure 2. Defense Spending as a Percentage of GDP
(Gray, 2009, p. 214.)

Note. * Fiscal year (FY) in which most months fall in 2007. Australia is average of 2006/2007 and 2007/2008, corresponding to calendar year;
** Real U.S. FY2009;
*** Based on publically available project data (i.e., 96 U.S. projects, 30 Australia projects, 37 Japan projects);
^ For consistency of sources, NATO figures are used. ^^ 2008 figure; ^^^ 2006 figure.

Acquisitions in the United States are a result of a complex process involving many organizations. In the past, procurement has been performed by the individual services, and the trend in recent years has been a movement to joint capabilities integration and development.[1] The Joint Requirements Oversight Council (JROC) reviews programs while the Functional Capabilities Board (FCB) assesses capabilities gaps and proposals. Overseeing defense acquisitions across various organizations is the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]). Working directly with suppliers, selecting contractors, writing contracts, and monitoring contractors' performance is the Defense Contract Management Agency (DCMA). Logistics support is provided by the Defense Logistics Agency (DLA; Gray, 2009, p. 216).

[1] Discussion of the U.S. acquisitions process as of 2009.

The procurement process is divided into several phases: Capabilities Assessment; Materiel Solution Analysis; Technology Development; Integrated System Design: System Capability and Manufacturing Process Demonstration; and Production & Deployment (Gray, 2009, p. 216). Figure 3 is an overview of the acquisitions process. Transitions from phases are decided by a materiel development decision (MDD) review, milestone review, or design review.

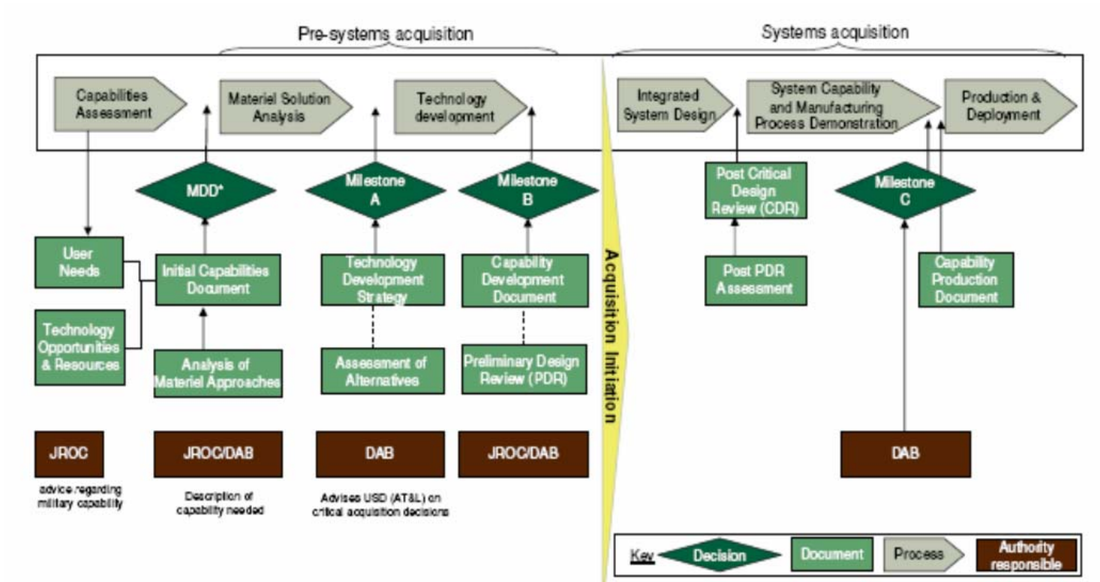

Figure 3. Overview of the Acquisition Process
(Gray, 2009, p. 217)

The DoD must make acquisitions that are of high quality, reliable, maintainable, and readily available to meet user needs. End-user needs consist of meeting mission capability and operational tasks at reasonable costs. Moreover, these costs are not just initial procurement costs but must extend throughout the entire system life cycle to include factors such as maintenance (Office of the Secretary of Defense & the Joint Staff, 2009, p. vii). In 2009, the USD(AT&L) issued new reliability, availability, and maintainability (RAM) guidance in DoD Instruction (DoDI) 5000.02. The guidance implemented RAM practices to ensure successful collaboration between procurement and the acquisition communities in the establishment of RAM requirements. Reliability and maintainability are critical issues during program acquisition phases because there is the “risk that programs will breach Acquisition Program Baseline thresholds with significantly higher development or acquisition costs due to resulting corrective action costs; will cost more than anticipated to own and operate; or will fail to provide availability expected by the warfighter” (Office of the Secretary of Defense & the Joint Staff, 2009, p. 1).

Figure 4 shows the significant reliability, availability, and maintainability cost (RAM-C) activities conducted during the life cycle. In addition, the stakeholder primarily responsible for that activity is also shown.

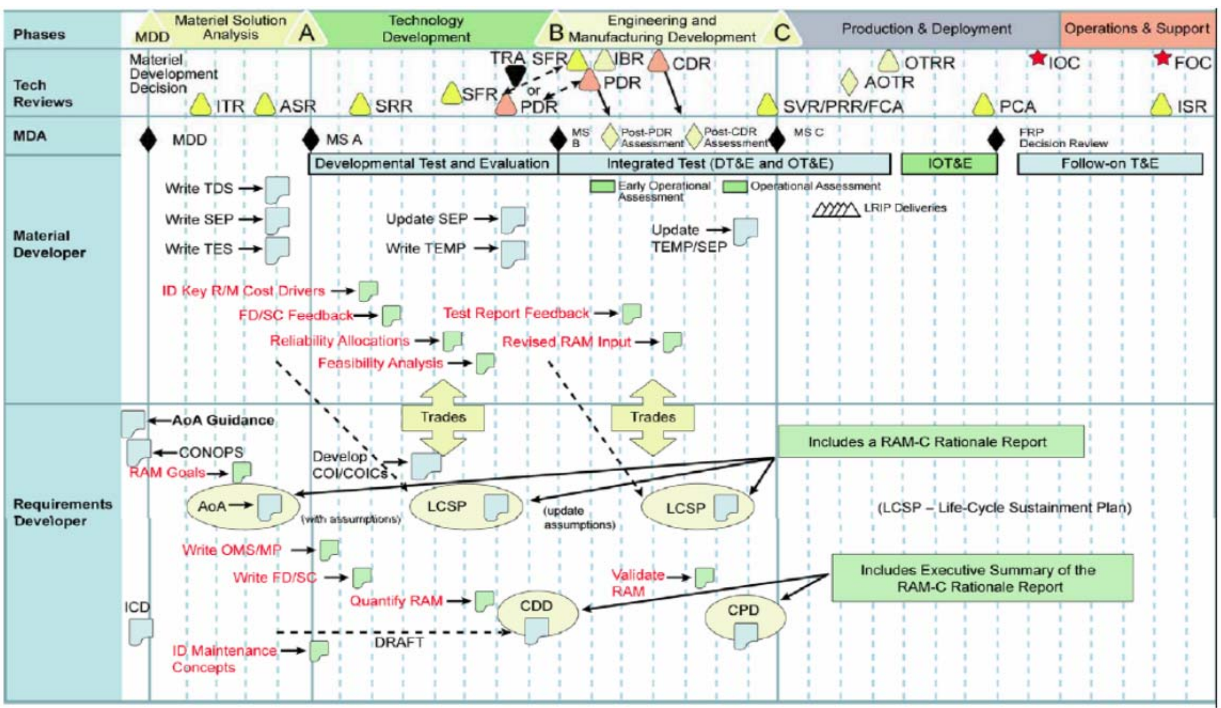

Figure 4. Reliability, Availability, Maintainability Cost (RAM-C) Activities Throughout the Life Cycle

(Office of the Secretary of Defense & the Joint Staff, 2009, p. 7)

Table 1 provides program phase-level activities related to sustainment requirements and measures.

Table 1. Sustainment Requirements and Measures by Phase
(Office of the Secretary of Defense & the Joint Staff, 2009, p. vii)

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
Availability Materiel Availability (A_M) Operational Availability (A_O) (KPP)	A	Comparative Analysis with Legacy Systems and/or Engineering Assessment	Program Manager (PM) or Program Sponsor if PM Not Assigned	Pre-Alternative System Review (ASR) for All Candidate Systems Post-ASR for Preferred System Selected	$\frac{\text{(number of operational end items)}}{\text{(total number of end items acquired)}}$ or $\frac{\text{uptime}}{\text{uptime + downtime}}$ Value is "as planned" given the expected system use and support concept.
	B	Demonstrated through Testing Plus Modeling/ Simulation Where Needed	Test and Evaluation Activity	During DT and Early Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise MDT* modeled from MTTR, LDT, and ADT values MDT estimates from early in program; Replaced by data as available
	C	Demonstrated through Testing and Analysis of Early Fielded System Performance	Test and Evaluation Activity and Program Manager	During DT, DT/OT, and Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise MDT* modeled from MTTR, LDT, and ADT values
	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout Remainder of System Life Cycle	$\frac{\text{(number of operational end items)}}{\text{(total number of end items acquired)}}$ or $\frac{\text{uptime}}{\text{uptime + downtime}}$

Note. MDT = MTTR + mean ADT + mean LDT.

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
Ownership Cost (OC) (KSA)	A	Comparative Analysis with Legacy Systems or Documented Analysis when Legacy Systems Unavailable	Program Manager or Program Sponsor if PM Not Assigned	Pre-ASR for All Candidate Systems Post-ASR for Preferred System Selected	Initial, rough approximation based on projected energy and maintenance costs for assumed inventory and operating tempos and "placeholders" for Sustaining Support and Continuing System Improvements
	B	Results of Prototype Testing; Projected Requirements for Sustaining Support and Continuing System Improvements As Described in the Cost Analysis Requirements Description (CARD)	Program Manager with Inputs from Test and Evaluation Activity and Contractors	During DT and EUT	For energy and maintenance, refined estimate based on demonstrated results in testing. Estimates for Sustaining Support and Continuing System Improvements, as described in the CARD, are refined based on analysis of test results and similar, legacy systems.
	C	Results of Prototype Testing During EMD; Approved Sustainment Plan, As Described in the CARD.	Program Manager with Inputs from Test and Evaluation Activity and Contractors	During DT, DT/OT, and LUT/ Operational Assessment	Further refined estimates for all four OC elements, based on EMD test results and validated requirements for Sustaining Support and Continuing System Improvements
	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout the Remainder of System Life Cycle	Updates based on actual energy consumption, maintenance, Sustaining Support and Continuing System Improvements costs.

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
Reliability (R_M) (KSA)	A	Comparative Analysis with Legacy Systems and/or Engineering Analysis	Program Manager or Program Sponsor if PM Not Assigned	Pre-ASR for All Candidate Systems Post-ASR for Preferred System Selected	MTBF/MTBM derived from warfighter's stated needs and translated into contract-level testable values.
	B	Demonstrated through Testing, Analysis, and Modeling/ Simulation	Test and Evaluation Activity	During DT and Early Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise
	C	Demonstrated through Testing, Analysis, Modeling/ Simulation, and Analysis of Early Fielded System Performance	Test and Evaluation Activity and Program Manager	During DT, DT/OT, and Operational Assessments	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise
	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout the Remainder of System Life Cycle	Scored failure rate per FD/SC MTBF if all failures classified as critical and MTBM otherwise

Metric	Milestone	How Measured	Responsible Activity	When Measured	Program Phase Metric
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	FRP and beyond	Demonstrated through Analysis of Fielded System Performance	OTA and Program Manager	During IOT and throughout the Remainder of System Life Cycle	Updates based on actual energy consumption, maintenance, Sustaining Support and Continuing System Improvements costs.

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III. Integrated Logistics Support

The DoD spends more than $200 billion a year to provide the Navy, Air Force, Army, Marine Corps, and other federal agencies with the full spectrum of logistics, acquisition, and other services. The DoD's DLA currently manages nine supply chains with five million items and supports more than 2,210 weapon systems, along with processing an average of 109,751 requisitions and more than 8,985 contracts per day. In the private sector, the agency would rank in the Fortune 500 top 10% of companies.

In FY2010, the DLA spent $210 billion on maintenance, supply, and transportation, as shown in Figure 5.

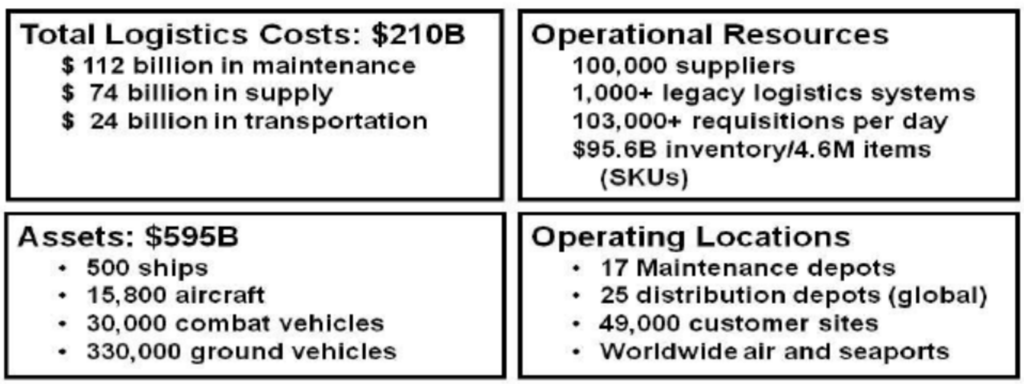

Figure 5. DoD's Logistics Operations (FY2010)
(Defense Business Board, 2011)

A. Integrated Logistics Support

For the DoN, *ILS* is defined as a composite of all support considerations necessary to ensure effective and economical support for the life cycle of ships, systems, and equipment. ILS's fundamental objective is to provide life cycle support.

In this broad context, ILS is a disciplined, unified, and interactive approach for the management of technical activities necessary to:

- develop support requirements consistent with the design and other requirements,
- integrate these considerations into the design, and
- provide the required support during the system or equipment life cycle at minimum cost.

ILS incorporates the following elements:

- Maintenance planning—process conducted to establish maintenance and support concepts and requirements for the defense system lifetime. The description of requirements and tasks for achieving, restoring, or maintaining the operational capability of a system, equipment, or facility is in the maintenance plan. The plan contains the performance requirements for each level of maintenance and lists all maintenance requirements.
- Manpower and personnel—people required to operate and support the system over its planned life cycle. Manpower and personnel analysis is the process conducted to identify and acquire military and civilian personnel with the skills and grades required to operate and support the system over its planned lifetime at both peacetime and wartime rates.
- Supply support—ensures spares (hardware, components, and computer programs) and repair parts required to operate and maintain a system provided on a timely basis. Hardware supply support consists of a provisioning phase followed by routine replenishment, and software supply support must include software and firmware cataloging and provisions for routine re-supply of media (e.g., magnetic tapes).
- Support and test equipment—all equipment (mobile or fixed) required to support the operation and maintenance of a materiel system. Support equipment consists of ground handling and maintenance equipment. Also includes acquisition of logistics support for support equipment.
- Technical data—all recorded information such as manuals and drawings of a scientific or technical nature. Plans include strategy, procedures, and schedules for identifying, specifying, preparing, collecting, publishing, distributing, updating, and archiving technical data related to the end item.
- Training and training support—processes, procedures, curricula, techniques, training devices, simulators, and equipment necessary to

train civilian and military personnel to operate and support equipment and systems. Logistics support must also be provided for the installation, operation, and support of devices for required training equipment.

- Computer resources support—includes the facilities, hardware, software, documentation, and manpower and personnel needed to operate and support embedded computer systems. If required, computer hardware and software performance requirements are also included.

- Facilities—permanent, or semi-permanent, real property assets required to support a materiel system. Includes studies to define types of facilities or facility improvements needed, locations, space needs, environmental requirements, and equipment needed in the facility. The use of organic depot and intermediate level maintenance activities is assessed as well as interim contractor support.

- Packaging, handling, storage, and transportation (PHS&T*)*—resources, processes, procedures, and design considerations related to the safe PHS&T of all systems, equipment, and support items. PHS&T includes environmental considerations and equipment preservation requirements for short- and long-term storage. Technical instructions must be developed to ensure safe packaging, handling, storage, and transportation of the end item or its components throughout the life cycle.

- Design interface—primary area of the integration among logistics and systems/software engineering functions. Includes design parameters such as reliability, maintainability, and supportability. Design interface provides product specifications that measure demands on the logistics system by system performance rather than inherent technical factors of design. (Naval Sea Systems Command [NAVSEA], 2012, p.14-6–14-9)

Integrated logistics support is a critical challenge, particularly given that operating and supporting new ships account for the vast majority of total ownership costs (TOC). The next section discusses some of the challenges that the DoD and the DoN are facing.

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IV. Challenges

The DoD and the DoN are facing a number of significant challenges, including reduced budgets, escalating shipbuilding costs, and soaring life-cycle costs.

A. Shrinking Maintenance Budgets

In FY2010, the DoD spent approximately $83.7 billion in FY2010 to maintain strategic materiel readiness for 13,900 aircraft, 800 strategic missiles, 350,000 ground combat and tactical vehicles, 283 ships, and myriad other DoD weapon systems (Office of the Assistant Secretary of Defense for Logistics & Materiel Readiness [OASD(L&MR)], 2011). Figure 6 shows the systems supported by the DoD. Maintenance was provided through the efforts of approximately 657,000 military and civilian maintainers and thousands of commercial firms.

Figure 6. Systems Supported by DoD Maintenance
(OASD[L&MR], 2011)

Performed at several levels, DoD materiel maintenance ranges in complexity from daily system inspections to rapid removal and replacement of components to complete overhauls or rebuilds of a weapon system. The three levels of maintenance are as follows: depot-level maintenance for the most complex and extensive work; intermediate-level maintenance for less complex maintenance activities performed by operating unit back-shops, base-wide activities, or consolidated regional facilities; and field-level maintenance, a combination of depot and intermediate levels.

In early 2011, the DoD operated 17 major depot activities and expended more than 98 million direct labor hours (DLHs) annually (Avdellas, Berry, Disano, Oaks, & Wingrove, 2011). Property, plant, and equipment of DoD depots were valued at more than $48 billion with an infrastructure consisting of more than 5,600 buildings and structures (Avdellas et al., 2011).

1. Navy Maintenance

The Navy must maintain and modernize its fleet to achieve full service life of current assets. Maintenance and modernization is essential to derive full benefits of current assets and, more importantly, enables the Navy to respond quickly to security challenges and offer humanitarian assistance around the world. In FY2011, total ship maintenance amounted to $8.5 billion and is expected to be reduced to $7.7 billion by FY2013. Figure 7 shows the Navy's maintenance budget.

(Dollars in Millions)	FY2011	FY2012	FY2013
Active Forces			
Ship Maintenance	$4,726	$4,533	$5,090
Depot Operations Support	$1,326	$1,296	$1,315
Baseline Ship Maintenance (O&M,N)	**$6,052**	**$5,829**	**$6,405**
Overseas Contingency Operations	$2,484	$1,493	$1,310
Total Ship Maintenance (O&M,N)	**$8,536**	**$7,322**	**$7,715**
Percentage of Projection Funded	100%	97%	100%
Annual Deferred Maintenance	$0	$217	$0
CVN Refueling Overhauls (SCN)	1,664	530	1,683
% of SCN Estimates Funded	100%	100%	100%

Figure 7. Department of the Navy Ship Maintenance
(Department of the Navy, 2012, p. 4-11)

Maintenance is crucial to maintaining the Navy's fleet readiness and ensuring that the fleet reaches its expected service life. However, budget reductions in naval aircraft depot maintenance will result in a $160 million backlog for aircraft and a $217 million backlog for ship maintenance for FY2013 (Greenert, 2012, p. 5).

2. Impact of Unscheduled Maintenance

The importance of maintenance is underscored by a 2006 analysis conducted by Boeing Corporation of historical data for modern long-range transport aircraft. In that study, unscheduled organizational-level maintenance and depot maintenance were found to be the largest contributors to downtime (Andersen & Williams, 2006, p. 1).

Using data from the U.S. Air Force Reliability and Maintainability Information System, one-third of aircraft downtime was connected with the aircraft being at the depot for inspection and refurbishment, as seen in Figure 8, which shows aircraft downtime distributions. The remaining downtime, a not mission capable (NMC) state, was associated with the aircraft not being able to perform any of its missions.

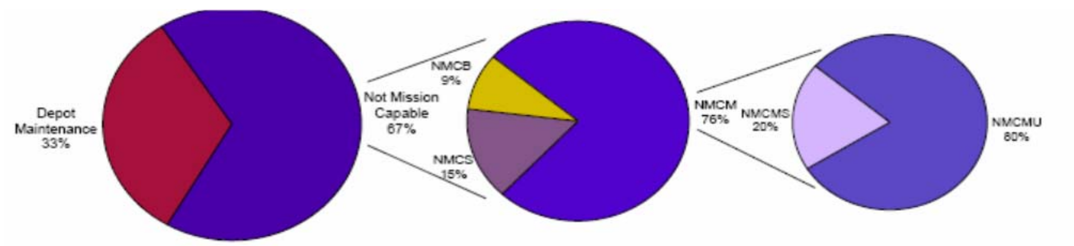

Figure 8. Long-Range Transport Aircraft Downtime Distributions
(Andersen & Williams, 2006)

In the NMC state, aircraft were not-mission-capable maintenance (NMCM) awaiting maintenance for more than 75% of the time; not-mission-capable supply (NMCS) for 15% of this time; and not-mission-capable-both (NMCB) awaiting a combination of both maintenance and supply for the remainder of the time. In a further analysis of NMCM downtime, 20% was attributed to scheduled maintenance (NMCMS) actions at the operational unit while 80% was attributed to unscheduled maintenance (NMCMU).

When these categories of downtime are compared in Figure 9, it can be seen that unit-level unscheduled maintenance requirements are the largest driver, with over 40% of the total aircraft downtime. Depot maintenance accounts for more than 30% of downtime with remaining downtime distributed among unit-level scheduled maintenance, awaiting supply, and awaiting both supply and maintenance.

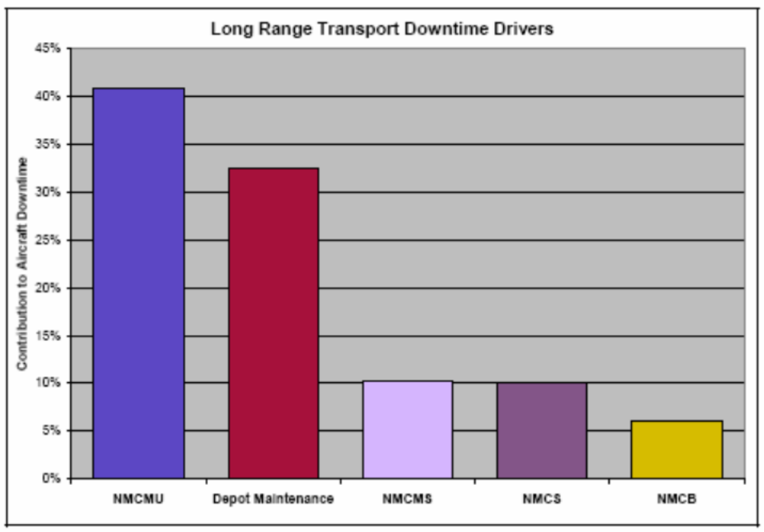

Figure 9. Long-Range Transport Aircraft Downtime Distributions
(Andersen & Williams, 2006)

B. Escalating Shipbuilding Costs

To become the next generation fleet, the Navy invests approximately $13 billion per year in shipbuilding, resulting in 41 new construction ships from FY2013 to FY2017. Table 2 shows the Navy's shipbuilding plans. Designed to balance future threat capabilities while supporting current irregular warfare operations and maritime security and stability operations in the littorals, the shipbuilding budget funds a range that includes second Ford class aircraft carrier (CVN 79), the covert Virginia class submarine, the multi-mission DDG 51 destroyer, the Littoral Combat Ship, and the Joint High Speed Vessel (JHSV).

Table 2. Navy's Shipbuilding Plan
(Highlights of the Department of the Navy FY 2013 Budget, p. 5-2)

	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FYDP
CVN 21	-	1	-	-	-	-	1
SSN 774	2	2	1	2	2	2	9
DDG 51	1	2	1	2	2	2	9
LCS	4	4	4	4	2	2	16
LPD 17	1	-	-	-	-	-	0
LHA (R)	-	-	-	-	-	1	1
T-ATF	-	-	-	-	2	-	2
MLP/AFSB**	1	-	1	-	-	-	1
JHSV	2	1	-	-	-	-	1
T-AO(X)	-	-	-	-	1	-	1
New Construction Total	**11**	**10**	**7**	**8**	**9**	**7**	**41**
LCAC SLEP	4	2	4	4	4	4	18
Oceanographic Ships	1	-	-	-	-	-	0
Ship to Shore Connector*	-	1	-	2	5	5	13
Moored Training Ships	-	-	-	1	-	1	2
CVN RCOH	-	1	-	-	1	-	2

*Two lead SSCs are funded in RDT&E
**MLP funded in NDSF (FY 2011: $800M, FY 2012: $400M, FY 2013: $38M)

Naval ships are extremely complex systems requiring design periods of five to 10 years from concept to start of construction and construction times ranging from two to seven years. Moreover, it will require 30 to 40 years to substantially change the Navy's force architecture with service lives of ships ranging from 25 years for smaller, less-complex ships and up to 50 years for aircraft carriers.

C. Soaring Life-Cycle Costs

The DoD spends billions of dollars each year to operate and support its weapon systems. These operating and support (O&S) costs can account for a significant portion of a weapon system's total life-cycle costs and include direct and indirect costs of sustaining a fielded system (i.e., maintenance, fuel, spare parts, personnel, support facilities, and training equipment). According to the DoD, O&S costs incurred after a system has been acquired account for at least 70% of a system's life-cycle costs (Government Accountability Office [GAO], 2010, p. 7).

A weapon system's life-cycle costs include the costs for research and development, procurement, sustainment, and disposal. Weapon systems are costly to sustain given the technologically complex array of subsystems and components requiring expensive spare parts and logistics support to meet readiness levels. Several examples of soaring life-cycle costs for weapon systems include the following:

- Life-cycle O&S costs for the F-35 Joint Strike Fighter—the newest aircraft being acquired for the Air Force, Navy, and Marines—are now estimated at about $916 billion, and its operating costs per hour are expected to exceed the legacy aircraft that it is replacing (GAO, 2010, p. 1).
- The Air Force's updated life-cycle O&S cost estimate for the F-22A in 2009 found a 47% increase in life-cycle O&S costs from the 2005 estimate. In 2009, it was estimated that it would cost approximately $59 billion to operate and support the F-22A, $19 billion more than was estimated in 2005. Life-cycle O&S costs increased despite a 34% reduction in fleet size, from 277 aircraft projected in the 2005 estimate to 184 aircraft projected in the 2009 estimate (GAO, 2010, p. 5).

Another example of discrepancies between projected and actual costs is the Navy's F/A-18E/F. Although the increase is not of the same magnitude as the F-22A example, direct comparisons between estimated and actual costs are more complicated because of program changes. In 2005, it was estimated that the Navy would have 428 aircraft in FY2009; the actual number was 16% less, at 358 aircraft. The Navy also estimated that the aircraft fleet as a whole would fly 780,628 hours from FY1999 through FY2009; actual hours flown was 20% less, at 625,067 hours (GAO, 2010, p. 26). On a per-flight-hour basis, the FY2009 O&S costs were $15,346, 40% higher than the $10,979 forecast in 1999. Although total actual costs were less than estimated for the 11-year period, actual annual costs for FY2005 through FY2009 have exceeded the annual estimates by an average of 10% after accounting for inflation (GAO, 2010, p. 26). Figures 10 and 11 show actual costs versus estimated costs.

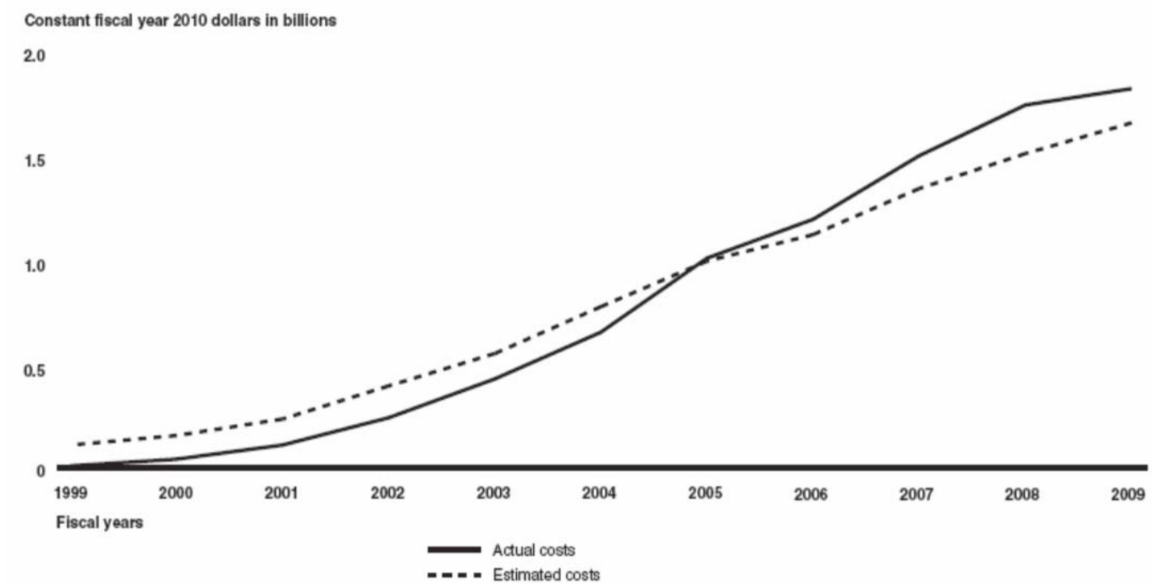

Figure 10. Comparison of Estimated and Actual O&S Costs for the Navy's F/A-18E/F (FY1999–FY2009)
(GAO, 2010, p. 27)

Note. The information presented in this figure is subject to limitations in the data contained in the Naval Visibility and Management of Operating and Support Cost (VAMOSC) system.

Cost element	Total estimated O&S costs, fiscal years 1999-2009	Percent of total estimated costs	Total actual O&S costs, fiscal years 1999-2009	Percent of total actual costs	Change in total O&S costs	Percent change
Constant fiscal year 2010 dollars in millions						
Manpower	$2,235	25%	$2,031	23%	$-204	-9%
Unit-level operations	3,573	41[a]	4,259	48[a]	685	19
Fuel	792	9	2,188	25	1,395	176
Materials and supplies	760	9	555	6	-205	-27
Repair parts	1,639	19	1,363	16	-276	-17
Training expendable stores	382	4	153	2	-229	-60
Intermediate maintenance	86	1	452	5	366	428
Depot maintenance	280	3	723	8	443	159
Contractor support	0	0	79	1	79	[b]
Sustaining support	2,638	30[a]	1,139	13[a]	-1,499	-57
Sustaining engineering	128	2	14	[c]	-114	-89
Modifications	742	8	946	11	204	27
Software maintenance	71	1	40	1	-30	-43
Simulator operations	62	1	17	[c]	-44	-72
Training	1,635	19	45	1	-1,591	-97
Other	0	0	77	1	77	[b]
Indirect support	0	0	36	[c]	36	[b]
Total	**$8,811**	**100%**	**$8,719**	**100%[d]**	**-$92**	**-1%**

Figure 11. Comparison of Navy F/A-18E/F Total Estimated and Actual O&S Costs, FY1999–FY2009
(GAO, 2010, p. 60)

Note.
(a) The percentages for the cost sub-elements listed under the unit-level operations cost element and the sustaining support cost element are shown separately and are also rolled up into the overall percentages for these two cost elements.
(b) Since these costs were not included in the production milestone estimate, a percentage increase or decrease could not be calculated.
(c) Percentage is less than 1%.

V. Open Architecture

The Navy has been transforming traditional business practices through Naval Open Architecture (NOA). NOA, a multi-faceted, enterprise-wide business model and product line strategy, leverages "open" computer design principles and architectures. It expands on the OA model and taps into a multiple developer network to deliver cost-effective, innovative, and rapid/spiral acquisition capabilities. Billions of dollars in acquisition expenditures, along with subsequent life-cycle costs, are at stake with the migration to an OA business model. OA could dramatically improve maintenance processes and substantially reduce costs over the 20-, 30-, and 50-year life cycle of Navy ships.

OA goals and practices are identified in Figure 12.

Figure 12. Business, Technical, and Cultural Changes From OA
(Guertin, 2009, p. 2)

OA and open-business models propel the Navy into the next era of joint interoperability while resolving legacy issues that provide new benefits, including the following:

- Lower life-cycle costs for IWS systems. Total cost of ownership decreases due to increased maintainability, interoperability, upgradeability, and use of a wider variety of vendors.
- Better performing systems. Ability to rapidly upgrade hardware and software with the latest technology enables greater capabilities, efficiencies, and interoperability to enable reengineered warfighting processes.
- Improved interoperability for joint warfighting. Software reuse and modularity facilitates interoperability between systems that use an open architecture framework.
- Facilitating competition and increasing cooperation between commercial and military electronics industries. Moving away from proprietary systems enables a broader range of ideas and technological solutions.

NOA is described as follows:

the confluence of business and technical practices yielding modular, interoperable systems that adhere to open standards and published interfaces. This approach significantly increases opportunities for innovation and competition, enables reuse of components, facilitates rapid technology insertion, and reduces maintenance constraints. (Naval Open Architecture Enterprise Team, 2008)

A set of principles guide NOA:

- encouraging competition and collaboration through alternative solutions and sources;
- building modular designs and disclosing data to permit evolutionary designs, technology insertion, competitive innovation, and alternative competitive approaches from multiple qualified sources;
- building interoperable joint warfighting applications and ensuring secure information exchange using common services (e.g., common time reference), common warfighting applications (e.g., track manager), and information assurance as intrinsic design elements;
- identifying or developing reusable application software selected through open competition of “best of breed” candidates, reviewed by subject

matter expert peers and based on data-driven analysis and experimentation to meet operational requirements; and

- ensuring life-cycle affordability including system design, development, delivery, and support while mitigating COTS obsolescence by exploiting the Rapid Capability Insertion Process/Advanced Processor Build methodology (Naval Open Architecture Enterprise Team, 2008).

Implementing OA requires the commitment and participation of all stakeholders across the naval enterprise OA, as seen in Figure 13.

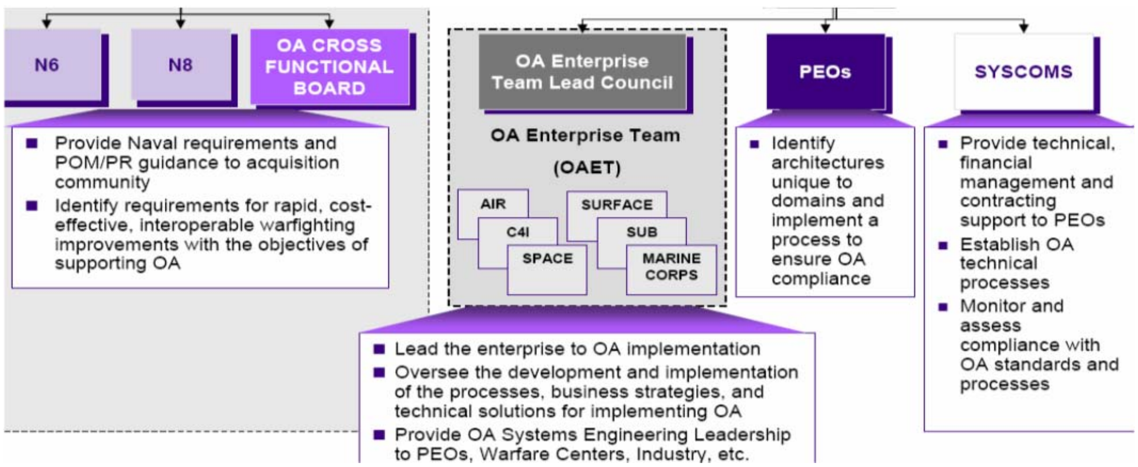

Figure 13. Naval Enterprise OA Stakeholders
(Guertin, 2009, p. 4)

A. Open Systems Architecture

NOA has evolved into open systems architecture (OSA). OSA, which is designed to develop and drive adoption of enterprise-level business and technical open-system approaches, is also anticipated to rapidly field new capabilities, lower total-ownership costs, reduce cycle-times, and enhance interoperability and access to innovation.

OSA also relies on open architecture and an open business model, requiring the DoN to leverage collaborative innovation among the numerous participants across the enterprise to facilitate risk-sharing, maximize asset reuse, and reduce

TOC. OSA attributes include design disclosure, published interfaces, open technology standards and tools, COTS hardware, design reuse, data rights, and open infrastructure. Several principles guide OSA:

- using modular designs based on standards and allowing for independent acquisition of system components;
- encouraging competition and collaboration through development of alternative solutions and sources;
- using components providing best return on investment (ROI; and
- implementing enterprise investment strategies that maximize reuse of system designs (NAVSEA, 2012).

VI. Maintenance Free Operating Period

For more than a decade, the concept of the Maintenance Free Operating Period (MFOP) has been analyzed, implemented, and debated. In general, *MFOP* is defined as

> The period of operation during which an item will be able to carry out all its assigned missions, without the operator being restricted in any way due to system faults or limitations, with the minimum of maintenance. (Kumar, Knezevic, & Crocker, 1999, pp. 127–131)

It is a period with no required, emergency, or unexpected maintenance needed. Following each MFOP is a maintenance recovery period (MRP) in which maintenance is done to ensure that the system is recovered to complete the next MFOP cycle. For our specific purposes, *MFOP* is defined as the specified period of time that a system must be available in support of its required mission, with a specified level of reliability with no open cabinet maintenance (Guertin & Bruhns, 2011, p. 2).

This section begins with a discussion of the MFOP's evolution in the United Kingdom (UK), potential applications, critical components, and MFOP applications and implementations.

A. Evolution of the MFOP

Procurement and support of military equipment consumed around 40% of annual defense cash expenditure in 2009 in the UK (Gray, 2009, p. 6). For more than three decades, there have been a number of reforms focused on logistics and acquisitions. Since the implementation of Smart Acquisition in 1998, the acquisition process has been continuously evolving with many reform programs aimed at process improvements, upgrading skills and driving efficiency. Figure 14 highlights some of those changes.

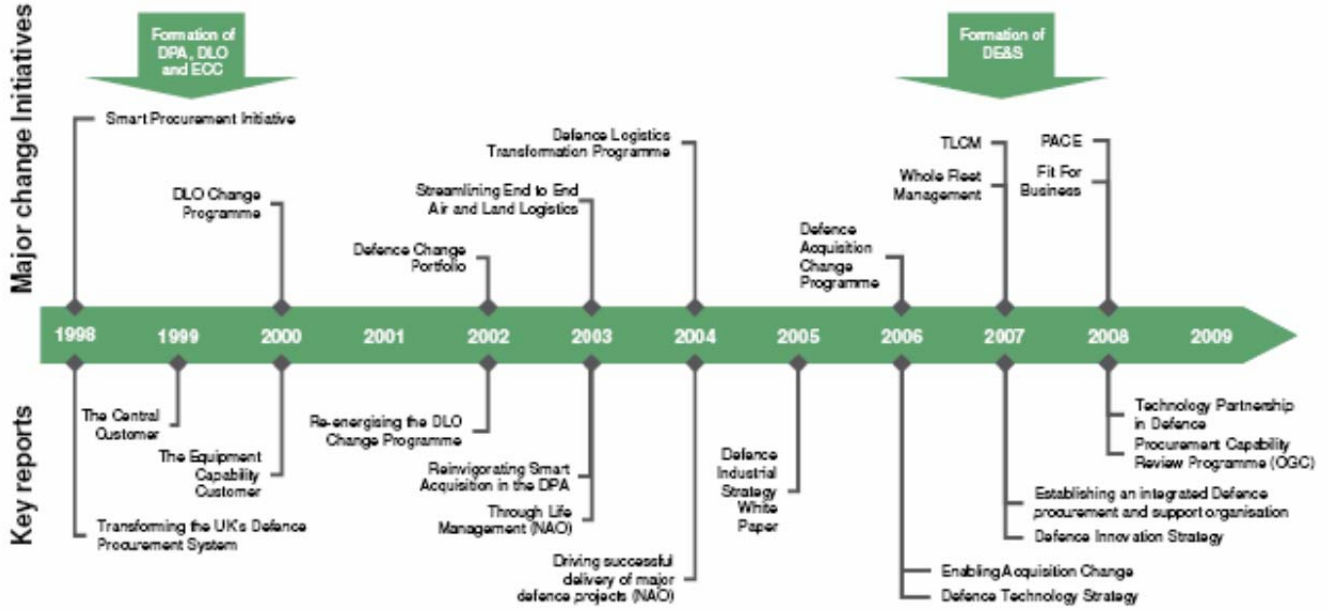

Figure 14. Select Key Reforms in the UK's Ministry of Defense Acquisition System
(Gray, 2009, p. 6)

Smart Acquisition had seven key principles:

- revising the project delivery front-end process to deliver robust requirements and increase value for money over the whole life of equipment;
- restructuring the organization around integrated project teams;
- reducing delays while introducing streamlined approvals and oversight mechanisms to deliver improved scrutiny;
- implementing powerful contractor incentives to reward co-operation in capturing savings and penalties to punish non-cooperation;
- simplifying procurement processes for smaller projects;
- clarifying accountabilities, roles, and organizational structures across the acquisition community; and
- restructuring in-service support (Gray, 2009, p. 59).

In 1998, a strategic defense review was conducted in the UK which identified future conflicts probably resulting from religious conflicts, terrorism, competition for scarce resources, drugs, or crime, and not from direct military threats in the UK or Western Europe. With the post–Cold War environment and those most likely sources of conflict, the 1998 UK Strategic Defence Review called for a more flexible, mobile, responsive fighting force and made a number of key recommendations:

- enhance joint capabilities: a strategy for increased cooperation between forces and rapid response;
- plug the gap: enhanced capability of defense medical services and remedies for weaknesses in logistics;
- modernize the services: commitment to defense hardware through to 2015;
- make the world a safer place: deterring and preventing conflict and crisis; and
- make every penny count: introduction of Smart Procurement, the joint Defence Storage and Distribution Agency (Gray, 2009, p. 66).

After the strategic defense review, changes had to be made in defense, particularly given the following factors:

- continued reductions in defense spending would occur;
- fewer personnel and less equipment would be deployed on maintenance and support;
- a quality product, with better availability and better mission reliability, would be required;
- increased flexibility and more deployments would become the norm; and
- future deployments would be to bare bases, necessitating the requirement for a minimal logistics footprint (Hockley, 2006, p. 23-1).

With this background, the United Kingdom's Royal Air Force (RAF) conducted a customer needs analysis and concluded the following:

- **Guaranteed periods of availability were required.** With a much smaller RAF in the future, manpower and resources would be overstretched. Fewer resources could be used more efficiently with periods of availability guaranteed.

- **Mission effectiveness was paramount**. Planning certainty would allow minimum resources to be organized to support the task and would result in giving the desired minimum logistics footprint for a sustained deployment (Hockley, 2006, p. 23-2).

To achieve the goal of guaranteed aircraft availability periods, fundamental changes in design and maintenance philosophy would be required. Regarding the design issue, mean time between failure (MTBF) had been the primary metric of reliability in acquisition contracts, and it is based on the assumption that failures will occur. The reliability specification for the Tornado GR1, for example, is an MTBF of 1.25 hours, which translates into 800 faults per 1,000 flying hours (Hockley, 2006, p. 23-2). However, the MTBF reliability metric was not consistent with the RAF's need for guaranteed periods of aircraft availability, and the metric failed to "engineer-in" the right solution (Hockley, 2006, p. 23-3).

By defining the needs of its customers, a paradigm shift and the concept of the MFOP emerged. The MFOP was an attempt to define mission and basic reliability requirements, giving operators guaranteed periods of availability with a minimal support logistics footprint (Hockley, 2006, p. 23-2).

B. The MFOP Metric

The MFOP is a reliability measure. There are four broad types of reliability measures, often used by customers and manufacturers to quantify system effectiveness, as seen in Figure 15.

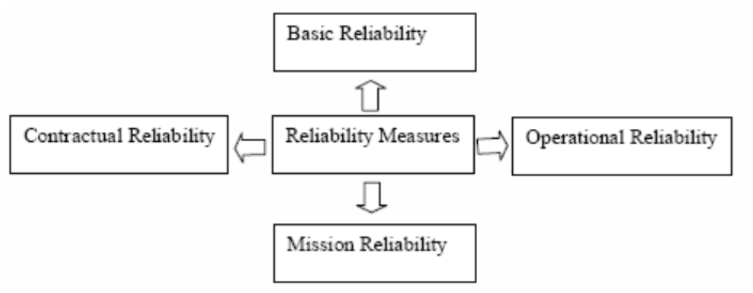

Figure 15. Categories of Reliability Measures
(Kumar, 2012, p. 50)

Basic reliability measures are used to predict the system's ability to operate without maintenance and logistics support. Measures such as reliability function and failure function fall under this category. *Mission reliability measures* are used to predict the system's ability to complete a mission. Measures in this category include mission reliability, MFOP, hazard function, and failure-free operating period (FFOP). *Operational reliability measures* are used to predict a system's performance in a planned environment (e.g., design, quality, maintenance, environment, support policy). This category includes measures such as the MFOP, mean time between critical failure (MTBCF), mean time between maintenance (MTBM), and mean time between overhaul (MTBO). *Contractual reliability measures* are used to define, measure, and evaluate a manufacturer's program. This category includes measures such as MTBF and mean time to failure (MTTF; Kumar, 2012, pp. 50–60). Table 3 summarizes those categories.

Table 3. Reliability Measures
(Adapted from Kumar, 2012, pp. 50–60)

TYPE	SUMMARY	MEASUREMENT
Basic Reliability Measures	• Predicts system's ability to operate without maintenance and logistics support	• Reliability function • Failure function
Mission Reliability Measures	• Predicts system's ability to complete a mission • Considers only those failures causing mission failure	• Maintenance free operating period (MFOP) • Failure free operating period (FFOP) • Mission reliability • Hazard function
Operational Reliability Measures	• Predicts system performance operating in a planned environment	• Mean time between maintenance (MTBM) • Mean time between overhaul (MTBO) • Maintenance free operating period (MFOP) • Mean time between critical failure (MTBCF) • Mean time between unscheduled removal (MTBUR)
Contractual Reliability	• Defines, measures, and evaluates manufacturer's program • Considers design and manufacturing characteristics • Essentially the inherent reliability characteristic	• Mean time between failure (MTBF) • Mean time to failure (MTTF)

C. Applications of the MFOP

The MFOP can be applied in several areas, including maintenance, technology refresh, technology insertion, and design.

- ***Maintenance.*** There are generally three types of maintenance: corrective, preventative, and prognostic. Corrective maintenance, or the "fix on failure" maintenance, is the system/part replacement when the system or part replacement fails. Preventative maintenance is scheduled in advance to prevent system/part failure and is typically triggered by a predetermined occurrence. Prognostic maintenance relies on a system sensor indicating impending system failure (total or part).

In addition, a system, or each part composing the system, often has multiple maintenance levels with various degrees of difficulty. For example, a computer server in a sonar system may have several maintenance levels. The first level is basic repairs while the second intermediate level requires more difficult repairs and the third level requires very difficult repairs that may only be performed at the original manufacturer's premises.

The MFOP provides an optimal maintenance plan because it defers corrective maintenance to the MRP, so the "unscheduled" element of maintenance is exchanged for more scheduled maintenance planning. Contingency resources could be re-allocated to scheduled work, and logistics support could be concentrated in one particular location of aircraft operations (Wu, Liu, Ding, & Liu, 2004, p. 17).

- ***Technology refresh.*** The replacement of earlier-generation parts with later generations because the earlier-generation parts are or are soon to be obsolete. After the refresh, the functional capacity of the system is typically the same as or greater than the functional capacity of the system before refresh.

- ***Technology insertion.*** The replacement of one or more earlier-generation parts of a system with parts of a later generation to increase the functional capacity of the system and/or to migrate to a different technology. Technology insertion is optional and typically done to upgrade system capabilities or migrate to newer technology.

- ***Design.*** The MFOP concept could be adapted as a performance requirement, perhaps a measure of effectiveness, in contracts. To achieve a specified aircraft MFOP, for example, all components would have to be designed and maintained to have an MFOP greater than the specification.

  Key to design is the consideration of failure life characteristics. The issue here is whether the designer can successfully address this issue to provide a sufficient amount of warning between the end of an MFOP and the predicted failure point, as seen in Figure 16 (Hockley, 2006, p. 23-6).

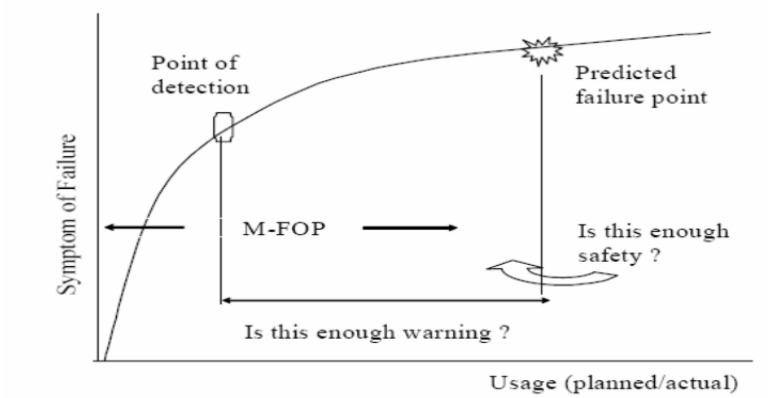

Figure 16. Failure Life Characteristics
(Hockley, 2006, p. 23-6)

D. Areas Critical to the MFOP

There are a number of enabling ideas and technologies contributing to the MFOP, as summarized in Table 4.

Table 4. Enabling Ideas and Technologies
(Mitchell, 1999, p. 14-3)

AREA	COMMENTS
Condition Monitoring	• Measurement and interpretation of data, condition indication, determination of maintenance requirement.
Redundant Systems	• To achieve fault tolerance, using either hardware, software or data duplication in various forms. Can achieve significant reliability gains but at cost of potential increased complexity, weight, volume and power consumption.
Reconfigurable Systems	• Recovery, automatic or otherwise, of a system after a failure without the need for the system to go off-line.
Prognostics	• The capability to detect early warning of impending failure, enabling pre-emptive maintenance action to be carried out or to trigger re-configuration or redundancy processes.
Diagnostics	• To enable timely, accurate failure diagnostics to support minimum repair times during the maintenance recovery period. • Location and isolation of a particular failed component or system enables reconfiguration of systems or mission objectives.
Reversionary Modes	• Allowing software to back up when a failure occurs and take a different path, thus bypassing failure causes.
N-version Programming	• A software form of redundancy, involving voting between differently, often independently, developed software units.
Recovery Blocks and Self Healing	• Backwards error recovery carried out by periodically saving the system state and reverting to it when necessary.
Exception Handling	• Giving the software the ability to deal actively with failures, so avoiding system crashes or erroneous results.

In addition, system reliability is a critical factor in the probability of completing an MFOP. System reliability normally diminishes as the equipment is used during its operating period, and an MFOP can be determined by plotting the reliability from time zero and overlaying the required probability of completion, as seen in Figure 17 (Hockley, 2006, p. 23-7).

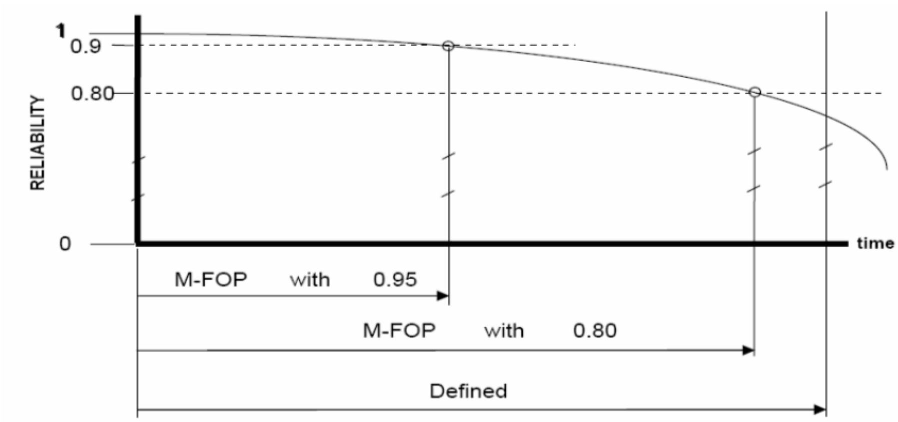

Figure 17. Reliability vs. Time and Probability of M-FOP Completion
(Hockley, 2006, p. 23-7)

E. Potential Benefits

When the MFOP concept was introduced, several benefits were cited. First, operational effectiveness would be greatly enhanced if a weapon system would only require specific maintenance levels at a pre-determined period. In addition, logistics support and repair costs could be minimized with maintenance downtime pre-programmed around operational commitments. According to RAF Squadron Leader Mitchell, other potential benefits included the following:

- Reliability of contracts would improve because the MFOP is a simpler concept than MTBF.
- There would be a greater understanding of failure mechanisms and subsequent development of necessary design tools.
- Random component failures would be reduced.

- True causes of failure would be identified because of the physics approach, rather than statistical analysis involving MTBF.
- The assumption of a constant failure rate would be challenged because system predictions would be built-up from the sum of the individual component failure distributions, rather than as a population, giving a more realistic bottom-up rather than top-down approach.
- Using the principle of a failure-free period rather than failures randomly occurring would alter the basis of logistics planning. Compared with using reliability predictions based on constant failure models, more realistic spares provisioning should be possible, and expensive, inconvenient unscheduled maintenance should be minimized.
- The approach would deliver a simple and more confident prediction of fleet costs and lease pricing details (Mitchell, 1999, p. 14-6).

F. Potential Risks

Alternatively, potential risks were also acknowledged by Mitchell (1999). In migrating from MTBF to the MFOP, inspection or refurbishment requirements for some parts may be increased while other components may be scrapped before the end of their previously used life. As a result, each component, line replaceable unit (LRU), and system would require some design analysis to establish its optimum MFOP and associated cost (Mitchell, 1999, p. 14-7). Under this scenario, modeling to determine potential manpower savings was difficult. Other risks included the following:

- Increased acquisition costs from a more rigorous design process. The trade-off between investment in design/manufacture for M/F-FOP and the cost/operational consequences of poor equipment reliability would have to be further understood.
- Extensive analysis, conducted by skilled technicians, would have to be done because a large number of individual LRUs, subsystems, and system MFOPs into an overall weapon system MFOP would have to be aggregated and understood completely.
- An integrated knowledge of engineering process design, an appreciation of practical in-use problems, and an understanding of statistics would be required to gain a deeper understanding of the MFOP concept.

- Partnership between subcontractors, suppliers, prime contractors, and customers will be essential to derive full benefits (Mitchell, 1999, p. 14-8).

G. Examples of the MFOP

Since the MFOP's introduction, there are several examples of how the concept has been used and investigated. The Ultra Reliable Aircraft (URA) project and the A400M program are two examples of the application of MFOP principles and techniques.

3. The Ultra Reliable Aircraft Project

The URA was a research project in the late 1990s focused on aircraft operational availability and reliability–involved MFOP concepts. At the time, consequences of unscheduled delays typically exceeded £1 million per aircraft per year in the private sector while the costs to the UK's Ministry of Defence was £1 billion per year for its entire fleet (Bottomley, 1999, p. 1). The URA was a private-/public–sector consortium comprising customers and platform/major systems with members that included British Aerospace Airbus and Military Aircraft and Aerostructures; GKN Westland Helicopters Limited; GEC Avionics; GEC Aerospace; GEC Marconi Electronic Systems; Lucas Aerospace; Messier Dowty Limited; Dowty Aerospace; Normalair Garrett; Rolls Royce Military and Civil; BMT Reliability Consultants; The Royal Air Force; The Defence Evaluation and Research Agency; and Warwick Manufacturing Group (University of Warwick; Bottomley, 1999, p. 2). The companies each contributed £0.5 million for a one-year study.

The project was broken down into a series of phases and work packages. First, a pilot study was done while the main project phase started April 1997. One of the work packages sought to identify the feasibility of achieving the complete removal of unscheduled maintenance and the provision of "guaranteed" MFOPs (Bottomley, 1999, p. 2).

4. MFOP Examples: The A400M Program

MFOP was applied to the A400M program. The A400M program, a cooperative between seven European nations, is managed by the Joint Organization for Armaments Cooperation (OCCAR) for the acquisition of a military transport aircraft system from Airbus Military. Using a commercial approach, the goal was to produce and deliver an aircraft at fixed prices with a single-phase contract (including development, production, and initial support at minimum life-cycle costs; Heuninckx, 2006, p. 10-3).

Deployment reliability is a key requirement of the A400M and is defined as the probability that one aircraft will complete a planned deployment period, using only spare parts contained in a transportable deployment kit if operated and maintained according to standard conditions. The A400M's deployment reliability was guaranteed as 90% for a deployment of 15 days. Although Airbus Military's objective was to provide users with an MFOP of 15 days, it was determined that it could not achieve a 15-day MFOP with 90% certainty. In this case, *MFOP* was defined as a "period of operation during which an aircraft is able to carry out its assigned missions without the need for any maintenance except pre-defined flight servicing (e.g. generic visual inspection, replenishment) and role change activities" (Heuninckx, 2006, p. 10-11).

H. MFOP Applicability to the DoD and DoN

The MFOP concept, in conjunction with technology enablers, is a proactive policy from the traditional reactive fix-on-failure one. It eliminates the need for corrective maintenance over a specific time frame, including overseas deployment periods or even technology refresh intervals. With its potential for substantial cost savings and improved performance, several pilot programs were conducted using MFOP concepts to determine whether the concept is a practical support alternative for deployed Navy ships. The next section discusses the Submarine MFOP Pilot (2005) and the Surface Ship MFOP Demonstration (2009–2010).

VII. Department of Navy MFOP Demonstrations

With its potential for substantial cost savings and improved performance, pilot programs were conducted using MFOP concepts to determine whether the concept is a practical support alternative for deployed Navy ships. MFOP-enabled systems provide better, cheaper, and faster products because MFOP designs

- increased operational availability to the warfighter;
- are cheaper—with less material, infrastructure, and training to provide and manage by eliminating platform/system-level material support packages; and
- are faster to deploy with distance support techniques, eliminating delays in supporting fielded products, and are available worldwide (Guertin & Bruhns, 2011).

In this section, we discuss those projects further. We begin with a general discussion of the MFOP and its implications for the DoN, then review the pilots and address some of the lessons learned.

A. MFOP Applicability to the DoN

MFOP is defined as a period of operation during which an aircraft is able to carry out its assigned missions without the need for any maintenance except pre-defined flight servicing (e.g., generic visual inspection, replenishment) and role change activities. During an MFOP, faults may occur in the aircraft but they must not require corrective maintenance action until the aircraft returns to the base. Once the MFOP is complete, an aircraft may have to be restored to its fully serviceable state at a suitable location (maintenance recovery period).

For the DoN, an MFOP may be an opportunity to leverage OSA and the use of COTS technologies. For example, an MFOP eliminates maintenance and the need for associated support while aligning logistics actions with preplanned COTS technology refresh and insertion for improved operational availability, as shown in Figure 18 (Margolis, 2005, p. 9).

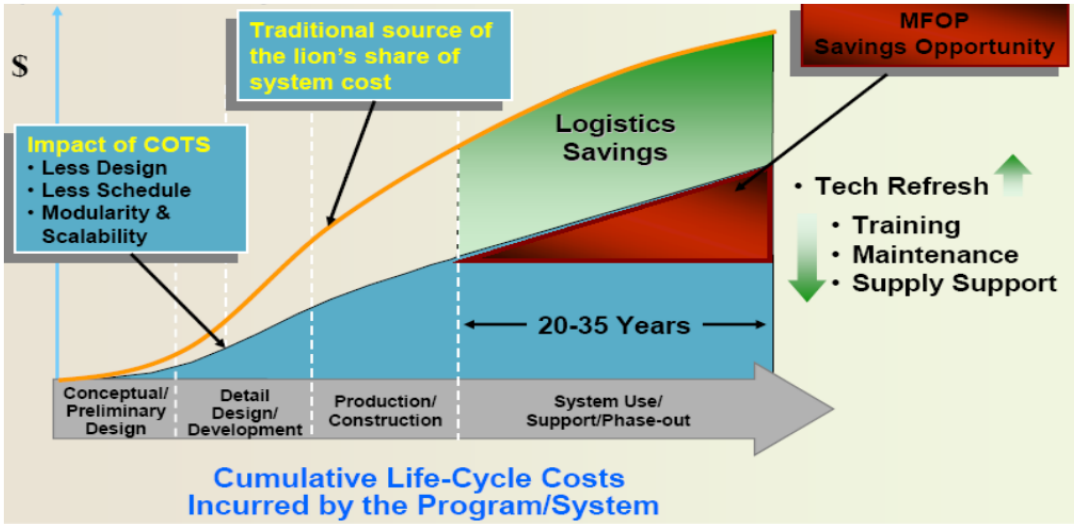

Figure 18. MFOP Wedge of Opportunity
(Margolis, 2005, p. 9)

An MFOP is also an opportunity to transform traditional ILS practices at the system, platform, and shore support levels, as seen in Figure 19.

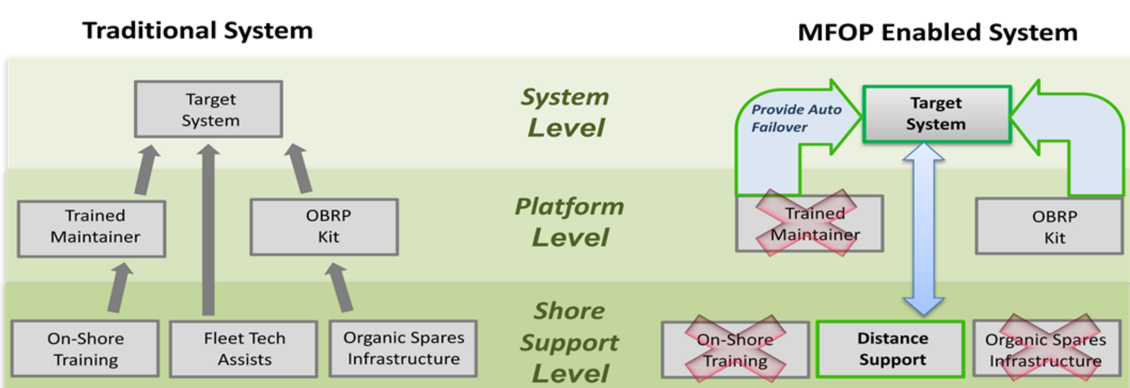

Figure 19. Shipboard ILS Is Eliminated in Favor of "Better–Cheaper–Faster" Distance Support
(Guertin & Bruhns, 2011, p. 13)

In particular, an MFOP could

- **Reduce system maintenance costs.** The cost of maintaining complex systems is high. A preventive, scheduled maintenance strategy such as the MFOP, where maintenance is performed only when the system needs maintenance, results in longer maintenance-free intervals and decreased downtime costs over time.

  In FY2011, total ship maintenance amounted to $8.5 billion. The leading driver of depot maintenance demand for the Navy (and the Air Force) is ownership of ships and aircraft, which generally operate at the same rates from year to year, according to an analysis conducted by the firm LMI in 2011.[2] In FY2009, the Navy's average depot maintenance cost was $2.9 million per destroyer and $5.2 million per cruiser.[3]

  Reduce spare parts inventory and costs/optimized spare parts management. The MFOP could improve inventory management and assist in eliminating unnecessary spare parts. It could impact how many spare parts would be needed and where they would be stored. A GAO analysis found that the average annual value of the inventory for FY2004 to FY2007 was about $13.7 billion. Of this total, about $7.1 billion (52%) was beyond the amount needed to meet the requirements objective and about $5.1 billion (37%) was not needed to meet the current requirements objective plus an additional two years of estimated future demand (GAO, 2010, p. 5). The DoD's total value of secondary inventory, including spare parts and other items, was about $94 billion in September 2008.[4]

  In a cost-efficiency analysis of the Navy's spare parts inventory, the GAO found that for FY2004 to FY2007, the Navy had significantly more inventory than was needed to support current requirements. During that time frame, the annual average of $18.7 billion of Navy secondary inventory exceeded requirements by approximately $7.5

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[2] The Duncan Hunter National Defense Authorization Act for Fiscal Year 2009 directed the Department of Defense to contract an independent study on the effectiveness and efficiency of DoD organic maintenance depots providing the logistics capabilities and capacities necessary for national defense.

[3] Based on data submitted to the Navy to the Depot Maintenance Cost System and averaged across the fleet.

[4] The DoD defines secondary inventory *items* to include reparable components, subsystems, and assemblies other than major end items (e.g., ships, aircraft, and helicopters), consumable repair parts, bulk items and material, subsistence, and expendable end items (e.g., clothing and other personal gear).

billion (GAO, 2008, p. 3). About half of the $7.5 billion of inventory exceeding current requirements was retained to meet anticipated future demands, and the remainder was retained for other reasons or identified as potential excess. Based on Navy demand forecasts, inventory that exceeded current requirements was sufficient to satisfy several years, or even decades, of anticipated supply needs. Moreover, a large proportion of items that exceeded current requirements had no projected demand.

- **Improve operations through higher availability.** With an MFOP, higher availability of systems could be achieved with improved operations. It could assist in ensuring that Navy forces are ready to surge forward on short notice, complementing other initiatives.

  At the time of the September 11 attacks and in preparation for Operation Iraqi Freedom, a GAO report found that only a small number of ships at peak readiness were deployed because most of the Navy's ships were unavailable (GAO, 2004, p. 1).

Several pilot programs were conducted using an MFOP to determine whether the concept is a viable option for deployed Navy ships, with its cost- and efficiency-savings potential.

B. DoN MFOP Pilots

Table 5 summarizes the MFOP pilots deployed twice aboard Navy ships.

Table 5. MFOP Pilot/Demonstration
(Guertin, 2010, p. 7; Ondish, 2006, p. 15)

	Submarine MFOP Pilot (2005)	**Surface Ship MFOP Demo (2009–2010)**
Summary	• 90-day MFOP conducted on 4 ships • Spare processors were embedded • Manual failover procedures conducted by ship's force • Remote reporting of system data logs not implemented	• 180-day MFOP conducted on LHD-7 • All IT-related spares embedded in test system • Auto failover accomplished in software • Remote reporting of system data logs over a secure internet protocol router network (SIPRNet) • Remote system log-in for system sustainment and maintenance at sea
Post Pilot and Demonstration Lessons	• Even limited MFOP boundary size can provide exponential gains to the logistics and maintenance business processes and organizational infrastructure. • Distance support processes from Customer Support Center produced cost saving to Fleet Technical Assistance dollars by a ratio of 7:1. • Substituted software reconfiguration/recovery (2 min. pilot demonstrated) for classic MTTR (20 min. for ARCI) to generate a ratio of 10:1. • Vendor mean time between failure (MTBF) data may vary significantly from actual MTBF data.	• Distance support 15:1 cost savings

The Acoustic Rapid COTS insertion (ARCI) MFOP Pilot Program first tested feasibility of COTS technology to achieve a maintenance-free operating environment for a 90-day operating period for one year, from September 3, 2004, to September

30, 2005. The principal objective of this pilot program was to install hardware, software, and COTS-based logistics capability into AN/BQQ-10 systems on selected submarines to demonstrate the ability to achieve a 90-day period of MFOP at a confidence at or above 95% (Rosenberger, Altizer, Ondish, & Steed, 2005, p. 3). Four U.S. Navy 688 class submarines participated in the MFOP Pilot Program, and each of the platforms entered into the pilot program after their TI02/APB03, AN/BQQ-I0 system was installed.[5] The submarines were augmented with additional embedded servers and additional design elements to ensure a 90-day MFOP period for tactical software availability within the MFOP boundary while the rest of the system was managed using a traditional ILS support system.

A subsequent demonstration five years later tested a range of technical challenges encountered during the earlier attempt. The 2010 Surface Ship demonstration aboard the USS *Iwo Jima* further explored the MFOP concept further, along with potential cost savings. The MFOP was doubled to 180 days, and the certified maintenance support package provided in the temporary installation (TEMPALT) included zero support items to the ship during this pilot. The following section provides an overview of both projects.

C. ARCI MFOP Pilot (2004–2005)

In March 2002, a Memorandum of Agreement (MOA) was established between the Navy Commercial Technology Transition Office (CTTO), the Chief of Naval Operations (CNO), and the Naval Sea Systems Command (NAVSEA). The MOA noted that with the increasing usage of COTS technology and to fully capitalize on benefits, DoN acquisition programs must develop effective sustainability

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[5] The ARCI program operated on a two-year cycle that created new hardware architecture using COTS technology and products. These series of hardware baselines are referred to as a technology insertion (TI). To date, a hardware baseline has been deployed in the submarine fleet for technology insertion in 1998, 2000, 2002, and 2004 (TI98, TI00, T102, and TI04). ARCI also uses a software update cycle which creates a new software baseline with additional functional capability each year. This series of software baselines are referred to as Advanced Processing Builds (APBs).

strategies. In particular, "Support requirements for military systems generally exceed 25 to 30 years, in contrast to the 4 to 7 year support cycles expected for commercial technical capital systems. Additionally, the military percentage of total commercial demand has dropped sharply. Thus, DoN does not receive the level of support customary in previous decades. The combination of extended support periods and diminished life cycle support makes military systems vulnerable to a host of supportability problems" (Rosenberger et al., 2005, p. 20). The MFOP was envisioned to derive several benefits, including dramatically reducing on-board repair part requirements, diminishing crew maintenance and training demands, reducing TOC, and potentially improving a sailor's quality of life.

The MOA defined the goals and expectations for demonstrating a COTS sustainability strategy that would eliminate unplanned system maintenance during a 90-day submarine operating period. Specific objectives in the MOA included the following:

- perform required engineering analysis to achieve improved reliability through redundancy concurrent with the installation of ARCI;
- develop hardware independent fault location, isolation, and fail-over software allowing automatic reconfiguration using hot spares within the ARCI system;
- develop an improved interactive electronic technical manual (IETM) focusing on software maintenance rather than hardware troubleshooting and repair/replacement procedures;
- provide updated IETM with reconfiguration instructions to make use of hot spares;
- develop data screening/mining software that automatically identify required maintenance actions and sparing requirements from available fault log information;
- develop automated message formatting of required maintenance actions and sparing requirements for subsequent off-board delivery to the Lifetime Support (LTS) partner; and

- update previously conducted surveys of commercially available technologies necessary to achieve high availability MFOP status (including storage area networks, system availability, operational availability, root cause analysis, system management, infrastructure resource management, network management, trouble ticket, remote support, software management, communications middleware, virtual command centers, and integrated databases; Rosenberger et al., 2005, p. 5).

At the time of the demonstration, U.S. Submarine Combat Systems installed on the Los Angeles class (688 and 6881), Seawolf class, and new construction Virginia class fast attack platforms used COTS technology and products. The ARCI program capitalized on cutting-edge technology given that rapid changes in technology result in forced obsolescence when commercial firms stop providing support for hardware. Forced obsolescence impacts a wide range of areas, including operations, maintenance modernization, repairs, spares, personnel, and training.

With the proliferation of ARCI installations, it was recognized that the traditional ILS structure and system support process could not manage the rapid pace required to make the many ILS product changes needed to support the hardware/software modifications that the ever-evolving ARCI systems were experiencing (Rosenberger et al., 2005, p. 2). As a consequence, there was a proposal to develop a system architecture incorporating the MFOP concept. The MFOP used technology to reduce/eliminate most existing on-board maintenance functions, generating shipboard operator actions, material, training, and documentation cost during a submarine’s defined deployment operating period (Rosenberger et al., 2005, p. 5). Automatic fail-over/error recovery routines, with redundant hardware/software architecture, allowed the system to operate at full functionality—without the usual reactive fix-on-failure maintenance/repair. The concept of MFOP enabled required hardware maintenance/repair/replacement to be done on a pre-planned, non-deployment period or during the next technology refresh or insertion period.

Based on the MOA, specific objectives were identified for this MFOP pilot:

- Select the best of breed by conducting lab tests with available real-world data.
- Conduct at-sea validation tests as part of the APB process on a not-to-interfere basis.
- Incorporate into curriculum and conduct commercially available training courses focused on software maintenance, and not hardware troubleshooting and repair/replacement procedures.
- Install additional hardware on selected submarines to begin migration towards a 90- day MFOP with 95% reliability.
- Install hardware independent fault localization, isolation, and fail-over software allowing for automatic reconfiguration using hot spares within the ARCI system in conjunction with APB 03 (Rosenberger et al., 2005, p. 10).

Figure 20 shows how the MFOP was anticipated to impact sea maintenance management.

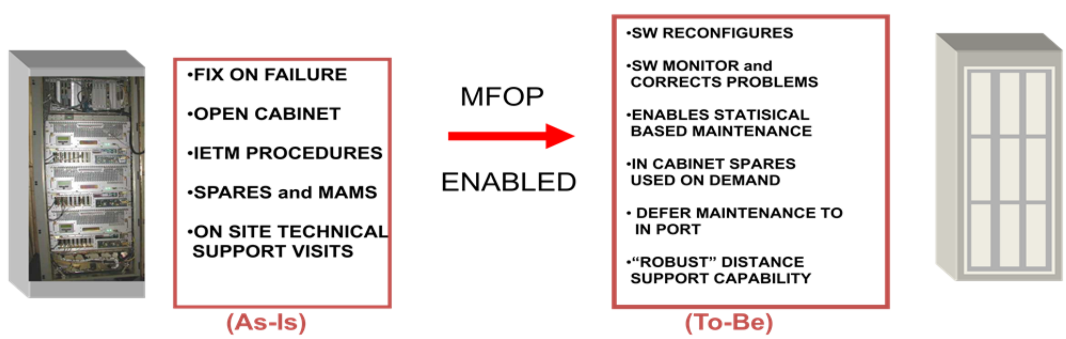

Figure 20. At-Sea Maintenance Management
(Ondish, 2006, p. 5)

1. Maintenance Issues

Maintenance requirements for each unique ARCI TI/APB are different and complicated. For example, the control and sensor data networks used in ARCI have evolved from an Ethernet/Fiber Distributed Data Interface (FDDI) in TI98 to an Asynchronous Transfer Mode (ATM)/Fiber Channel Standard (FCS) in TI00 to Gigabit Ethernet (GIGE)/FCS in TI02 to GIGE/GIGE in TI04 (Rosenberger, 2005, p. 4). With each successive TI/APB, more functionality was introduced (i.e., performance prediction and lineup, data recording, and ship monitoring), along with advanced techniques and algorithms for detection, track, and classification functions. The responsibility of maintaining logistics products such as system maintenance training and troubleshooting technical documentation included in the IETM became extremely challenging.

One solution to updating maintenance-related logistics products with each TI/APB was to architect a period of deferred maintenance to planned, in-port periods. During this planned period, maintenance would be done by intermediate-level maintainers and not operational-level boat sailors.

2. MFOP Pilot Phases

The MFOP Pilot Program was divided into several phases. During the engineering phase, the following steps were taken to ensure that the MFOP could be achieved:

- The system architecture was reviewed. This was done to identify which portions were maintenance free. The number of processing resources required to execute full system functionality and construct a model of the candidate maintenance-free boundary were determined (see Figure 21).
- The best available MTBF was used. MTBF data was used to determine, via simulation, the number of embedded spares required to achieve a high confidence (normally > 95%) of maintaining sufficient processing resources to execute full functionality for the entire MFOP.
- The system footprint and budget were reviewed. This review was conducted to ensure that both the system footprint and budget were sufficient to embed the additional resources required for the MFOP.
- The system software management scheme was implemented. This was done to allow processing to be relocated from one resource to another, allowing for system reconfiguration in the event of a failure to maintain full functionality.

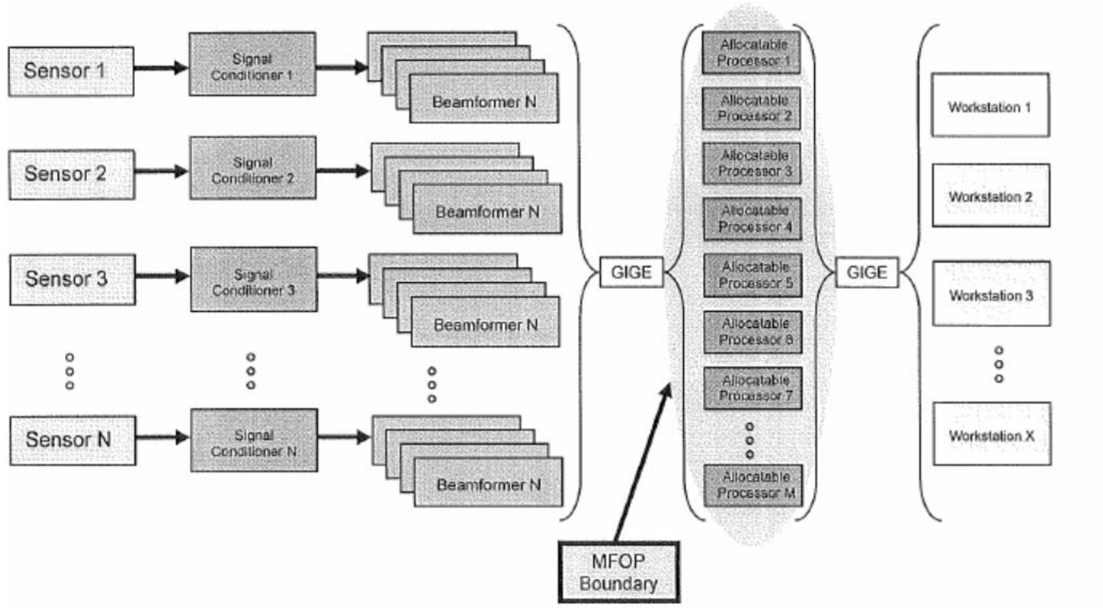

Figure 21. ARCI Processing Block Diagram
(Rosenberger, 2005, p. 5)

During the deployment/execution phase, a MFOP support team was established that consisted of Lockheed Martin and Navy Regional Maintenance Center development, integration, test, installation, and maintenance engineers. This team was responsible for any required maintenance within the MFOP boundary. A customer support center (CSC) was also created as a single point of contact for servicing of ARCI maintenance requests.

A critical aspect of this MFOP pilot was the use of an off-hull server that downloaded system maintenance data—data that was subsequently used by shore-based technicians to assess system performance. These shore-based technicians could troubleshoot and maintain faulty systems as part of the Fleet Technical Assistance (FTA) process. The Remote Off-Hull Maintenance Support (ROHMS), the web services component, enabled authorized personnel at an off-hull maintenance location to execute predefined queries for system maintenance–related data, retrieve that data through a SIPRNet connection, and provide feedback to the on-hull system or system operator (Rice, 2010). Figure 22 shows this process.

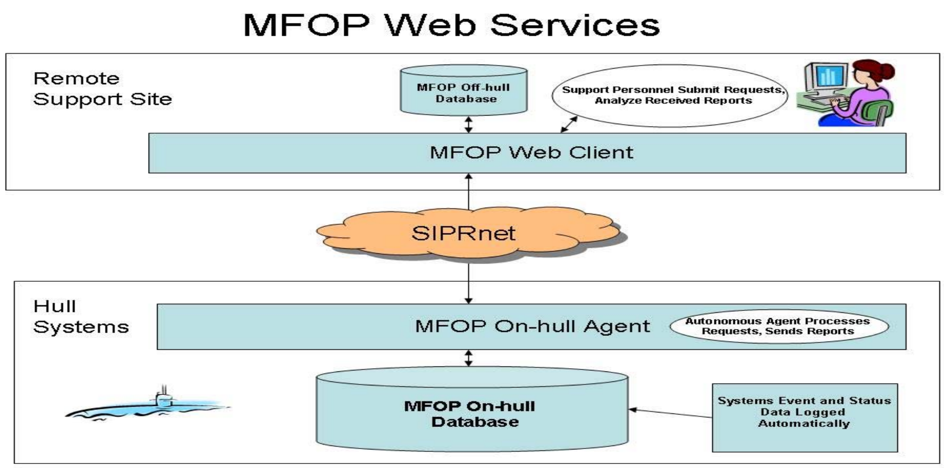

Figure 22. Web Services
(Ondish, 2006, p. 21)

This capability enables shore-based technicians to conduct system assessments and troubleshoot problems reported via casualty reports (CASREP) or through any other means of requesting fleet technical assistance. ROHMS demonstrated the potential of applying this capability to supporting the maintenance, manning, repair, and upgrade of the submarine fleet. Figure 23 shows ROHMS testing that was conducted at Norfolk, Virginia.

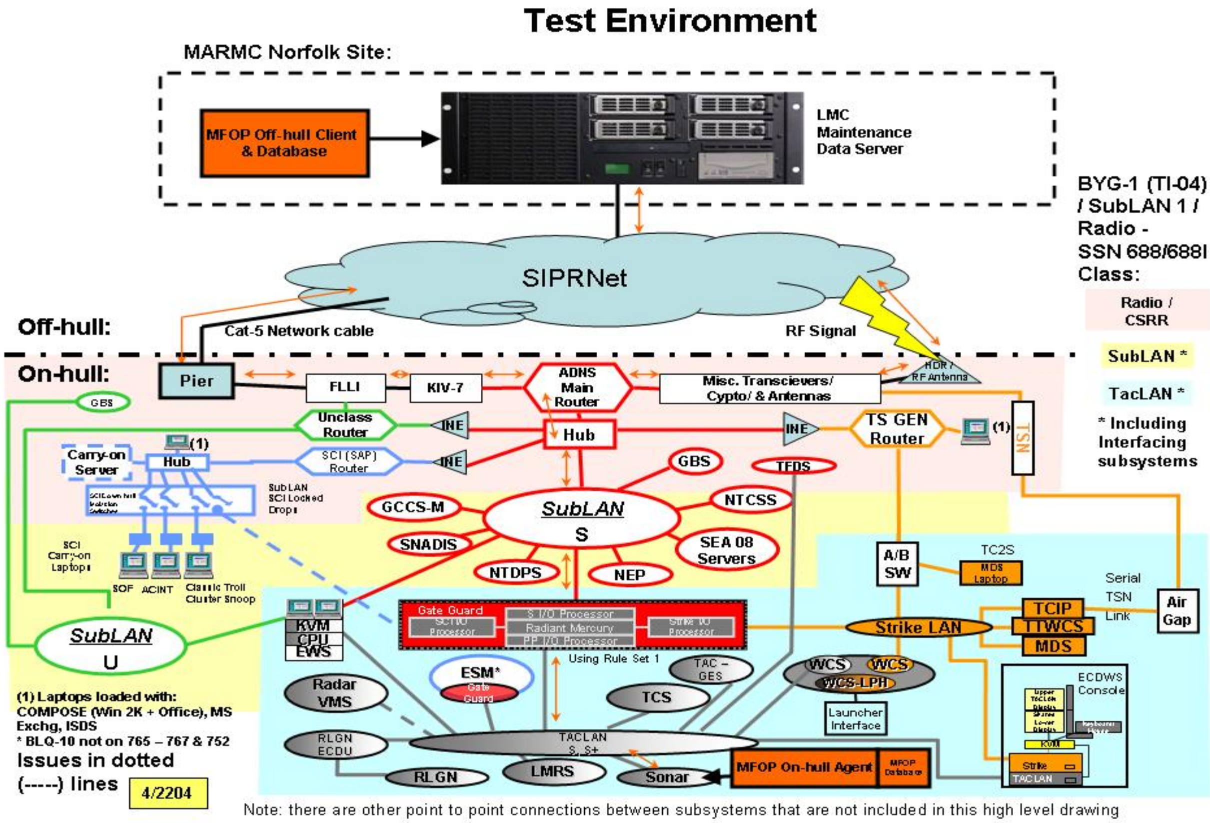

Figure 23. ROHMS: Testing of MFOP Functionality Conducted in Norfolk
(Ondish, 2006, p. 22)

3. MFOP Pilot Program Results

The MFOP Pilot Program far exceeded predictions and expectations. Of the four SSN 688 class platforms participating in the pilot program, no maintenance was required on the portion of the system designed to be maintenance free for the entire one-year period. In addition, available embedded spares remained consistently high through the pilot program. Table 6 shows the final results of the pilot.

Table 6. MFOP Pilot Program Final Results
(Rosenberger et al., 2005, p. 12)

MFOP Pilot	Pilot Start	Days In	Final Available	Days	% of Days
SSN 721	5-Sep-04	390	14 of 15	84	21.5%
SSN 710	3-Sep-04	392	12 of 12	185	47.1%
SSN 713	22-Nov-04	312	11 of 14	179	57.2%
SSN 705	8-Apr-05	175	14 of 14	110	62.5%

4. Lessons Learned

There were a number of valuable lessons learned and technological advances resulting from the pilot project. For example, the number of embedded spares was revised to a more accurate figure based on historical data (Figure 24) from vendor-supplied data. A model, initially developed to determine the number of embedded spares required to achieve a 90-day maintenance free operating period, was rerun. In the rerun model, actual observed MTBF data obtained during the execution of the MFOP Pilot Program was used. The MTBFs used in the updated analysis are based on over 20 million module operating hours and 82 failures. Figure 25 shows revised predicted reliability based on actual data.

Vendor MTBF Data

Allocatable 2U Server Arrangement	Predicted Reliability 90 days
22 of 23 (1 spare)	0.566
22 of 25 (3 spares)	0.774
22 of 27 (5 spares)	0.872
22 of 29 (7 spares)	0.954
22 of 31 (9 spares)	0.983

Actual MTBF Data

	Predicted Reliability				
Allocatable 2U Server Arrangement	90 days	1 yr	3 yrs	5 yrs	10 yrs
22 of 23 (1 spare)	0.9	0.55	0.06	0	0
22 of 25 (3 spares)	0.99	0.92	0.31	0.05	0
22 of 27 (5 spares)	1	0.99	0.61	0.16	0
22 of 29 (7 spares)	1	0.99	0.85	0.38	0
22 of 31 (9 spares)	1	1	0.96	0.64	0

Figure 24. Vendor and Actual MTFB Data
(Ondish, 2006, p. 13)

	Predicted Reliability				
Allocatable 2U Server Arrangement	90 days	1 yr	3 yrs	5 yrs	10 yrs
22 of 23 (1 spare)	0.9	0.55	0.06	0	0
22 of 25 (3 spares)	0.99	0.92	0.31	0.05	0
22 of 27 (5 spares)	1	0.99	0.61	0.16	0
22 of 29 (7 spares)	1	0.99	0.85	0.38	0
22 of 31 (9 spares)	1	1	0.96	0.64	0

5 Additional 2u servers provides 99% confidence of achieving maintenance free operation for 1 year

Figure 25. Predicted Reliability Based on ACTUAL MTBF Data
(Rosenberger et al., 2005, p. 14)

System maintenance data also proved very valuable when used by CSC staff to determine system health status and to provide efficient distance support. The data provided several lessons regarding inefficiencies in current maintenance data collection and analysis processes. First, the time to create summary data reports sent to the ARCI CSC became excessive because the MFOP maintenance database grew over the logging period. Secondly, the amount of operator intervention to create and send reports was not efficient. Finally, the process of physically removing MFOP data hard drives and returning complete data sets to ARCI CSC required replacement drives to be sent to the boats as dataset swing drives. This process for the complete data set retrieval process involved unnecessary hard drive movement and, more importantly, was very labor intensive.

One unanticipated result of the ARCI pilot involved spare components that reduced the need for open cabinet repairs to sonar systems while on deployment (Boudreau, 2006, p. 34). In a 2006 NPS study conducted by Michael Boudreau, Boudreau found that

- sonar system spare components could be installed and fully powered in electronics cabinets, enabling them to be used in the event of a primary system malfunction;
- if a system failure occurred in the operating system, it could be switched to a spare module without physical access to the cabinet;
- the necessary quantities of plugged-in spares were calculated that would achieve a high likelihood of continued operation; and
- open cabinet maintenance during deployment had been virtually eliminated (Boudreau, 2006, p. 34).

Technological advances resulting from the ARCI pilot are summarized in Table 7.

Table 7. Summary of ARCI Technological Advances Resulting From the MFOP Pilot
(Adapted from Rosenberger et al., 2005, pp. 9–10)

AREA	RESULTS
Operational Availability	• ARCI System Operational Availability improved by embedding spares within system. • In the case of a failure, software reconfiguration to utilize an embedded spare is approximately 2 minutes. • By contrast, the mean time to repair requirement is 20 minutes for a failed server. • A 10x improvement is achieved by having embedded MFOP spare assets and deferring the repair to a planned maintenance period.
Network Management	• System Network Management tools were being included into the ARCI TI04 system based on this pilot and fleet lessons learned.
Remote Support	• Remote Support/Distance Support became critical part of MFOP Pilot and ARCI program. • Routine communication to the MFOP pilot platforms was established from the ARCI CSC. • Recommendations for keyboard recovery or placing an MFOP asset into a failed state were returned to the platform based on this analysis. • Additional non-MFOP related system problems were identified to CSC for recovery recommendations.
Integrated Data Bases	• Prior to the MFOP Pilot Program, integrated databases were used for system management, target classification, and mission planning. • As part of the MFOP Pilot Program, a maintenance or MFOP database was added to the ARCI system. • Logging and analysis of critical system parameters was used in lab testing to assist in determining system problems and severity. • This data was used by MFOP Support Team personnel to expedite maintenance actions. • Analysis tools were being developed to better translate the maintenance data into maintenance support information as a follow-on to pilot.

5. Summary

The MFOP Pilot Program was conducted for a period of one year to test the feasibility of today's COTS technology and the support tools it provides to design into the ARCI system architecture the ability to obtain a maintenance-free operating environment for a 90-day period. The results of the MFOP Pilot Program far exceeded predictions and expectations. A viable maintenance strategy, MFOP could potentially eliminate unplanned maintenance, along with its associated training, documentation, and supply support during the platform operating period. Figure 26 is a sample data analysis report.

688 (SSN 710) Underway Data Analysis #2								
Underway Period: 20 Days								
	NMCAV	TB23	SA DIMUS	TSMS	STDA	HA/TB16	DDCS	SA LINEAR
Total Recoveries	58	13	35	57	111	84	21	45
Total Runtime (hrs)	494.9	497.8	491.9	495.9	473.9	484.1	501.2	490.8
Avg Longevity (hrs)	8.5	38.3	14.1	8.7	4.3	5.8	23.9	10.9

5-6 hours is not normal for HA/TB16. This should be approximately 24 hours. Confirmed with crew that troubleshooting was in progress during this period and provided Distance Support.

Figure 26. MFOP Sample Data Analysis Report
(Rosenberger et al., 2005, p. 20)

D. Surface Ship MFOP Demonstration (2010)

The surface ship OA/MFOP's objective was to develop a scalable and extensible demonstration system providing more than 99% probability tactical capability for a combat ship with 180 days of no open cabinet maintenance and eliminating the traditional shipboard maintenance support package (Guertin &

Bruhns, 2011, p. 4). A number of commercial companies worked alongside the DoN to complete this pilot, as seen in Figure 27.

Figure 27. Participants in Surface Ship Demonstration
(Guertin, 2010, p. 2)

The surface ship demonstration was designed to ensure that lessons learned could be used for large-scale, complex National Security Systems (NSS) programs. For this demonstration, three particular design features were used: remote connectivity, data capture/collection, and fault tolerance. Figure 28 shows the design elements of this project.

Figure 28. OA/MFOP Design Elements
(Guertin & Bruhns, 2011, p. 5)

1. Fault Tolerance

To ensure that the hardware platform was fault tolerant, redundancy was added and embedded based on the hardware vendor's supplied component MTBF data. An additional method for controlling spare resources (failover) was also added. The IBM Blade Center "T-Chassis" was selected given the inherent redundancy built into the product design. In addition, the number of power, cooling, network communications, processors, and other elements were scalable to meet the reliability demands of the operating period (Guertin & Bruhns, 2011, p. 3). The application server magnetic hard drives were relocated to the IBM DS3400 to further improve MTBF.

Beyond redundancy, the ratio of uptime to total mission time had to be analyzed to achieve full operational availability. In this case, *uptime* is defined as the availability of warfighting capability and not a function of hardware longevity. While components can fail at any time, the probability for failure is higher when a component is new and declines to a low probability for the bulk of the hardware life span. Although components are relatively stable during this period, components do fail, so an automated failover and network reporting were critical to an MFOP-enabled system.

Alternatively, component failures also rise toward the projected in-service life of the product and are significantly influenced by environmental conditions (i.e., temperature and humidity). Environmental monitoring to track system operating conditions, in conjunction with historical environmental data, was essential to an MFOP system. After conducting a survey of commercially available data center management software solutions, the IBM Director management software product was selected because it not only met monitoring and failover requirements, but it also offered a unique feature called “open fabric manager.” This feature not only managed all worldwide names and logical unit numbers for application servers, but it also automatically reconnected the application storage volume on the storage area network (SAN) to a spare processor and resumed processing.

2. Data Capture/Collection

All components were monitored and the data was continuously collected for online assessment and post-mission analyses. Using a layered approach, the OA/MFOP demonstration captured data that included time series monitoring of critical performance and environmental parameters. This layered approach is a critical design element that ensured scalability to multiple warfighting platforms and domains.

Crucial information was made available that allowed decision-makers to perform prognostic maintenance decisions. If a failure had occurred, automatic reconfiguration also occurred and a report was generated. The distance support specialist had information on the system’s state, remaining hardware availability, and the likelihood of future component failures that reflected life and environmental conditions. Based on this information, three decisions were possible:

1. Near-term corrective action is necessary to sustain operational availability of the capability during the deployment period.

2. No action is required and corrective action can wait until after the deployment is complete.

3. No action is required until the next full technology insertion event. (Guertin & Bruhns, 2011, p. 7)

More importantly, these decisions could be made throughout the system's life span and were fully available throughout the operational command and support infrastructure. This was not possible under previous processes without an OA/MFOP-enabled system.

The specific solutions to handle monitoring requirements are found in Table 8.

Table 8. Monitoring Requirements
(Guertin & Bruhns, 2011, p. 8)

Hardware Monitoring	• All replaceable component devices in the OA/MFOP system were monitored. • Components within the Blade Center hardware boundary were monitored by the two (redundant) Advanced Management Modules (AMMs). • Those external to the blade center were attached to the Ethernet network, and their state data collected through SNMP and SMI-S traps. These data were then interfaced with the IBM Director management software for monitoring and event action purposes. • The captured data were stored in an Oracle database that could be queried by subject matter experts as well as life-cycle support planners, project managers, and Type Commanders. This data served in off board analyses leading to proactive decision-making.
Environmental Monitoring	• The physical environment is key to determining cause and effect properties of deployed hardware. • Most hardware failures that occur outside the machine's expected longevity envelope are caused by extreme temperature, humidity, dust, power surges, and vibration. • The OA/MFOP demonstration system included an NTI Inc. Enviromux 16™ processor to collect and transmit this data to the management server. • This data was time tagged for correlation and trending purposes in support of off-board analyses.
Application Server Monitoring	• Several software agents provide various levels and degrees of application server monitoring. Generally, they all log application uptime, and provide some level of basic resource monitoring, such as CPU load percentage, Memory percentage, I/O throughput levels, and storage system utilization. • The OA/MFOP system selected and used the IBM Director management software "Level II Managed Agent" product for all application servers in the system.

3. Remote Connectivity

The OA/MFOP system was connected to SIPRNet. This link enabled the collection of reliability performance information for online assessment and allowed subject matter experts (SMEs) ashore to restore system operation in the event of a software failure. Figure 29 shows the distance support component.

Figure 29. The Surface Ship MFOP Demonstration System
(Guertin, 2010, p. 8)

Three technologies were used to perform remote monitoring and administration functions:

- The IBM Director management console, which provided remote administration functionality;
- ROHMS, which provided off-hull transport mechanisms to collect and transport OA/MFOP system data; and
- Virtual Network Connection (VNC), which provided remote login capability as a root user to any selected server.

To monitor the system, the OA/MFOP system re-used the ROHMS software developed by NAVSEA PMS 401 contract that is based on open source software. Concise reports, about the size of a typical e-mail record, were sent. Under normal conditions, system stakeholders (i.e., SMEs, program managers, and type commanders) only want to know the status of the deployed system, so as long as the system was functioning as designed, brief reports were sufficient (Guertin & Bruhns, 2011, p. 9). The types of reports generated were the following:

- a daily summary status report that listed the status of all hardware, environmental levels, application availability, and resource utilization;
- an event report if a system event or hardware failure occurred, in which case, the ROHMS connector on the ship transmitted an event report that listed cause, effect, and restorative action; and
- a detailed report that provided event detail to be used by SMEs to determine if follow-up action or planning was necessary.

The OA/MFOP system used two remote system administration techniques over SIPRNet, as seen in Table 9.

Table 9. Remote System Techniques
(Guertin & Bruhns, 2011, p. 9)

TYPE	PURPOSE
Web Browser	• Menu driven login using HTTPS with Secure Socket Layer (SSL) encryption. • Used because system was deployed as autonomous, with no ship's force assistance. • This method is very network bandwidth efficient, but in most instances the utility provided does not necessarily require the services of an off board SME.
Virtual Network Connection (VNC)	• Technique allowed remote SME to login to a specific server/processor at the system administrator level. • VNC used frame buffer relay techniques to provide the SME with a remote interface to the target machine. From there, the system could be analyzed, restored, and updated. • Real VNC product used to positively control the system during deployment.

Figure 30 shows the daily message data set.

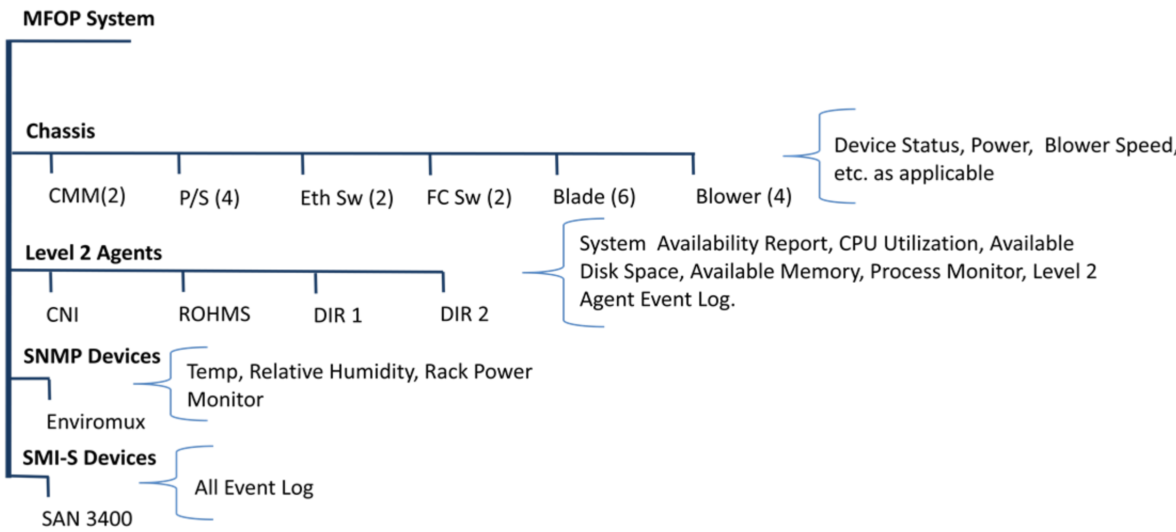

Figure 30. System Daily Status Message Data Set
(Bruhns, 2009, p. 19)

4. OA/MFOP Demonstration Results

The demonstration successfully met expectations. In the area of measured operational availability, the Common Network Interface (CNI) operational software was 99.67% over the deployment period. The remaining unreliability level (0.33%) was due to the two induced failures used to test the automatic failover response of the system. The operational availability of the ROHMS application server was measured at 100%, because ROHMS was not intentionally failed while deployed (Guertin & Bruhns, 2011, p. 11).

In addition, there were no actual hardware failures during the deployment period. The system was in continuous operation for two years with no physical failures noted. Six distance support objectives were also successfully demonstrated. These objectives, designed to eliminate the need for shipboard ILS products and Fleet Technical Assistance "fly-away" time and cost, were the following: monitoring all hardware statuses; monitoring server operations and resources; collecting system availability and environmental data; remotely inducing simulated failures/observed automatic failover and recovery using embedded spares; and performing remote IT, including restarts, pushing files, adding applications, and correcting code errors.

E. Summary

To date, two projects involving MFOP concepts have been conducted by the Navy. Both projects exceeded expectations with a number of efficiency and cost savings. The ARCI pilot resulted in distance support cost savings by a ratio of 7:1 while the USS *Iwo Jima* demonstration achieved a savings ratio of 15:1. Although one of the original project goals was to estimate the relative cost savings and ROI advantages of the MFOP, further research needs to be conducted into costs and ROI because the cost savings ratio was the only quantifiable data researchers had access to.

VIII. MFOP Models

There have been efforts to quantify and apply the MFOP with mathematical models and simulation software. This section briefly discusses some of those efforts and in the appendix, we provide an example of a future MFOP model that was initially developed by NPS.

A. Maintenance Free Operating Period Model

In 1999, U. D. Kumar, J. Knezevic, and J. Crocker developed the first MFOP mathematical models (Kumar et al., 2009). In their paper, *Maintenance Free Operating Period—An Alternative Measure to MTBF and Failure Rate for Specifying Reliability?*, the authors developed two mathematical models to predict MFOPs:

- a prediction based on a mission reliability approach and
- a prediction based on an alternating renewal approach (Nowakowski & Werbinka, 2009).

Under the first example, consider a system with n components connected in a series. The probability that the system will survive the i-th cycle of the MFOP, given that it survives (i − 1) cycles, is

$$MFOPS(t_{mf}, i) = \prod_{k=1}^{n} \frac{R_k\left(i \cdot t_{mf}\right)}{R_k\left([i-1] \cdot t_{mf}\right)} \qquad (1)$$

Rk(*tmf*) is the reliability of the *k*-th component for (the first) *tmf* life units (Nowakowski & Werbinka, 2009). This model is based on the following assumptions:

- The system time to failure and repair follows arbitrary distributions.
- The time to failure distributions of various items of a system are independent.

In the second alternating renewal approach, the MFOPs is found during a stated period of T along with the maintenance recovery period. The probability that a system operates for at least t_{mf} life units before it fails during T hours of operation is

$$P_1(T) = R(t_{mf}) + \int_0 f(\mu | t_{mf}) P_0(T - \mu) \, \mathrm{d}\mu$$

and

$$P_0(T) = \int_0^T g(\nu) P_1(T - \nu) \, \mathrm{d}\nu \qquad (2)$$

where $f(\mu / t_{mf})$ is the probability that the system fails at time μ (Nowakowski & Werbinka, 2009). This model is based on the following assumptions in a repairable system:

- the time to failure distribution of an item follows arbitrary distribution with density function *f(t),*
- the maintenance recovery time of the item follows arbitrary distribution with density function *g(t),* and
- the item can be in one of two states {1,0}, where 1 is up state and 0 is down state (Nowakowski & Werbinka, 2009).

B. Phased Mission Modeling Using MFOP and Petri Nets

Chew, Dunnett, and Andrews (2007) described the use of a Petri net to model the reliability of the MFOP under phased-mission scenarios. By using a form of the Monte-Carlo simulation to obtain results, in conjunction with Petri nets modeling power, the phased mission model of systems considers various complexities, including component failure rate interdependencies, multi-mission periods, and mission abandonment. Figure 31 shows the master Petri net model.

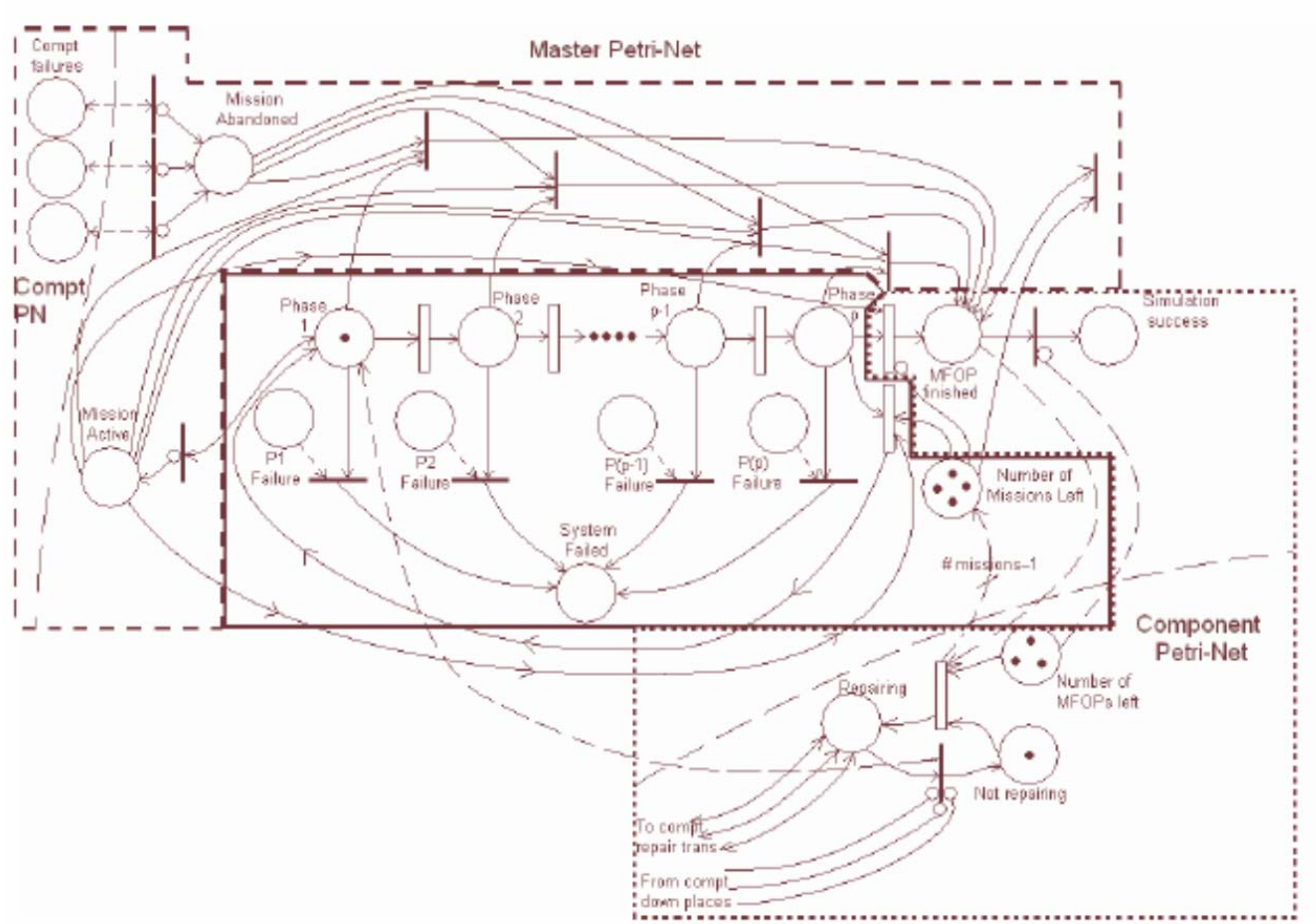

Figure 31. Master Petri Net
(Chew et al., 2007, p. 227)

Key. The solid line border indicates control of the sequence of phases, and failure or success of each mission. The dotted line border indicates the ending of each mission or MFOP and performing repairs. The dashed line border indicates the abandoning of the mission due to specific component or system failures.

C. Minimum Failure-Free Operating Period Model

Extending the MFOP model, M. T. Todinov proposed the minimum failure-free operating period (MFFOP) as a new reliability measure. The MFFOP is defined as a combination of specified minimum intervals before random variables in a finite time interval are guaranteed with a minimum probability P_{MFFOP} (Nowakowski & Werbinka, 2009). For example, consider a system comprised of a non-repairable component, with the following assumptions:

- replacement of a component that is “as good as new” and
- in a critical event, a “critical repair” leads to a system halt or degeneration of the required function below a minimum acceptable level and to require an immediate intervention for repair.

The random failures following a homogeneous Poisson process, minimum probability P_{MFFOP} is

$$P_{MFFOP} = \sum_{k=0}^{r} \frac{(\lambda a)^k \exp(-\lambda a)}{k!} \times \left(1 - \frac{ks}{a}\right)^k \quad (3)$$

where $(\lambda a)^k \exp(-\lambda a)/k!$ is the probability of exactly k failures in the finite time interval a, and $p(S/k) = (1 - ks/a)^k$ is the conditional probability that—given k random failures—before each failure, there will be a failure-free gap of length of at least s (Nowakowski & Werbinka, 2009).

D. Integrated Logistics Model Using the MFOP

R. Fritzsche and R. Lasch (2012) developed an integrated logistics model of spare parts maintenance planning for the aviation industry using MFOP concepts. The authors developed a three-level model for simplified decision support in the aviation industry. By dividing the whole planning process into three simpler planning sub-areas, network planning complexity was decreased. In this model, the MFOP was used to calculate failure rates of installed components, which could be continuously adjusted downwards. The model was designed to support the tactical and strategic decisions of an airline, with the ultimate objective of reducing unscheduled maintenance events and minimizing total costs.

The three-level model, as seen in Figure 32, shows the impact of maintenance upon the whole network. The model represents the total costs of an airline and identifies opportunities for the maximum supply of spare parts at minimal costs. It also offers an opportunity for a more efficient use of the components’ lifetime and ordering of spare parts at the optimal time.

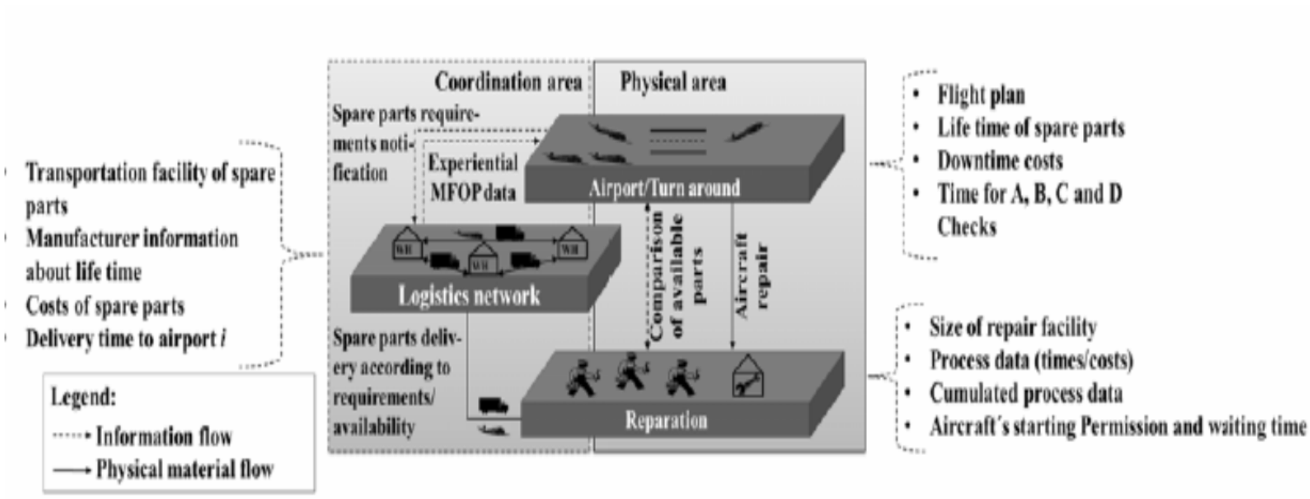

Figure 32. Three-Level Model
(Fritzsche & Lasch, 2012, p. 4)

In the model, three parallel operating levels are connected by flows of information and goods. The first level is the airport/turnaround where aircraft departure, flight, and landing occur. In the second level, repairs such as replacing defective components take place. The third level is the logistics network where principally planning and decision processes are made. Because the first level of the model is responsible for movement of aircraft according to the flight plan and degrading of failure rates, it is here that all items are checked for their remaining MFOP time (Fritzsche & Lasch, 2012, p. 4). If a component does not have enough MFOP remaining useful life, the optimal exchange point and location is calculated. A message is then forwarded to the logistics network and the aircraft is transferred to the repair facility.

The Fritzsche and Lasch model minimizes the total cost of an airline under a preventive maintenance strategy with a dynamic failure rate adjustment. The formula used to calculate total costs is shown as follows.

$$C_{Tot} := \sum_j (c_I \cdot S_j + c_T \cdot T_j + c_D \cdot U_j) \rightarrow Min$$

C_{Tot}	Total cost
c_I	Inventory cost
c_T	Transportation cost
c_D	Downtime cost
S_j	Inventory level at station j
T_j	Expected transportations to station j
U_j	Downtime at station j

$$0 \leq C_{Tot}, c_I, c_T, c_D, S_j, T_j, U_j < \infty$$

(Fritzsche & Lasch, 2012, p. 5)

Fritzsche and Lasch ran a simulation to validate their model. The simulation's objective was to provide continuous availability of spare parts at the lowest cost.

- ***Model Validation Through Simulation***

Fritzsche and Lasch's model compared three maintenance strategies: prognostics and health management (PHM) scheduled, PHM time based, and unscheduled maintenance. To validate the model, the authors created a simulation study involving four airlines based on a real airline flight plan with 45 aircrafts (20 for Quantas Airline [QF], nine for Virgin Airlines [VS], seven for Korean Airlines [KE], and nine for Thai Airlines [TG]) and four main bases with 10 outstations, as shown in Figure 33.

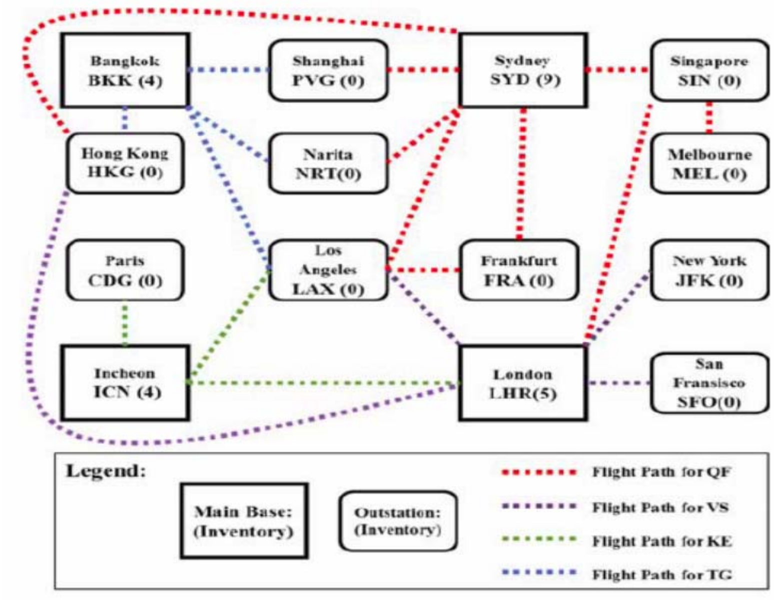

Figure 33. Airline Network Information Used in Simulation
(Fritzsche & Lasch, 2012, p. 5)

Table 10 lists the data and parameters required to run the simulation.

Table 10. Simulation Parameters
(Fritzsche & Lasch, 2012, p. 8)

Price of the installed spare part	$50,000
MTBUR	1500h
Weibull scale parameter	948h
Weibull shape parameter	1.7
PHM time based exchange interval	750h
Installed spare parts per aircraft	1
Replacement time of the spare part	20min
Repair time of the installed spare part	25 days
Renewal time of the installed spare part	60 days
Turn around time of an aircraft	45min
Annual inventory costs of the spare part	$10,000
Logistics costs for a spare part transport	$2,000
Downtime costs per minute	$50
Penalty downtime costs per minute for unscheduled failures	$90
Maintenance costs	$300 per man hour
Delay costs per minute	$175
Cancellation costs	$60,000

- ***Simulation Results***

Figure 34 shows the calculated cost of the network, comprised of transportation costs, downtime costs, and inventory costs. Under the PHM scheduled maintenance strategy, the total costs hardly varied given that strategy costs are predictable and projectable. Alternatively, the other two strategies are very volatile and result in significantly higher total costs. Randomly occurring component failures result in very high penalty costs and in further delays, or even cancellations, of aircraft. The cumulative total costs over the simulated two years amount to $26.4 million for the unscheduled maintenance strategy, $6.5 million for the PHM scheduled strategy, and $29.8 million for the PHM time-based strategy (Fritzsche & Lasch, 2012, p. 7).

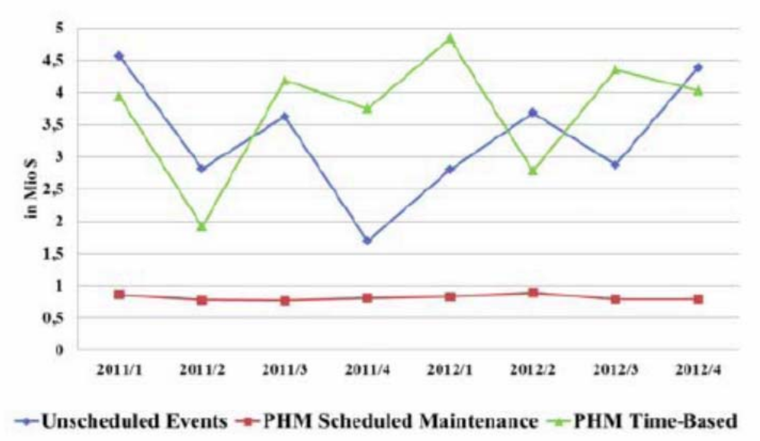

Figure 34. Quarterly Calculated Total Costs
(Fritzsche & Lasch, 2012, p. 7)

The advantages of a preventive maintenance strategy are shown in Figure 35. Although the PHM scheduled strategy and the PHM time-based strategy generated more overall maintenance actions, it resulted in avoidable unscheduled maintenance activities. Many unscheduled maintenance events result in associated penalty costs, so the overall cost to the airline increases significantly. Under the PHM scheduled maintenance scenario, most scheduled maintenance events occur, yet there are no additional running costs because required spare parts are already available at a predicted location.

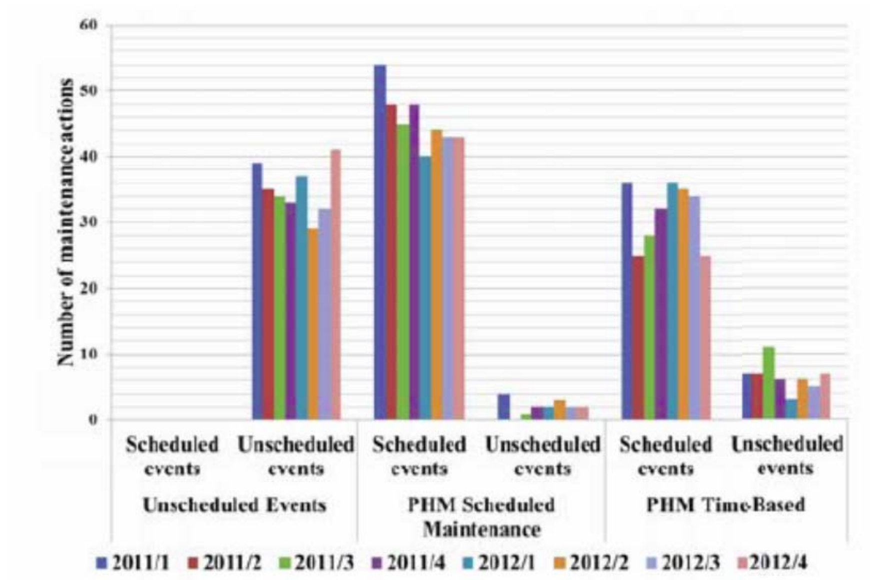

Figure 35. Types of Maintenance Actions
(Fritzsche & Lasch, 2012, p. 8)

In Figure 36, the results of a reactive maintenance strategy are shown with significantly more unscheduled failures. Under this strategy, installed components are used until failure with no prediction of impending failure.

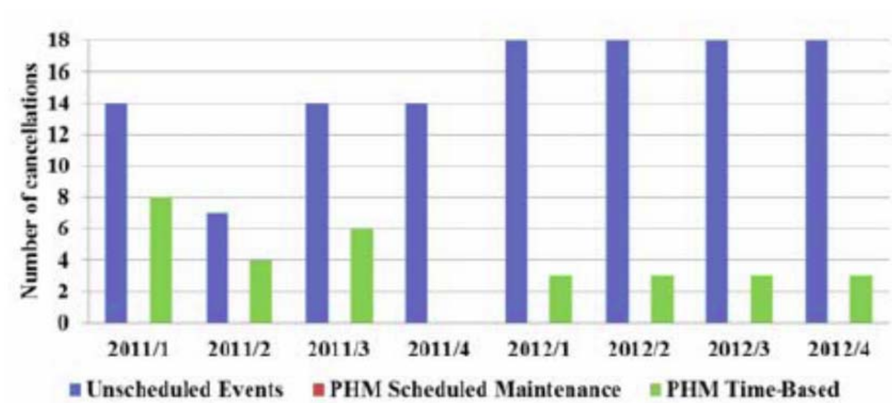

Figure 36. Constituted Aircrafts Cancellations
(Fritzsche & Lasch, 2012, p. 8)

The simulation study conducted by Fritzsche and Lasch showed that a well-selected and appropriate maintenance strategy could result in significant cost reductions.

E. Systems Reliability Modeling for Phased Missions Using the MFOP

In 2010, S. Chew investigated the creation of a modeling method to consider as many features of systems undergoing both MFOPs and phased missions as possible. Through the use of Petri nets and Monte-Carlo simulation, he presented a simple and then a more complex model to deliver MFOP with a high confidence level.

One goal driving this research was to develop methods enabling accurate analysis of the MFOP and its applications. In addition, the analysis method should allow further insight into as-yet-unforeseen problems that may arise and should contribute to assessments into whether the MFOP is a metric that will be useful in future applications (Chew, 2010, p. 10). The analysis method must also consider multiple phases of missions.

1. Development of the Simple Model

The Petri net technique can be used to model a basic MFOP. Petri nets can provide an easier way of predicting system or platform reliability and can be used in phased missions. Chew first developed a model that accounted for reliability considerations (i.e., system, component, phase, mission, and MFOP failure; mission abandonment; the MRP and component failures affecting the failure rate of another component).

This initial model that Chew developed focused on the simplest MFOP type, where one mission is repeated a finite number of times before the MRP. To develop this model, Chew analyzed a simple repetitive mission and MFOP profile containing a defined sequence of phases and then used the Markov analysis tool within a software program to find the MFOP success and failure rates. These rates were also predicted using the Petri net modeling software after performing 10,000,000 simulations (Chew, 2010, p. 134). Table 11 shows both sets of results from the two tools.

Table 11. Results From the Markov Analysis and the Petri Net Model
(Chew, 2010, p. 135)

MFOP	Platform unreliability up to end of MFOP (Markov)	MFOP Failure Prob. (Markov)	MFOP Failure Prob. (Petri Net Model)	Percentage Error between results
1	0.32473	0.324730	0.324872	0.0437%
2	0.5498	0.333304	0.333222	0.0246%
3	0.7026	0.339405	0.339228	0.0522%
4	0.7992	0.324815	0.324865	0.0154%
5	0.8661	0.333167	0.332750	0.1252%
6	0.91157	0.339582	0.339362	0.0648%
7	0.94029	0.324777	0.323946	0.2559%
8	0.96018	0.333110	0.333117	0.0021%
9	0.97370	0.339528	0.339884	0.1049%
10	0.98224	0.324715	0.324741	0.0080%
11	0.98816	0.333333	0.333041	0.0876%
12	0.992179	0.339443	0.339061	0.1125%

As seen in Table 11, the MFOP failure rates produced by the Markov model and the Petri net model software show a high degree of correlation. Due to the possible repair of C and D only after the third MFOP, the results follow a cycle where the MFOP failure probability increases slowly and then returns to the initial level after the third MRP (Chew, 2010, p. 135).

The modeling method was then applied to a larger 10-phase, 10-component system. Three missions were performed in each MFOP, and three MFOPs were carried out in each simulation. 1,000,000 simulations were performed to reach an estimate of the likelihoods of failure of the MFOPs, missions, and phases (Chew, 2010, p. 136). The number of simulations, failures, abandonments, and conditional failure probabilities for each of the MFOPs and missions are shown in Table 12 while Table 13 shows the number of failures of each phase in each mission and their total failure probability.

Table 12. MFOP and Mission Failure Results
(Chew, 2010, p. 138)

MFOP/ Mission	Starts	Failures	Abandon- ments	Failure Prob.
MFOP 1	1000000	113270	618047	0.731317
MFOP 2	886730	60814	766730	0.933253
MFOP 3	825916	34780	778346	0.984514
Mission 1	2712646	105400	928724	0.381223
Mission 2	1678522	67725	805461	0.520211
Mission 3	805336	35739	428938	0.576998

Table 13. Phase Failure Results
(Chew, 2010, p. 139)

Phase	Starts	Failures in			Total	Failure
		Mission 1	Mission 2	Mission 3	Failures	Prob.
1	5196504	3300	72030	34800	110130	0.021193
2	5086374	45587	60528	33264	139379	0.027402
3	4946995	9	27	24	60	0.000012
4	4946935	37868	30475	20633	88976	0.017986
5	4857959	274334	310171	187647	772152	0.158946
6	4085807	32128	22453	9263	63844	0.015626
7	4021963	51337	41698	22158	115193	0.028641
8	3906770	151011	88526	36544	276081	0.070667
9	3630689	0	0	0	0	0
10	3630689	438550	247278	120344	806172	0.222044

Chew then developed a more complex model, which considered multifaceted aspects of phased missions and MFOPs.

IX. Conclusions

The purpose of the research was to understand the potential impact of the MFOP on processes, procedures, and costs in acquisition planning. The research team from NPS investigated the MFOP concept and analyzed pilot demonstrations previously conducted on four submarines and the USS *Iwo Jima*. Based on the research, the MFOP could provide life-cycle savings and innovation in system sustainment.

The two DoN demonstrations involving the MFOP exceeded expectations with a number of efficiency and cost savings. In the first ARCI pilot, distance support cost savings of a 7:1 ratio was achieved, while in the latter USS *Iwo Jima* demonstration, a 15:1 savings ratio was achieved. The ARCI pilot also resulted in the reduction of open cabinet repairs to sonar systems while on deployment and the issue of spare components. In that pilot, open cabinet maintenance while underway was virtually eliminated. Although further research needs to be conducted with statistical data that the NPS researchers did not have access to, given the initial results of the DoN pilots, the MFOP could be a viable strategy for the naval enterprise.

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Appendix. Future MFOP Model Requirements

(Pfeiffer, Kanevsky, & Housel, 2010)

The following outline posits the requirements for a future MFOP model. The model was developed with limited inputs from discussions with the sponsor and represents a first cut on an improved model. It does not include parameters for humidity and heat, which were not specified before the development of the model.

The model requirements outline is as follows:

- Modular structure: $S = \{M_1, \ldots, M_n\}$ - functionally mutually independent, testable and replaceable units.
- Prior probabilities: $p_1, \ldots, p_n$ to find the i-th module immediately incorrect.
- $F_i(t) = P(\tau_i > t)$, where τ_i is a moment of the i-th module's first failure. $F_i(t) = 1 - F_i(t)$ is the distribution function and $f_i(t) = F'_i(t)$ is its density function.
- The state of the system is determined by the states of its modules and some random factors attributed to the specifics of a failure mode.

The following is a listing of the formal properties of the system described in the preceding outline.

It is also useful to introduce a *failure rate* functions $\varphi_i(t) = f_i(t)/F_i(t)$ in the model, which can be interpreted as the probability of almost instantaneous failure after *failure free* work up until moment t, i.e., $\varphi_i(t)\Delta t$ is the probability of a failure during time interval $(t, t+\Delta t)$ given that no failure happened prior to moment t. A failure of the i-th unit/module is associated with the loss/cost, which is usually measured either in dollars or out-of-service (down time) units C_i.

The test map requirements for the proposed system are as follows:

- Test is a map from the space of the system's states S to {0, 1}:

$$T: S \rightarrow \{0, 1\}$$

- Testing of the whole system or its parts is intended to identify the states of its units/modules and/or to assess the likelihood *of* a failure during a given time period (e.g., the remaining part of the mission).

- Execution of T is associated with cost C(T).

- The ability of a test T_j to detect a “bug” given a single-module M_i system is bad is called *coverage* w_{ji} of test T_j on module M_i. Formally:

$$P(T_j = 1 \mid M_i \text{ is bad}) = w_{ji}$$

The following paragraph answers the question, What is the test, and what does it do?:

Effectively test T—more specifically, its result (“Fail”(1) or “Pass”(0))—changes the probability of the system’s modules’ state into conditional probabilities given the test result. Since the test is not free, the following questions arise:

What test from the available menu should be applied first?

What is the next best test to apply given results of the previous test?

Scenario

- *System failure* is defined as a failure of at least one of its modules. Given that the system was operational up until moment (k-1)Δt, probability of failure during the following Δt time interval can be computed as

$$h(k, \Delta t) = 1-\prod[1- \varphi_i((k-1)\Delta t)\Delta t]^{k-1}$$

- The imbedded monitoring and control system carries over an online probability of system failure computation at time moments kΔt. The system alarm goes off if h(k, Δt) exceeds its critical value, which was set up under tolerable risk considerations.

- If the alarm is accepted, mandatory testing starts over.

It is intuitively appealing to go for the best “bang for the buck,” that is, start with the test that has the best ratio.

Reduction of Uncertainty and Cost

Mathematically, the model translates into a sequential decision process driven by the value of the ratio:

- information acquired by the test/test's cost
- information acquired by the test = H(system before test) - H(system after test)
- *H* stands for entropy
- entropy H for the system, whose N states have probabilities

$p_1, \ldots, p_N$ is defined as

$$\mathbf{H} = -\sum p_i \log p_i$$

- In our case, probabilities p_i are conditional given test results.

This work is built based on our previous research. We tested the described approach on simulated data with consistently good results.

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