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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPTIMIZED PROCUREMENT AND RETIREMENT PLANNING OF NAVY SHIPS AND AIRCRAFT

by

Ruben M. Garcia

December 2001

Thesis Advisors:	Robert F. Dell
	Javier Salmeron
Second Reader:	Gerald G. Brown

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The Capital Investment Planning Aid with Air Planning Update (CIPA APU) is a force structure planning tool that can be used to suggest ship, submarine, and aircraft procurement and retirement schedules over a 30-year horizon. These plans represent over a $1 Trillion commitment to ensure the Navy stays capable to fulfill its missions. Navy long-range force structure planners at the Chief of Naval Operations, Assessment Division (N81), currently manually prepare alternate future ship, submarine, and aircraft procurement and retirement schedules and evaluate these with a contractor-developed spreadsheet tool. This tool, the Extended Planning Annex/Total Obligated Authority (EPA/TOA) model, estimates the financial impact of any complete future plan over a 30-year horizon. While manually preparing such plans, N81 Force Structure Planners must consider annual budget, industrial base, and force structure requirements expressed in terms of the number of platforms needed to support a mission. With yearly time fidelity, CIPA APU replaces manual planning with optimized budget planning, with, for example, 19 mission areas, 19 ship classes, 58 aircraft types, five ship-production facilities, and three categories of money. CIPA APU tracks average aircraft age, expected attrition, and allows planners to specify a platform's mission suitability. It also provides expeditious feedback to requests for alternate scenario feasibility and budget impact. We demonstrate CIPA APU capabilities using a few realistic scenarios.

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OPTIMIZED PROCUREMENT AND RETIREMENT PLANNING OF NAVY SHIPS AND AIRCRAFT

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

The Capital Investment Planning Aid with Air Planning Update (CIPA APU) is a force structure planning tool that can be used to suggest ship, submarine, and aircraft procurement and retirement schedules over a 30-year horizon. These plans represent over a $1 Trillion commitment to ensure the Navy stays capable to fulfill its missions. Navy long-range force structure planners at the Chief of Naval Operations, Assessment Division (N81), currently manually prepare alternate future ship, submarine, and aircraft procurement and retirement schedules and evaluate these with a contractor-developed spreadsheet tool. This tool, the Extended Planning Annex/Total Obligated Authority (EPA/TOA) model, estimates the financial impact of any complete future plan over a 30-year horizon. While manually preparing such plans, N81 Force Structure Planners must consider annual budget, industrial base, and force structure requirements expressed in terms of the number of platforms needed to support a mission. With yearly time fidelity, CIPA APU replaces manual planning with optimized budget planning, with, for example, 19 mission areas, 19 ship classes, 58 aircraft types, five ship-production facilities, and three categories of money. CIPA APU tracks average aircraft age, expected attrition, and allows planners to specify a platform's mission suitability. It also provides expeditious feedback to requests for alternate scenario feasibility and budget impact. We demonstrate CIPA APU capabilities using a few realistic scenarios.

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DISCLAIMER

The reader is cautioned that the computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS

APN	Aircraft Procurement Navy
CBO	Congressional Budget Office
CIPA APU	Capital Investment Planning Aid Air Planning Update
EPA/TOA	Extended Planning Annex/Total Obligation Authority
FY	Fiscal Year
FYDP	Fiscal (Future) Years Defense Plan
ISR	Intelligence Surveillance and Reconnaissance
JSF	Joint Strike Fighter
JSFN	Joint Strike Fighter, Navy Variant
JSFMC	Joint Strike Fighter, Marine Corps Variant
N78	Chief of Naval Operations, Air Warfare Division
N81	Chief of Naval Operations, Assessment Division
OMN	Operation and Maintenance Navy
O&M	Operating and Maintenance
OPN	Other Procurement Navy
PMAA	Primary Mission Aircraft Authorized
QDR	Quadrennial Defense Review
RDT&E	Research Development Test and Evaluation
SCN	Ship Conversion Navy
SEAD	Suppression of Enemy Air Defenses
STOVL	Short Take-Off and Vertical Landing
TACAIR	Tactical Aircraft
TOA	Total Obligation Authority
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Air Vehicle

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EXECUTIVE SUMMARY

The Capital Investment Planning Aid with Air Planning Update (CIPA APU) is a force structure planning tool that can be used to suggest ship, submarine, and aircraft procurement and retirement schedules over a 30-year horizon. These plans represent over a $1 Trillion commitment to ensure the Navy stays ready to fulfill its missions. Navy long-range force structure planners at the Chief of Naval Operations, Assessment Division (N81), currently manually prepare alternate future ship, submarine, and aircraft procurement and retirement schedules and evaluate these with a contractor-developed spreadsheet tool. When provided a complete procurement and retirement schedule as input, this tool, the Extended Planning Annex/Total Obligated Authority (EPA/TOA) model, estimates the financial impact of any complete future plan over a 30-year horizon.

CIPA APU replaces manual planning with optimization, recommending the best yearly force structure procurement plan based on industrial constraints, budget constraints, mission inventory requirements, and force mix requirements. CIPA APU allows budget violations in some years that can be repaid by other savings in other years. This is accomplished with long-term, cumulative budget goals. Given constraints for a planning scenario, CIPA APU recommends an optimum solution. CIPA APU can emulate EPA/TOA if CIPA APU's discretionary variables are all fixed to constant values. But, as a prescriptive model, CIPA APU suggests optimum solutions that might not otherwise be discovered by manual planning and EPA/TOA evaluation.

CIPA APU builds on a prior CIPA optimization-based decision support system that has been custom built for N81 and packaged in a user-friendly graphic user interface. This thesis focuses on improving the underlying optimization modeling for aircraft procurement and retirement scheduling with the expectation that these new features will be added to the custom built decision support system. Most CIPA APU improvements center around tracking aircraft average age. Such tracking allows CIPA APU to model increasing Operation and Maintenance Navy (OMN) costs as aircraft age increases and model an age-dependent aircraft effectiveness of an aircraft type for a mission.

We demonstrate CIPA APU with a few realistic scenarios that plan for 19 mission areas, 19 ship classes, 58 aircraft types, five ship-production facilities, and three

categories of money. These scenarios highlight how CIPA APU optimally alters procurement and retirement schedules to respond to: increasing OMN costs as aircraft ages increase; different effectiveness for aircraft performing Strike Fighter and Ground Attack missions; and the introduction of Unmanned Air Vehicles (UAV) and Unmanned Combat Air Vehicles (UCAV). Results show that explicit consideration of aircraft age and varying effectiveness for mission performance have a pronounced effect on optimal procurement and retirement planning.

CIPA is the only Navy decision support system that integrates aircraft and ship procurement decisions with fiscal, industrial, and mission requirements to render the best integrated long-term advice. When added to CIPA, the CIPA APU enhancements will more realistically model the impact of aircraft procurement and retirement.

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I. PROCUREMENT AND RETIREMENT PLANNING FOR NAVY SHIPS AND AIRCRAFT

The U. S. Navy will spend more than $1 Trillion over the next 30 years to procure ships, submarines, and aircraft that will keep it capable to fulfill its missions. Navy long-range force structure planners at the Chief of Naval Operations, Assessment Division (N81), currently manually explore alternate future ship, submarine, and aircraft procurement and retirement schedules aided only by a contractor developed spreadsheet tool. The spreadsheet tool, the Extended Planning Annex/Total Obligated Authority (EPA/TOA) model, estimates the financial impact of any complete future plan over a 30-year horizon. N81 Force Structure Planners must manually consider annual budget, industrial base, and force structure requirements expressed in terms of the number of platforms needed to support all missions required.

CIPA (Capital Investment Planning Aid), introduced by Field [1999], with the aircraft extensions described here, is a force structure planning tool that complements the EPA/TOA model. The changes to CIPA are referred to here collectively as CIPA APU (Air Planning Update). CIPA APU allows Navy force structure planners to quickly evaluate the impact of changes in budget and/or force structure requirements. For scenarios considered in this thesis, CIPA APU optimizes annual procurement and retirement planning for 25 years, 19 mission areas, 19 ship classes, 58 aircraft types, five ship production facilities, and three categories of money. The 58 aircraft types support 14 of the 19 mission areas. In addition to the preexisting features of CIPA [Field 1999, Baran 2000], CIPA APU now considers aircraft-specific budget constraints, aircraft mission effectiveness, aircraft attrition, minimum and maximum average aircraft age, minimum and maximum average aircraft age designated for a specific mission, and minimum aircraft retirement age.

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II. BUDGET PLANNING STRATEGY

The Navy budget for Fiscal Year 2002 is $99 billion. As of 5 September 2001, the 2003 and beyond annual Navy budget was expected to be cut to $80 billion [Holzer 2001]. Since then, a new worldwide military operation lead by deployed Navy ships and aircraft may have changed this forecast. The point is that budget and force structure planners must constantly develop plans to respond to emergent guidance from the Secretary of Defense and Chief of Naval Operations while meeting tight budget limits. The priorities set within this guidance are always changing. CIPA APU augments current force structure planning tools and ushers in the use of optimization based decision models for N81 force structure and budget planning.

A. CHANGING PRIORITIES

N81 planners face many problems determining and dealing with force structure priorities. Priorities change for many reasons including: a new President and administration, world events, new technologies and systems. CIPA APU can help address some of the competing priorities and allow planners to quickly explore optimized solutions to their ever-changing environment. Below we provide many recent examples of scenarios that must be considered by N81 Force Structure Planners.

1. New Administration

The Defense Planning Guidance (DPG) outlines the missions the U.S. military services must fulfill to satisfy United States National Military Strategy. The George W. Bush administration plan for sizing the force structure started with a pledge to put strategy priorities first and budget priorities second [Scarborough 2001a]. President Bush directed Defense Secretary Rumsfeld to conduct a total review of the 1.36 million person armed forces and reorganize it to meet the 21st century threats. President Bush told our troops, "We must put strategy first, then spending. Our defense vision will drive our defense budget; not the other way around." Rumsfeld requested a $329 billion 2002 budget, the largest one-year defense increase since the 1980's. Rumsfeld implied that the

2002 budget is still considered far less funding than required to meet existing National Military Strategy. Rumsfeld argued that the armed forces have been so under funded and overused in the 1990s that one budget cycle cannot repair all the damage [Scarborough 2001a].

Rumsfeld stated that the average age of aircraft has gone up about 10 years since the 1990s and high maintenance costs are consuming the budget [Thomas 2001]. The Navy is forced to invest valuable maintenance man-hours on aircraft cannibalization, transferring scarce parts from aircraft to aircraft. Rumsfeld states that the "ship-building budget at the current rate is on a trajectory from 310 ships to 230 ships" [Thomas 2001]. The Bush administration's challenge is persuading Congress to supply the money necessary to fix this aging fleet.

The initial 2001 Quadrennial Defense Review (QDR) guidance stated that the U.S. forces must be sized and shaped to concurrently perform three major tasks: defend the U. S. against attacks on the homeland or on defense-related information infrastructure; deter forward in critical areas of the world; and win decisively against an adversary in any one of these critical areas of the world [Grossman 2001]. Secretary Rumsfeld later revised the QDR guidance to eliminate the requirement to perform the major tasks concurrently. This change to QDR guidance reflects the tough compromises being made to fulfill mission requirements while meeting tight budget realities. Defense planners acknowledge that the mismatch between strategy and resources has created a very large number of budget shortfalls. One of these is military modernization. The military wants to get away from having aircraft, ships, and other equipment that are extremely old that drive up operating and maintenance costs [Weinberger 2001].

Facing future budgets as much as $20 billion less than what they expect to receive in 2002, U.S. Navy officials are eyeing deep cuts in force structure, primarily in aviation assets. Navy budget planners have been given guidance from Pentagon officials to expect budgets in 2003 and beyond to be about $80 billion per year. This level is far below the $99 billion the service is set to receive in 2002. Some of the proposed Naval aviation cuts include retiring an aircraft carrier in 2004, retiring all AV-8B Harriers by 2005,

retiring all F-14s by 2006 instead of 2009, retiring two P-3 maritime patrol squadrons in 2004, and retiring two Naval Reserve P-3 squadrons in 2003 [Holzer 2001].

2. World Events and Responses in Force Structure Planning

World events impact our Defense budget and force structure planning. The USS Cole attack [Navy Public Affairs Library, 2000] and the EP-3 collision with a Chinese fighter [Navy Public Affairs Library, 2001] are recent examples with minimal initial impact on Naval inventories, but with potential widespread influence on force structure planning.

On 11 September 2001, terrorists crashed two hijacked commercial airliners into the twin towers of the World Trade Center in New York and a third jet into the Pentagon [Rhem 2001]. In the wake of these terrorist attacks, Congress approved $40 billion in emergency defense funds. The Pentagon plans to spend half of the first $2.5 billion installment on intelligence upgrades and is expected to spend an additional $1 billion with the next installment [Capaccio 2001]. The Pentagon plan is to improve Intelligence Surveillance and Reconnaissance (ISR) aircraft and to buy more unmanned reconnaissance planes and privately-owned satellite imagery. The Pentagon wants more specialized airborne and ground sensors that can spot and analyze fixed or moving targets. The 2001 QDR now includes specific allocations of money and tasks to homeland defense [Liang 2001]. It will take almost a year after the 2001 QDR release to refine the areas involving personnel, the National Guard, and Reserves. Part of the first installment includes $200 million for repairs to the Pentagon and increased fuel costs; $196 million for increased flying hours, maintenance, ship steaming, and mobilizing the National Guard.

The 11 September 2001 terrorist attacks have increased efforts to upgrade the Pentagon's aging fleets of surveillance and tanker aircraft. The Navy is considering accelerating purchases of C-40 transport planes to replace its much older C-9 cargo planes [Pasztor et al. 2001].

Since President Bush declared war on terrorism, more money has been promised to the Defense Department. The QDR retains 12 Navy carriers [Scarborough 2001b].

The big question is whether more money will be available to upgrade the rest of the fleet. Anti-terrorist operations will place more wear and tear on the combat fleet that is already in urgent need of updated platforms. Another question is what additional money will be provided to pay for operating and maintaining the Navy's ships and planes already deployed in support of the war on terrorism. The United States must be prepared for homeland defense and information warfare in the wake of recent events.

3. New Systems

New technologies and systems change the way we perceive and react to threats. These altered perceptions serve to shape our National Military Strategy, the Defense Planning Guidance, and consequently our force structure planning. The tri-service, multi-national Joint Strike Fighter (JSF) program (Figure 1), V-22 Osprey, Unmanned Combat Air Vehicle (UCAV), and Unmanned Air Vehicle (UAV), are aircraft examples that will impact our force structure for the next decade and beyond.

Figure 1. An artist's rendition of the Lockheed Martin Joint Strike Fighter (JSF). The procurement plan calls for the Navy to buy 480 carrier versions and 609 Marine Corps short take-off and vertical landing (STOVL) versions. The $200 billion JSF contract is the largest in U.S. military history. Figure from - [LockheedMartin.com, 2001].

The Pentagon has been considering eliminating the Marine Corps' short take-off and vertical landing (STOVL) requirements from the JSF program to reduce costs and speed up the overall JSF program schedule [Wolfe 2001]. One option being discussed is an acceleration of the Navy JSF program and a termination of the Navy's F/A-18E/F after the current buy ends in FY04. The early lots of JSF are to be less capable than those bought later. The current JSF procurement plan calls for the Navy to buy 480 Navy carrier versions, and 609 Marine Corps STOVL versions to replace its AV-8B Harriers.

Many assumed the Pentagon would split the more than $200 billion JSF contract, the largest in U.S. military history, to keep both main fighter-jet makers (Boeing and Lockheed Martin) in the business for decades. If the contract were split, upfront costs would jump between $900 million and $1.4 billion to accommodate the two separate production lines. This was a contingency that Navy planners had to consider. Senator Christopher Bond (R-MO) considered the added expense "well worth the price" for the $200 billion JSF program as it would keep both companies in the fighter manufacturing business and would preserve competition and make it easier to speed up production if needed [Selinger 2001]. In the end, the Pentagon selected Lockheed Martin as the sole contract winner.

The Marine Corps would get $592.3 million less than requested and build nine instead of 12 V-22 Osprey tilt-rotor aircraft next year under the new defense bill approved by the Senate Armed Services Committee [Whittle 2001]. A special Pentagon panel recommended that the Pentagon hold Osprey production to a minimum while flaws that led to one of last year's crashes are fixed. The Marines want 360 V-22s to replace Vietnam-era helicopters.

To reduce combat fatalities, new systems such as the Predator Unmanned Air Vehicle (UAV) are being used to support Intelligence Surveillance and Reconnaissance missions while minimizing risk to our pilots and aircrew. The Unmanned Combat Air Vehicle (UCAV), Figure 2, is the next step toward minimizing combat fatalities while supporting two major combat roles: Suppression of Enemy Air Defenses (SEAD) and precision strike. The initial operational capability of the UCAV system is now planned for approximately 2010 [Baker 2001].

Figure 2. An artist's rendition of the Boeing Unmanned Combat Air Vehicle (UCAV). The UCAV is the next step toward minimizing combat fatalities while supporting two major combat roles: Suppression of Enemy Air Defenses and precision strike. Figure from - [Boeing.com, 2001].

The multi-billion dollar JSF, V-22, UAV, and UCAV programs may affect our defense budget for decades and significantly alter the way we prepare for and fight future battles. Force structure planners require flexible tools to deal with new system capabilities, uncertainties, and vulnerabilities.

B. N78 AND N81 METHODS

The Chief of Naval Operations, Air Warfare Division (N78), works closely with N81 to shape present and future Naval Aviation warfighting capabilities. N78 determines required aviation force levels necessary to support our National Military Strategy and Defense Planning Guidance. N81 incorporates N78 inputs into the overall Navy force structure plan.

1. N78 Force Structure Planning

Force structure planners at N78 must maintain air warfighting capabilities to meet present and future threats, using aircraft modernization, procurement, and retirement

scheduling. Currently, planners strive to support 10 active and 1 reserve Carrier Air Wings (CVW) with at least 50 tactical aircraft and support aircraft per wing [Paine and Drohr 2000]. Planners must also support 3 active and 1 reserve Marine Air Wings. The inventory required for each specific aircraft is determined by first establishing the number of squadrons of that type of aircraft that will support each wing. The total Primary Mission Aircraft Authorized (PMAA) number of squadrons multiplied by number of aircraft per squadron is the basis for all future inventory calculations [Paine and Drohr 2000]. To determine an overall procurement objective for each aircraft, the PMAA must be supplemented to account for training aircraft, test and evaluation aircraft, and aircraft undergoing maintenance. Fleet Replacement Squadron (FRS) training aircraft account for about a 25% inventory increase. Research, Development, Test and Evaluation (RDT&E) aircraft account for about a 7% increase. Aircraft in the maintenance pipeline add about 10%. Finally, planners must adjust for annual aircraft attrition, which ranges from a fraction of a percent to almost 3% per year depending on the aircraft. The grand total of the above adjustments results in a procurement objective for each aircraft.

2. EPA/TOA at N81

N81 contracts with Systems Planning and Analysis, Incorporated, to maintain the EPA/TOA model. EPA/TOA is a series of 62 linked spreadsheets that are manually manipulated to reflect planning considerations and scenario development. The EPA/TOA model estimates long-range Navy force structure costs. This cost estimation is based on a manually prepared input with a procurement, delivery, and retirement schedule. Field [1999] presents an N81 planning review that is still current at this writing.

C. CAPITAL INVESTMENT PLANNING AID (CIPA)

The Capital Investment Planning Aid (CIPA) is designed to augment the EPA/TOA model by using optimization to replace much of the manual work performed by EPA/TOA contractors and N81 planners. CIPA has been tested with a 25-year planning horizon with eight mission areas, 19 ship classes, five aircraft types, five production facilities, and three categories of money. CIPA recommends the best yearly force structure procurement plan based on industrial constraints, budget constraints,

mission inventory requirements, and force mix requirements. CIPA allows budget violations in some years that can be repaid by other savings in other years. Given constraints for a planning scenario, CIPA recommends an optimum solution. CIPA can emulate EPA/TOA if CIPA's discretionary variables are all fixed to constant values. But, as a prescriptive model, CIPA suggests optimum solutions that might not otherwise be discovered by manual planning and EPA/TOA evaluation. CIPA has been demonstrated for a 25-year plan with a representative subset of ships, submarines, aircraft, and three major budget categories. [Field 1999]

D. A CIPA EXTENSION: GENERALIZING PROCUREMENT PLANNING FOR NAVAL SHIPS AND AIRCRAFT (GENSA)

Generalizing Procurement Planning for Naval Ships and Aircraft (GENSA), extends CIPA to include additional ship classes, aircraft types, and Manpower Navy (MPN) funding [Baran 2000]. GENSA extends the planning horizon to 30 years, 29 mission areas, 45 ship classes, 30 aircraft types, and 13 production facilities. GENSA is designed to add more detail to the CIPA model while easing post-optimization analysis.

III. OPTIMIZED PROCUREMENT AND RETIREMENT PLANNING FOR NAVY SHIPS AND AIRCRAFT

A. CIPA APU MODEL OVERVIEW

CIPA APU optimizes, with annual fidelity over a 25-year planning horizon, procurement and retirement planning for 58 aircraft types supporting 14 air mission areas while considering several categories of budget constraints, aircraft mission effectiveness, aircraft attrition, minimum and maximum average aircraft age, minimum and maximum average aircraft age designated for a specific mission, and minimum aircraft retirement age. CIPA APU has incorporated air budget constraints to allow flexibility to meet both political and warfare community priorities while striving for optimum overall Navy budget usage. CIPA APU models increased operating and maintenance costs as each aircraft ages, accounts for aircraft average ages, and accumulates expected flight hours. Tracking age also allows us to assess mission performance as a function of average age and to plan realistic retirement scheduling based on age. Aircraft inventory is also adjusted according to historical attrition rates that are reflected in CIPA APU as the yearly survival rate of each aircraft.

B. NEW CIPA APU MODEL FEATURES

1. Air Budget Constraints

Officials believe the Navy needs to explore new long-term operational and force concepts to provide better information on future requirements and capabilities [General Accounting Office (GAO) 2001]. The GAO concluded that "implementing the Navy's transformation will be complicated and will require careful consideration of near-term needs, as well as fundamental changes in the force structure, concepts, and organizations required to meet future security challenges within likely budgets" [GAO 2001 p.16]. The GAO suggests this transformation will involve using improved decision support systems performing resource and asset optimization [GAO 2001 p.21].

Budget is a major factor determining a force structure plan. Currently, planners explore force structure scenarios that are bounded by budget limits. In FY2001, the Air Procurement Navy (APN) limit was nominally $6.2 billion, with TACAIR receiving half [Ruck 2001]. These seemingly arbitrary limits serve as good starting points as the Navy divides up its total service budget. When no bounds are set on overall APN and specific mission APN, CIPA APU will spend as much as needed to meet overall Navy budget and air mission requirements. CIPA APU introduces cumulative elastic [Brown, Dell, and Wood 1997] air budget and air mission budget constraints to replicate planning limits. The elastic variables allow budget violations in some years that can be repaid in others. This flexibility can be key when trying to start production of a new airframe.

2. Aircraft Average Age

Reduced procurement in the 1990s has left the military with aging aircraft that are increasingly expensive to maintain [Congressional Budget Office (CBO) 2001]. Many aircraft are being flown well beyond their expected service life in order to meet crucial mission needs. The force structure plan must retire its aging aircraft while replacing those aircraft with an affordable mix of new and upgraded aircraft.

Brown, Clemence, Tuefert, and Wood [1991] develop a large-scale capital budgeting model, named PHOENIX, to aid Army helicopter force planners modernize an aging Army fleet composed of Vietnam era aircraft. CIPA APU uses average age constraints similar to those in the PHOENIX model. As an aircraft inventory reaches the maximum average age limit, older aircraft provide a retirement option to balance mission inventory needs with maximum age limits. Violations of maximum average age may be tolerated with a policy penalty to discourage excessive delays of necessary retirements.

3. Operating and Maintenance Costs as Function of Age

The Navy's aircraft inventory is aging and it is the only Navy weapon system type that has significantly increased in average age. Over the last 20 years, aircraft average age has risen from 11 years to more than 16 years. In contrast, the average age of ships has changed very little.

The aging aircraft (Figure 3) inventory has required more funding to maintain older equipment at the expense of new procurement, which has in turn lead to even older systems being kept in inventory with still higher OMN costs [Congressional Budget Office (CBO) 2001]. CBO agrees that aircraft do become more costly to maintain as they age. Aircraft OMN increases by 1 percent to 3 percent for every additional year of age, after adjusting for inflation. Aging aircraft, part shortages, and high operations tempo are draining funds [Brown 2001].

CIPA APU indexes OMN costs by aircraft type and age. OMN costs can be expressed as a function of aircraft age, which is more realistic than assuming OMN costs remain fixed over the aircraft's service life. Reality may conflict with planning: OMN budgets are sometimes held fixed as an aircraft ages, resulting in parts shortfalls, reduced mission capability, and reduced morale. If we plan for increasing costs, we prepare for a likely future.

Figure 3. An embellished Navy Times cover story photo of a duct taped F-14A. Operating and Maintenance costs are increasing between one and three percent per year. Spare parts shortfalls are causing increased cannibalization and forcing Navy maintainers to work harder and smarter to maintain full mission-capable aircraft. Figure from - [Fondersmith, 2001].

4. Mission Effectiveness

Each aircraft type within a mission area may have different effectiveness from its cohorts. The F18AB may be less effective than the proposed JSFN in the Strike Fighter air mission area. It is difficult to quantify relative mission effectiveness.

The F/A-18E/F program conducted a detailed analysis to determine the overall combat effectiveness of its aircraft [Navy Public Affairs Library 1997]. A poll of experts, aviators, aeronautical engineers, and intelligence specialists within the intelligence community, were asked their opinion of aircraft capabilities in six important areas of merit: maneuverability, range, radar signature, radar guided weapons, infrared weapons, and avionics suite.

Mission effectiveness is evidently a function of the empty gross weight of an aircraft and its vintage [Van Brabant 2001]. This makes sense because larger aircraft usually have a longer range, can carry more weapons, have larger radar antennas and power sources and thus have greater radar detection ranges. Conversely, a larger aircraft might be less maneuverable and have a larger radar cross section. Because technology changes significantly over time, the era in which an aircraft is conceived affects the platform's ability to integrate advanced weapons and avionics. Stealth, sensor integration, and human factor improvements also affect combat performance and are a function of aircraft vintage. CIPA APU uses aircraft and air mission average age constraints to limit the number of aircraft kept in inventory beyond their service lives.

C. CIPA APU FORMULATION

The summary below outlines the primary model characteristics. The complete CIPA APU formulation is found in the Appendix.

Main Decision Variables:

- number of aircraft to procure at the start of a fiscal year;
- number of aircraft to retire at the end of a fiscal year that is a specific age;
- number of ships to procure at the start of a fiscal year;
- number of ships to retire at the end of a fiscal year; and

- magnitude of each constraint violation.

Objective Function:

Minimize the penalty for violating constraints for the following areas:

- Annual air and ship mission inventory;
- Annual aircraft and air mission average age;
- Annual and cumulative total budget;
- Annual air and cumulative air budget;
- Annual air mission and cumulative air mission budget; and
- Annual ship labor requirements.

Subject to the following annual constraints:

- Limit annual minimum ship inventory;
- Limit the annual number of ships produced per plant;
- Limit annual ship retirements;
- Limit annual maximum ship-plant labor;

- Limit annual minimum aircraft inventory;
- Limit the annual number of aircraft produced;
- Limit annual aircraft retirements;
- Limit annual maximum aircraft average age;
- Limit annual maximum air mission average age;

- Limit minimum and maximum annual and cumulative total budget;
- Limit minimum and maximum annual air and cumulative air budget; and
- Limit minimum and maximum annual air mission and cumulative air mission budget.

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IV. IMPLEMENTATION AND ANALYSIS

A. IMPLEMENTATION

CIPA APU is implemented in the General Algebraic Modeling System (GAMS) [Brooke et al. 1998] with the CPLEX solver, Version 6.6 [ILOG 2001]. CIPA APU is a mixed-integer linear program, which for a representative scenario exhibits about 114,000 equations and 167,000 variables, of which about 6,700 are binary variables. It generally runs in less than 7 minutes on a personal computer equipped with a Pentium III 700 MHZ processor and 1048 MB of RAM, when accepting any solution guaranteed to be within 10% of optimal.

CIPA APU adds new elastic constraints to the previous CIPA models [Field 1999, Baran 2000]. CIPA APU uses upper and lower elastic constraints for the overall air budget, cumulative air budget, air mission budget, and cumulative air mission budget limits. Upper elastic constraints are used for maximum aircraft average age and air mission average age limits.

CIPA APU introduces penalties associated with the new elastic variables. Similar to the CIPA implementation, budget excesses and shortages are penalized at a 7% rate (1.07 multiplied by the unit budget violation) and all other penalties are based on this rate. Labor and mission penalties are unchanged from prior CIPA implementations [Field 1999, Baran 2000]. The penalty for violating average age constraints is equal to the maximum OMN cost per year, for each respective aircraft or mission area. All of the aforementioned penalty values, if active, are held constant for the entire planning horizon.

CIPA APU schedules procurement only if production can be completed and delivery accepted within the scenario's planning horizon (FY04-FY28). Therefore, near the end of this scenario's planning horizon, procurements decrease to zero. For purposes of results reported here, FY24 to FY28 may be truncated from the planning results because those "end effects" portray unrealistic procurement and retirement scheduling.

B. VARIABLES AND PARAMETERS

Because CIPA APU needs to account for aircraft age, planning starts with the expected aircraft inventory, rounded to the nearest integer year, at the beginning of the planning horizon. Table 1 shows that the total F/A-18E inventory at the start of the planning horizon, FY04, is expected to be 61.

Aircraft Type	Age (years)	Inventory
F18CD	58	0
F18CD	59	0
F18CD	60	0
F18E	1	14
F18E	2	15
F18E	3	14
F18E	4	5
F18E	5	8
F18E	6	0
F18E	7	5
F18E	8	0
F18E	9	0
F18E	10	0
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Table 1. Initial FY04 Aircraft Age Inventory. For example, of 61 F18Es: 15 are two years old.

CIPA APU uses as much of the existing CIPA and EPA/TOA data as possible to ensure model integration, consistency, and continuity. The most significant data changes deal with the new constraints for overall APN, air mission APN, air mission average age, aircraft average age, relative air mission effectiveness, and aircraft OMN costs.

Maximum APN is prototypically set to $6.2 billion annually, with a nominal lower bound of $5.4 billion. These budget limits are held constant for the entire planning horizon. Cumulative air budget limits are simply the sum of all previous annual yearly budgets. Budget limits are also imposed on the Strike Fighter mission area, with a maximum of $3.1 billion and a minimum of $2.7 billion. The other 13 air mission areas have no separate air mission budget limits.

Aircraft average age limits are set using three different profiles. If the aircraft average age at the start of the planning horizon is younger than it's expected service life (ESL), the maximum average age limit is held constant at the respective ESL. If the aircraft has already exceeded it's service life, either the maximum average age limit is held constant somewhere above the ESL or it is set one year older than current average age and linearly decreased until the ESL limit is reached. The third profile accounts for a large variability in aircraft age associated with procuring aircraft over several years. In this case, some individual aircraft will reach their ESL before the aircraft type average age reaches the maximum age limit. This may cause an aircraft to remain in inventory long after its ESL. To account for this, we set the maximum average age limit below the ESL limit and linearly increase it until the ESL limit is reached. In this scenario, a constant limit profile is predominantly used except in cases where the ESL is already exceeded. In those cases, a linearly decreased limit is used as described above.

CIPA APU introduces survival, retirement, and air mission effectiveness parameters. Yearly aircraft survival rates mimic EPA/TOA yearly attrition rates. The minimum retirement age parameter limits aircraft to "retire no earlier than" 50% of ESL. For example, if the F-14B's ESL is 30 years, no F-14B is retired unless it is at least 15 years old. The mission effectiveness parameter values can be highly subjective and are all initially set to 1.0. This means any aircraft assigned to a specific air mission is viewed as fully capable to perform that air mission.

C. RESULTS OF SEVERAL PLANNING EXCURSIONS

We report on several realistic CIPA APU excursions. First, we present a baseline case from which we compare the other excursions. Second, CIPA APU emulates a notional N81 mission inventory example. Third, we increase OMN costs as a function of increasing aircraft age. Fourth, we change relative Strike Fighter and Ground Attack air mission effectiveness to explore planning impact. Finally, we include UAV and UCAV to forecast how incorporating these new aircraft may impact overall force structure planning.

1. Baseline Case

This baseline case includes air budget and air mission budget constraints as depicted in Table 2 and 3 below.

Fiscal Year	Maximum Air Budget	Minimum Air Budget	Maximum Cumulative Air Budget	Minimum Cumulative Air Budget
FY04	6.2	5.4	6.2	5.4
FY05	6.2	5.4	12.4	10.8
FY06	6.2	5.4	18.6	16.2
FY07	6.2	5.4	24.8	21.6
FY08	6.2	5.4	31.0	27.0
FY09	6.2	5.4	37.2	32.4
FY10	6.2	5.4	43.4	37.8
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Table 2. Air Budget and Cumulative Air Budget Table (Billions of Dollars). The maximum APN is set to $6.2 billion with a nominal lower bound of $5.4 billion. These budget limits are held constant for the entire planning horizon. Cumulative air budget limits are also derived from these yearly limits.

Air Mission	Fiscal Year	Maximum Budget	Minimum Budget	Maximum Cumulative Budget	Minimum Cumulative Budget
Strike Fighter	FY04	3.1	2.7	3.1	2.7
Strike Fighter	FY05	3.1	2.7	6.2	5.4
Strike Fighter	FY06	3.1	2.7	9.3	8.1
Strike Fighter	FY07	3.1	2.7	12.4	10.8
Strike Fighter	FY08	3.1	2.7	15.5	13.5
Strike Fighter	FY09	3.1	2.7	18.6	16.2
Strike Fighter	FY10	3.1	2.7	21.7	18.9
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Table 3. Air Mission Budget and Cumulative Air Mission Budget Table (Billions of Dollars). The maximum Strike Fighter air mission budget is $3.1 billion with a minimum budget of $2.7 billion. Cumulative air mission budget limit are derived from these limits.

The minimum yearly procurement limit is zero for all aircraft with a generous maximum yearly procurement level set for those aircraft scheduled for procurement during the planning horizon. Table 4 shows the F18F maximum procurement over the planning horizon is 320 aircraft, 40 aircraft per year from FY04 through FY11. The N81

plan procures approximately 200 aircraft over that same time. Aircraft committed for delivery in FY04 and FY05 are specific lots of aircraft which are purchased in FY02 and FY03. Those aircraft will be delivered two years later and are viewed as committed procurement in the year they are delivered.

Mission inventory levels are set high enough to require aircraft procurements to meet mission inventory requirements. The Strike Fighter mission inventory level is 1100 aircraft, the Ground Attack mission inventory level is 500 aircraft. These levels match the N81 TACAIR inventory level, 1300, and account for the 300 additional AH1 and UH1 helicopters included in the CIPA APU Ground Attack mission area.

Aircraft Type	FY	Minimum Procurement	Maximum Procurement	Committed Procurement
F18F	FY04	0	40	24
F18F	FY05	0	40	24
F18F	FY06	0	40	0
F18F	FY07	0	40	0
F18F	FY08	0	40	0
F18F	FY09	0	40	0
F18F	FY10	0	40	0
F18F	FY11	0	40	0
F18F	FY12	0	0	0
F18F	FY13	0	0	0
F18F	FY14	0	0	0
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Table 4. Yearly F18F Procurement Limits. The F18F maximum procurement over the planning horizon is 320 aircraft, 40 aircraft per year from FY04 through FY11. The N81 plan procures approximately 200 aircraft over that same time period.

Figure 4 shows the CIPA APU TACAIR inventory projection. CIPA APU TACAIR inventory is Strike Fighter and Ground Attack mission areas combined without attack helicopters. The TACAIR inventory goal is approximately 1300 aircraft. CIPA APU aircraft procurements are restricted due to lack of sufficient funding. The most inexpensive aircraft, F18E and F18F, are viewed more favorably for procurement than the more expensive JSFN and JSFMC aircraft.

The overall air budget and TACAIR budget is shown in Figure 5. The CIPA APU solution minimizes the penalties associated with violating the respective air budget and

air mission budget limits. The previously discussed end effects are apparent as procurement spending goes to zero near the end of the planning horizon. Although budget violations exist for both air and mission budget limits, the average yearly budget for the planning horizon is less than the maximum yearly budget limit.

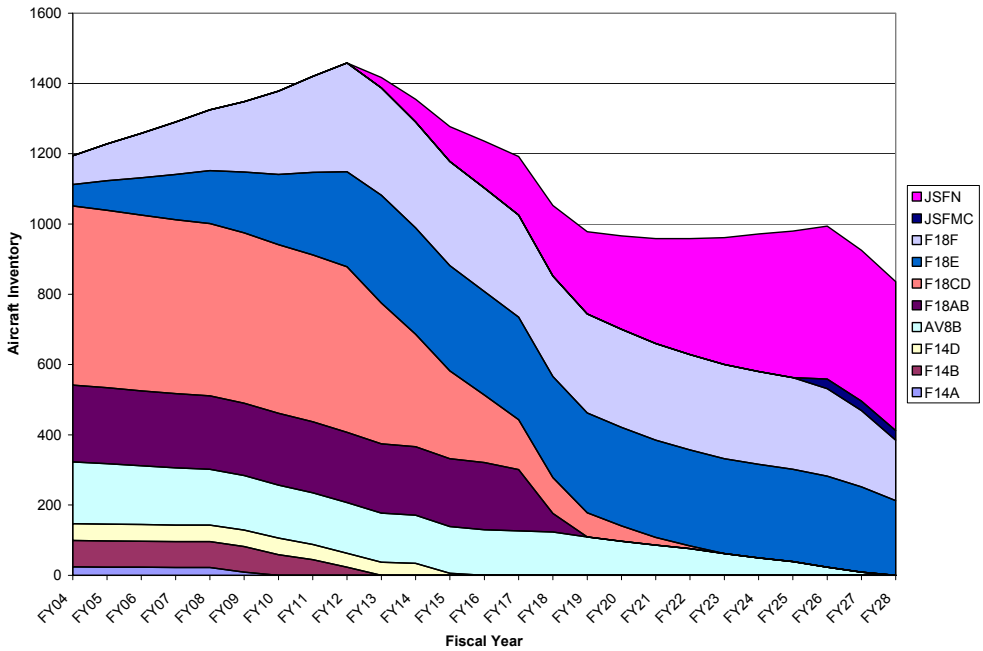

Figure 4. Baseline, CIPA APU TACAIR Inventory Projection. Planned procurements are restricted due to lack of sufficient funding. The most inexpensive aircraft, F18E and F18F, are viewed more favorably for procurement than the more expensive JSFN and JSFMC aircraft.

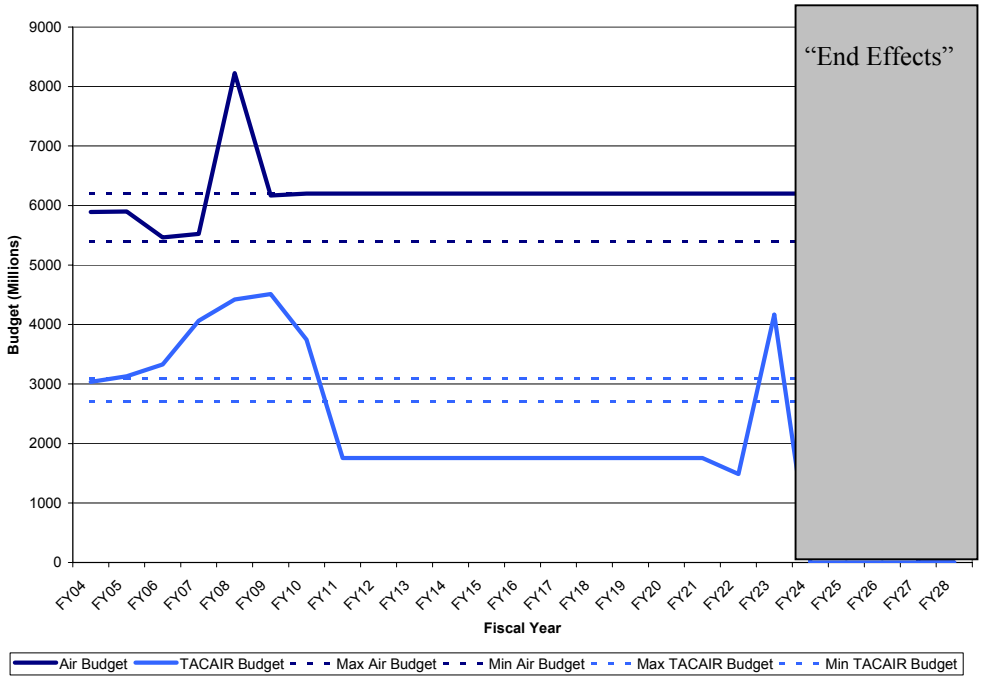

Figure 5. Baseline, CIPA APU Air Budget Chart. End effects are apparent as procurement spending goes to zero near the end of the planning horizon. The "bow wave" at the beginning of the planning horizon represents initial expenditures to repair deficiencies. These are repaid in later years. Although budget violations exist for both air and mission budget limits, the average yearly budget for the planning is less than the maximum yearly budget limit.

2. Excursion 1: Restrict CIPA APU to emulate a notional N81 Plan

CIPA APU can be forced to emulate a manual schedule and then results can be compared with EPA/TOA. Figure 6 shows a notional N81 TACAIR inventory projection as entered in EPA/TOA during May 2001. Figure 7 shows the CIPA APU emulation for comparison. Retirement schedules differ slightly between the notional N81 plan and those allowed in CIPA APU which accounts for the bow-wave in aircraft inventory, FY10-FY18, as shown in Figure 7. The N81 TACAIR inventory level is relatively steady throughout the planning horizon, Figure 6.

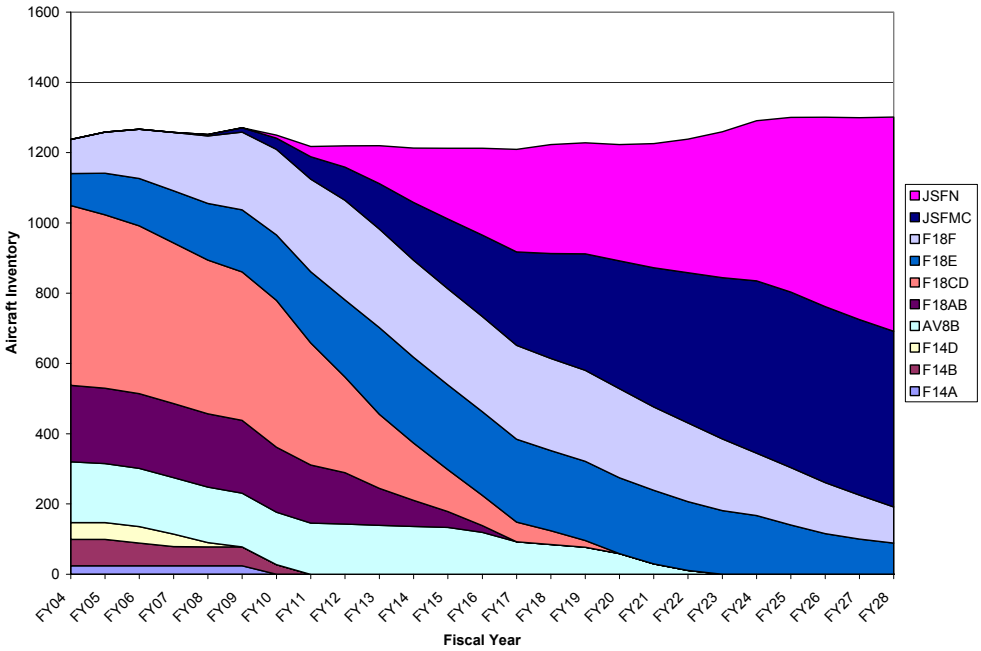

Figure 6. Notional N81 TACAIR Inventory Projection. This sample inventory projection attempts to maintain approximately 1300 tactical aircraft but does so using significantly more dollars than were available in the baseline scenario (Figure 5) and by significantly changing year-to-year funding.

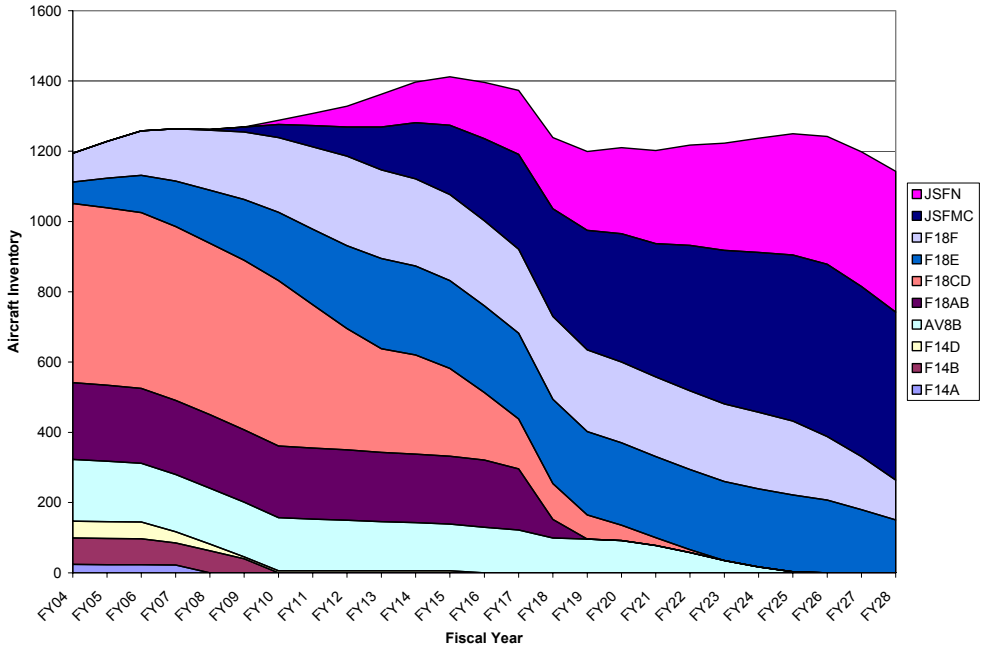

Figure 7. Excursion 1a, CIPA APU TACAIR Inventory Projection. Because there is insufficient funding, the minimum number of aircraft are procured each year. The "hump" between FY10 and FY18 is caused by differing CIPA APU and N81 retirement rates.

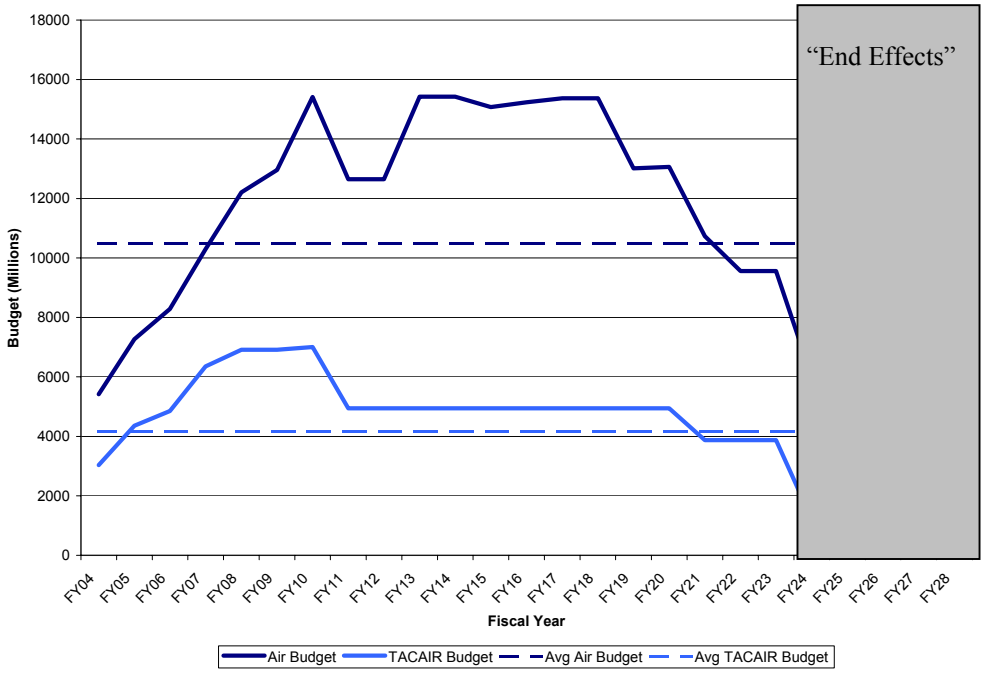

Figure 8. Excursion 1a, CIPA APU Air Budget Projection. The average yearly air budget required to support this procurement plan is about $10.5 billion. The average yearly Strike Fighter air mission budget is about $4.2 billion.

We now focus on the procurement results. Regardless of budget limits, CIPA APU produces the desired procurement schedule at the expense of violating the baseline air and mission budget limits (Figure 8). With the budget limits still set at the baseline case level, the optimized plan selects the minimum procurement levels available. We can control this behavior and honor budgets at the expense of procurement schedule, but either way, CIPA APU is telling us we have a conflict between funding and requirements.

Aircraft Type	FY	Minimum Procurement	Maximum Procurement	Committed Procurement
F18F	FY04	0	40	24
F18F	FY05	0	40	24
F18F	FY06	24	40	0
F18F	FY07	24	40	0
F18F	FY08	24	40	0
F18F	FY09	24	40	0
F18F	FY10	24	40	0
F18F	FY11	24	40	0
F18F	FY12	0	0	0
F18F	FY13	0	0	0
F18F	FY14	0	0	0
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Table 5. Revised Yearly F18F Procurement Limits. This revised table includes minimum procurement limits that attempt to emulate the notional N81 procurement plan.

We allow CIPA APU to optimize the desired aircraft procurements, by running the model again, this time with annual budget levels centered around $10.5 billion. Similarly, we set a reasonable bound around the average Strike Fighter air mission budget, $4.2 billion. When the model is run again without the minimum procurement limits, CIPA APU fulfills the mission requirements with the revised budget limits, Figures 9 and 10. The total air budget stays within the limits better than the Strike Fighter air mission budget because we impose a penalty for yearly and cumulative air budget violations and imposed only a cumulative air mission penalty for Strike Fighter air mission budget violations.

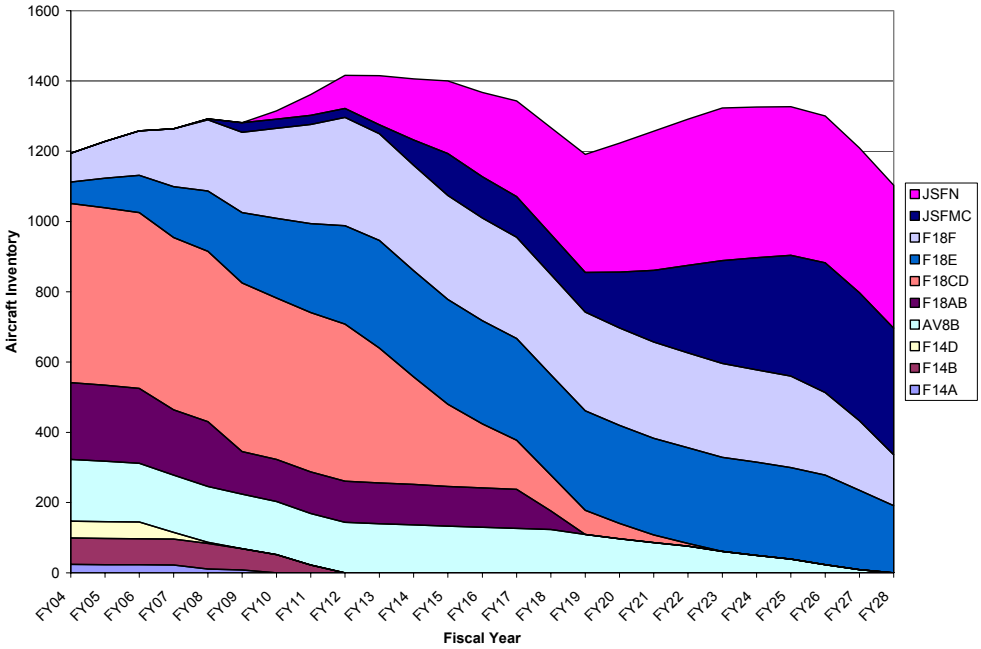

Figure 9. Excursion 1b, CIPA APU Inventory Projection. By allowing CIPA APU more flexibility, we obtain similar inventory levels to those obtained in Figure 7 but with more consistent yearly expenditures (Figure 10).

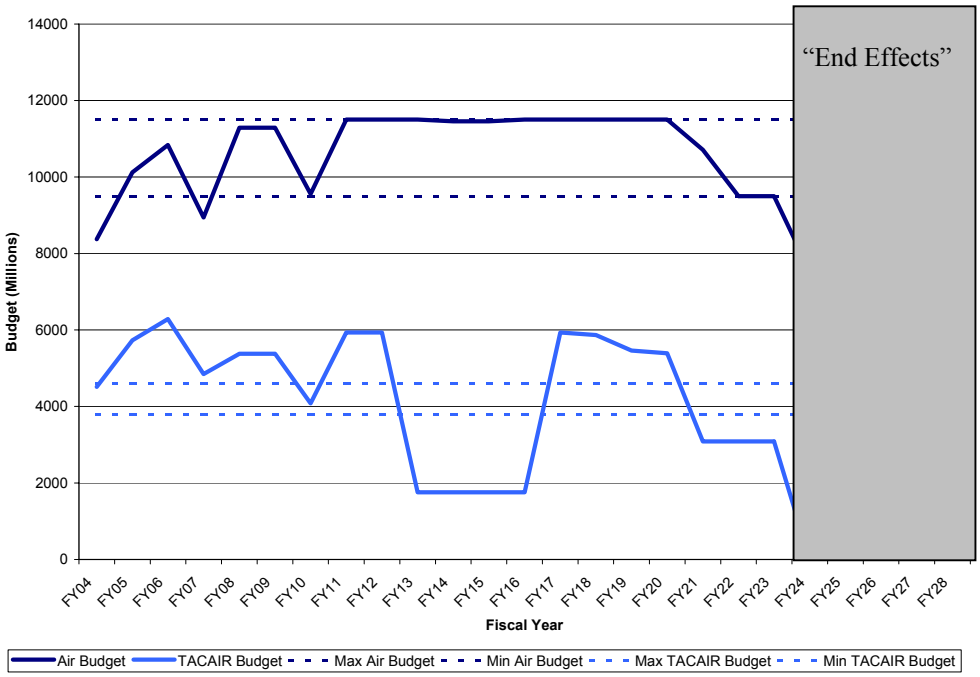

Figure 10. Excursion 1b, CIPA APU Air Budget Projection. The total air budget stays within the limits while satisfying required inventory levels (Figure 9). We impose a penalty for yearly and cumulative air budget violations and impose only a cumulative air mission penalty for the Strike Fighter air mission budget violations.

3. Excursion 2: OMN as Function of Age

OMN costs change over time. In this excursion, we hold the OMN cost constant up to the average age of the aircraft at the start of the planning horizon. From that average age forward, we increase aircraft OMN costs 3% per year of age until the maximum age limit, 60 years old. For example, the expected F-14D average age is 15.8 years at the start of the planning horizon. The OMN cost is held constant at $2.96 million per year for all F14Ds 16 years old or younger. OMN costs are increased 3% per year of age for every year after 16. These increases are in constant year dollars.

Aircraft Type	Years	Age	OMN
.	.	.	.
F14D	FY04 through FY28	14	2.96
F14D	FY04 through FY29	15	2.96
F14D	FY04 through FY30	16	2.96
F14D	FY04 through FY31	17	3.05
F14D	FY04 through FY32	18	3.14
F14D	FY04 through FY33	19	3.23
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Table 6. OMN as Function of Aircraft Age. We hold OMN cost constant up to the average age of the aircraft at the start of the planning horizon. We increase aircraft OMN costs 3% per year of age until the age limit, 60 years old.

This excursion sets air budget limits around $10.5 billion per year and Strike Fighter air mission budget limits around $4.2 billion per year as before. Likewise, we set only maximum aircraft procurement limits.

Figure 11 shows aging F14B's are retired earlier than in excursion 1 with accelerated F18E and F18F procurement. By increasing the OMN costs 3% per year of aircraft age, the final solution is significantly changed, Figures 11 and 12.

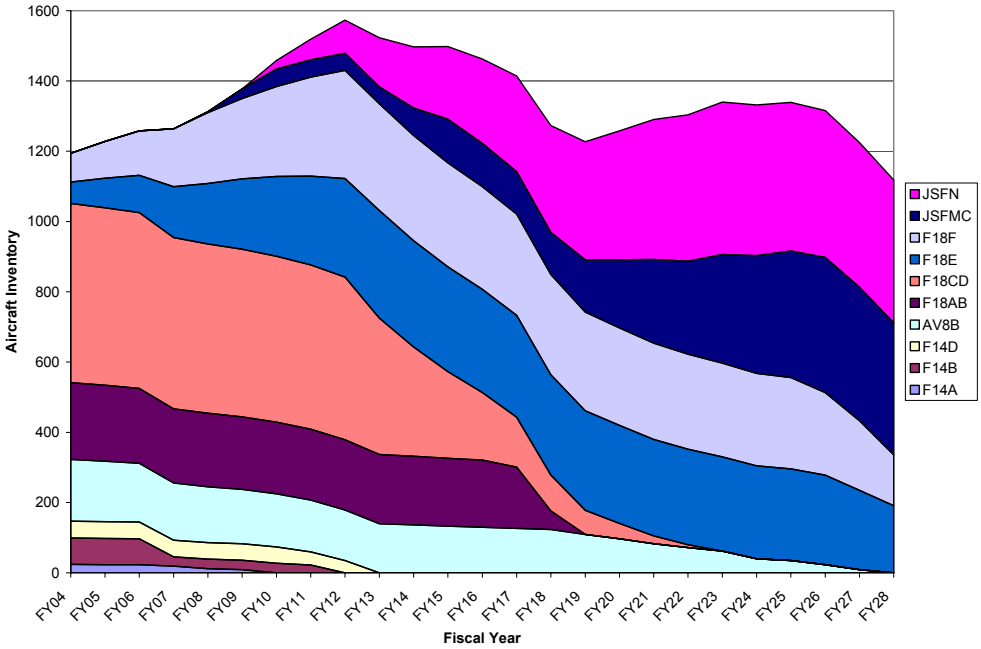

Figure 11. Excursion 2, CIPA APU Inventory Projection. We increase OMN costs 3% per aircraft year of age and bound air budgets around $10.5 and $4.2 billion, with no minimum procurement limits. In FY06, aging F14B's have earlier retirements and accelerated F18E and F18F procurement compared to excursion 1b results.

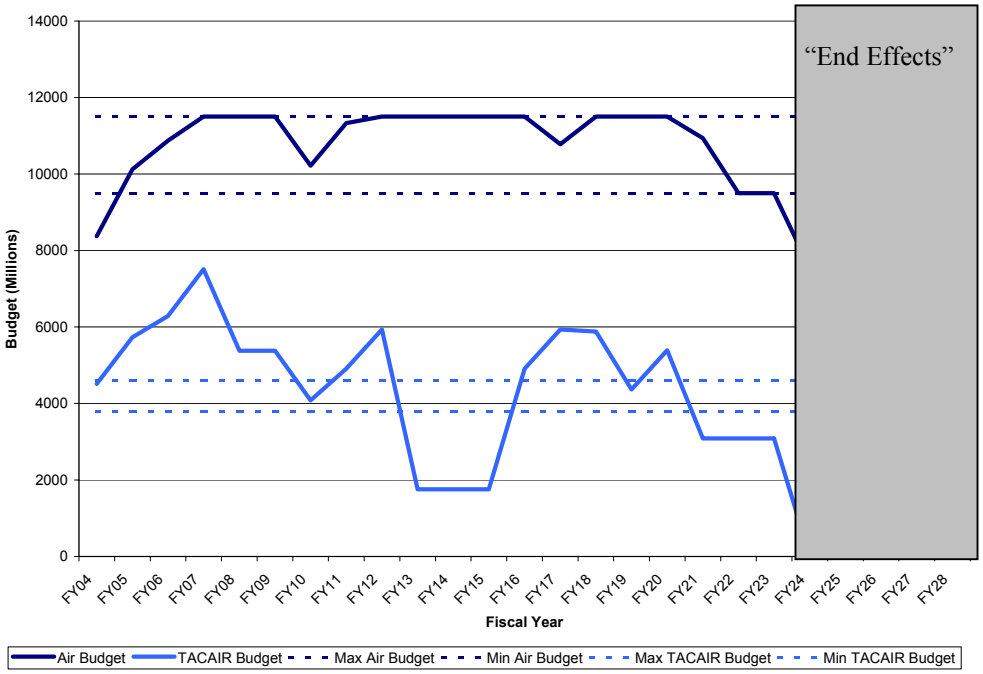

Figure 12. Excursion 2, CIPA APU Air Budget Projection. The increased OMN costs as a function of age cause changes to aircraft procurement and retirements to keep within budget limits.

4. Excursion 3: Mission Effectiveness

All aircraft within the same mission area are not equally effective. In this excursion, aircraft mission effectiveness is subjectively set within the Strike Fighter and Ground Attack air missions. The author sets the values in relation to the aircraft's vintage and perceived capability in their respective mission area. JSFN and JSFMC are the reference aircraft for their respective Strike Fighter and the Ground Attack air missions. We change the Strike Fighter inventory goal to 900 aircraft and the Ground Attack inventory goal to 400 aircraft.

Air Mission	Aircraft Type	Age	Effectiveness
Strike Fighter	F14A	1 through 60	0.75
Strike Fighter	F14B	1 through 60	0.85
Strike Fighter	F14D	1 through 60	0.85
Strike Fighter	F18AB	1 through 60	0.75
Strike Fighter	F18CD	1 through 60	0.85
Strike Fighter	F18E	1 through 60	0.95
Strike Fighter	F18F	1 through 60	0.95
Strike Fighter	JSFN	1 through 60	1.00
Ground Attack	AV8B	1 through 60	0.75
Ground Attack	AH1	1 through 60	0.75
Ground Attack	UH1	1 through 60	0.75
Ground Attack	JSFMC	1 through 60	1.00

Table 7. Relative Aircraft Mission Effectiveness for Strike Fighter and Ground Attack Air Missions. JSFN and JSFMC are the reference aircraft for their respective Strike Fighter and the Ground Attack air missions. We change the Strike Fighter inventory goal to 900 aircraft and the Ground Attack inventory goal to 400 aircraft.

The most effective aircraft are viewed more favorably for procurement and less favorably for retirement. The F14B and F18CD have delayed retirements compared to excursion 1b results. Changing the relative air mission effectiveness and air mission inventory goals affect the associated TACAIR budgeting results shown in Figure 12.

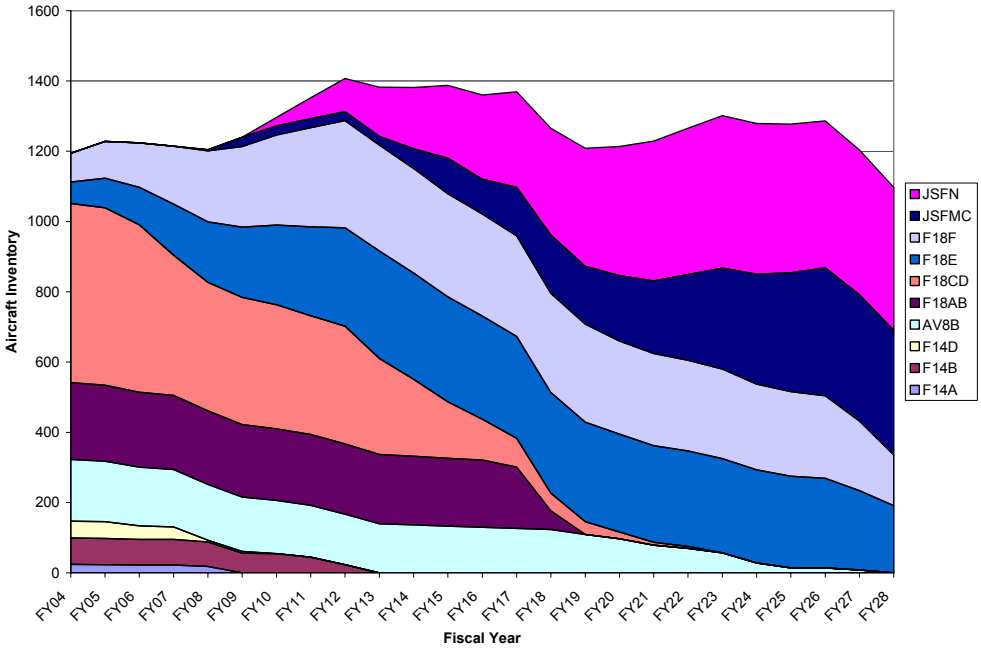

Figure 13. Excursion 3 (Varying Aircraft Effectiveness), CIPA APU Inventory Projection. The most effective aircraft are viewed more favorably for procurement and less favorably for retirement. The F14B and F18CD have delayed retirements compared to excursion 1b results.

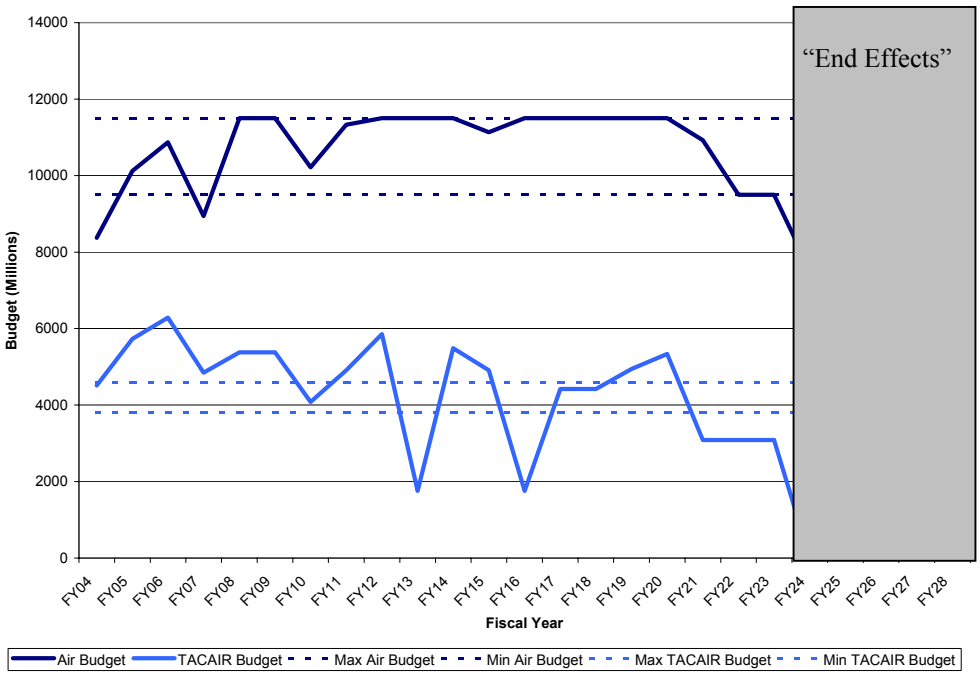

Figure 14. Excursion 3, CIPA APU Air Budget Projection. Changing the relative air mission effectiveness and air mission inventory goals affect the associated TACAIR yearly budgeting results shown in Figure 12.

5. Excursion 4: New Air Platforms

The UAV and UCAV aircraft are added to the respective aircraft and air mission inventory lists to see the possible affects of these new platforms on force structure planning. The Naval UAV is expected to cost about $900,000 per aircraft, the UCAV is expected to cost about $5.25 million per aircraft [UAV Forum 2001]. The expected service life for these aircraft is 12 and 6 years, respectively. The lifecycle OMN for the UCAV is expected to be about $7.5 million [AerospaceWeb.org 2001]. The author takes the liberty of estimating the respective cost curves and yearly OMN costs based on the previous data, using scaling similar to that of aircraft currently being procured. Because these aircraft are significantly cheaper than other aircraft in their mission areas and are less capable, we reduce the UAV and UCAV mission effectiveness to balance the cost differential. For this excursion, the UAV and UCAV have only 50% relative mission effectiveness with a maximum procurement of 200 UAV and 300 UCAV. In addition, we eliminate F18E and F18F minimum procurements while setting JSFN and JSFMC minimum procurement levels to honor contract commitments. For this excursion, JSFN and JSFMC maximum total procurement was cut in half over the planning horizon.

The first "hump" in inventory level, Figure 15, is caused by forced minimum JSF procurement between FY08 and FY18. The second "hump" is an a correction to pay the cumulative liability of the early over-expenditure, Figure 16. The unmanned aircraft, cheaper and less expensive to operate and maintain, are procured to their maximum levels once the mission deficit penalty exceeds the budget limit penalties. Although we set no minimum F18E and F18F procurement limits, the F18E and F18F are still procured to meet the mission inventory goal. Initial UCAV procurement is delayed almost eight years, waiting for funding to become available after earlier, pre-committed JSFN and JSFMC procurements.

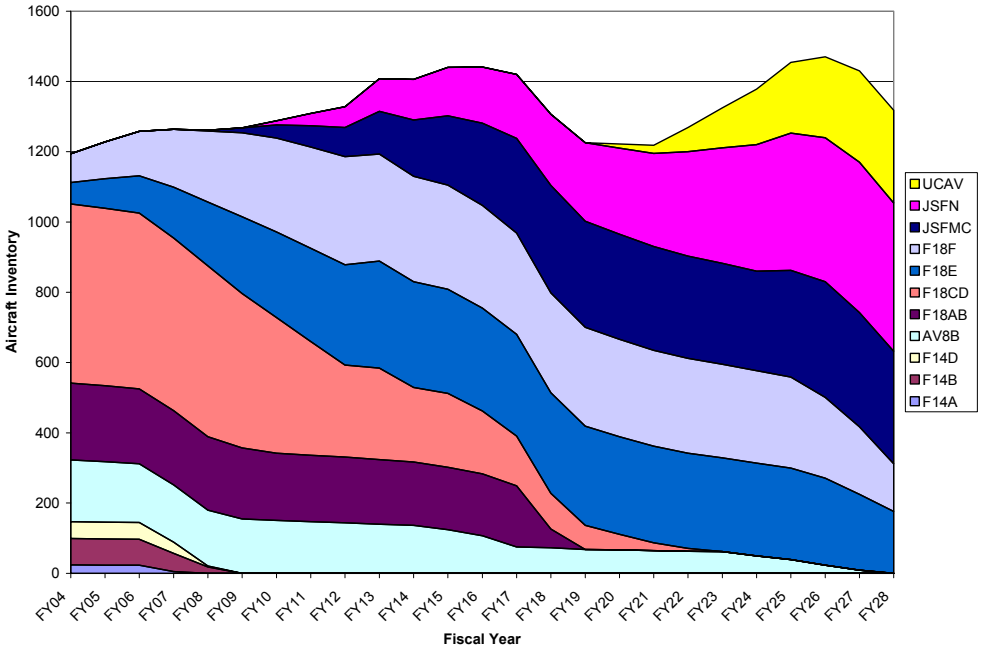

Figure 15. Excursion 4, CIPA APU Inventory Projection. The unmanned aircraft, cheaper and less expensive to operate and maintain, are procured to their maximum levels once the mission deficit penalty exceeds the budget limit penalties. Although we set no minimum F18E and F18F procurement limits, they are still procured to meet the mission inventory goal. Initial UCAV procurement is delayed almost eight years until funding becomes available after earlier, pre-committed JSFN and JSFMC procurements.

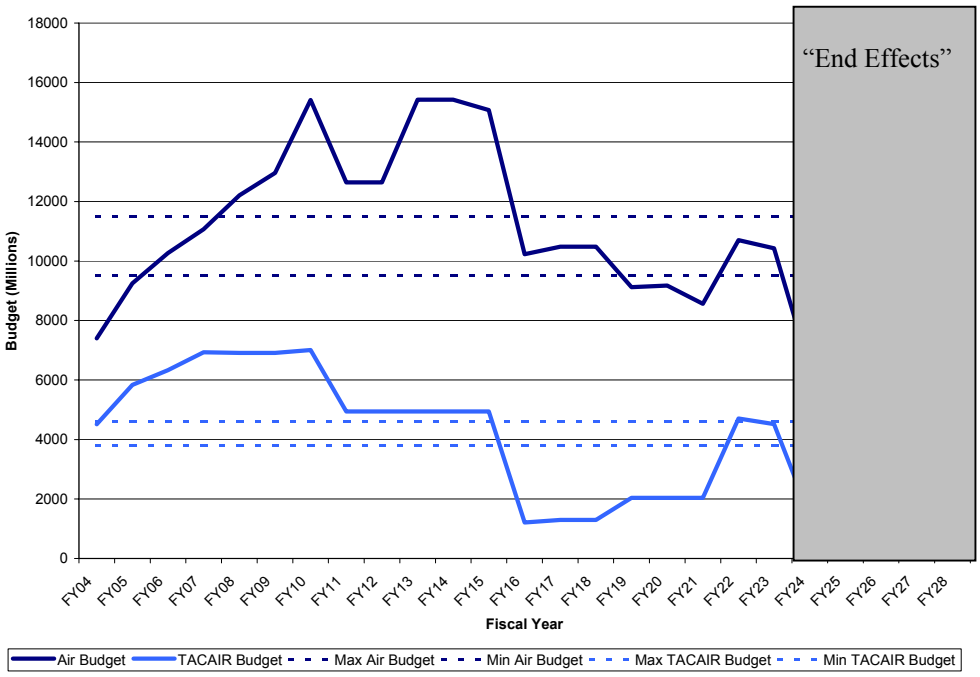

Figure 16. Excursion 4, CIPA APU Air Budget Projection. Early F18E and F18F procurements to meet mission inventory goal and committed JSFN and JSFMC procurement result in delayed but maximized UCAV procurement later in the planning horizon.

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V. CONCLUSIONS AND RECOMMENDATIONS

We have explored several scenarios to demonstrate the new CIPA APU capabilities. Overall, CIPA APU proves effective and realistically portrays quantifiable planning considerations.

A. CONCLUSIONS

CIPA APU replaces manual planning with optimization, recommending the best yearly force structure procurement plan based on industrial constraints, budget constraints, mission inventory requirements, and force mix requirements. CIPA APU allows budget violations in some years that can be repaid by other savings in other years. This is accomplished with long-term, cumulative budget goals. Given constraints for a planning scenario, CIPA APU recommends an optimum solution. As a prescriptive model, CIPA APU suggests optimum solutions that might not otherwise be discovered by manual planning.

Prototypic scenarios have shown how CIPA APU optimally alters procurement and retirement schedules to respond to: increasing Operation and Maintenance Navy (OMN) costs as aircraft ages increase; different effectiveness for aircraft performing Strike Fighter and Ground Attack missions; and the introduction of Unmanned Air Vehicles (UAV) and Unmanned Combat Air Vehicles (UCAV).

B. RECOMMENDATIONS

Enrich the scope and vision of Navy force structure planning to accommodate as many of the essential details as possible while generating optimal plans. CIPA is the only Navy decision support system that integrates aircraft and ship procurement decisions with fiscal, industrial, and mission requirements to render the best integrated long-term advice. When added to CIPA, the CIPA APU enhancements will more realistically model the impact of aircraft procurement and retirement.

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APPENDIX. CIPA APU FORMULATION

SETS AND INDICES

- Time

Y, set of years (planning periods) of the planning horizon; $y, y' \in Y$. For convenience it is assumed that $Y = \{1,2,3...,|Y|\}$

T, set of aircraft ages; $t, t' \in T$. For convenience it is assumed that $T = \{1,2,3...,|T|\}$

- Platform

A, set of aircraft types; $a \in A$

S, set of ship classes; $s \in S$

- Mission

M^A, set of air missions; $m \in M^A$

M^S, set of ship missions; $m \in M^S$

$A_m \subseteq A$, subset of aircraft types that perform mission $m \in M^A$

$S_m \subseteq S$, subset of ship classes that perform mission $m \in M^S$

- Production

I_a, set of cost increments for aircraft $a \in A$; $i \in I_a$

P, set of production facilities; $p \in P$

$P_s \subseteq P$, subset of facilities that produce ship class $s \in S$

Q_{spy}, set of quantities available for ship $s \in S$ procurement at facility $p \in P_s$ in year $y \in Y$. This set is defined in terms of the $\underline{sproc}_{spy}$ and $\overline{sproc}_{spy}$ parameters (see below) as follows:

$q \in Q_{spy} = \{\underline{sproc}_{spy}, \underline{sproc}_{spy} + 1, \cdots, \overline{sproc}_{spy}\}$

- Others

Z^+, set of non-negative integers, $Z^+ = \{0,1,2,...\}$

PARAMETERS (and units)

- Conventions

The word "procurement" or "to procure" refers to "delivery" or "to deliver", respectively, unless explicitly stated otherwise. Therefore, we refer to "procure" as the action that takes place at the moment (year) that the platform is delivered and available for use from that year onwards, regardless when the real "procurement" arrangements were made.

The words "time period" and "year" are used interchangeably.

The words "facility" and "plant" are used interchangeably.

- Objective-terms: Penalties

$ampen_m$,	penalty for shortage in completing air mission $m \in M^A$ ($ per aircraft)
$smpen_m$,	penalty for shortage in completing ship mission $m \in M^S$ ($ per ship)
$agepen_a$,	penalty for aircraft average age excess ($ per year of age)
$magepen_m$,	penalty for air mission $m \in M^A$ average age excess ($ per year of age)
$bpen_y^+$,	penalty for budget excess ($ per $)
$bpen_y^-$,	penalty for budget shortage ($ per $)
$cbpen_y^+$,	penalty for cumulative expenses excess ($ per $)
$cbpen_y^-$,	penalty for cumulative expenses shortage ($ per $)
$abpen_y^+$,	penalty for air budget excess in year $y \in Y$ ($ per $)
$abpen_y^-$,	penalty for air budget shortage in year $y \in Y$ ($ per $)
$cabpen_y^+$,	penalty for cumulative air budget excess in year $y \in Y$ ($ per $)
$cabpen_y^-$,	penalty for cumulative air budget shortage in year $y \in Y$ ($ per $)
$ambpen_{my}^+$,	penalty for air mission budget excess in air mission $m \in M^A$ in year $y \in Y$ ($ per $)
$ambpen_{my}^-$,	penalty for air mission budget shortage in air mission $m \in M^A$ in year $y \in Y$ ($ per $)
$cambpen_{my}^+$,	penalty for cumulative air mission budget excess in air mission $m \in M^A$ in year $y \in Y$ ($ per $)
$cambpen_{my}^-$,	penalty for cumulative air mission budget shortage in air mission $m \in M^A$ in year $y \in Y$ ($ per $)
$lpen_p^+$,	penalty for labor excess at plant $p \in P$ ($ per worker)
$lpen_p^-$,	penalty for labor shortage at plant $p \in P$ ($ per worker)

- Time periods: epochs used for lead and lag events

SBb_{sp}, number of years before (starting at 0) the procurement of ship class $s \in S$ from plant $p \in P_s$ requires budget (i.e. in 0,1,... $SBb_{sp} - 1$ years before) (# years)

SCb_{sp}, number of years before (starting at 0) the procurement of ship class $s \in S$ from plant $p \in P_s$ requires labor (i.e. in 0,1,... $SCb_{sp} - 1$ years before) (# years)

SBa_{sp}, number of years after (starting at 1) the procurement of ship class $s \in S$ from plant $p \in P_s$ requires budget (i.e. in 0,1,... SBa_{sp} years after) (# years)

SCa_{sp}, number of years after (starting at 1) the procurement of ship class $s \in S$ from plant $p \in P_s$ requires labor (i.e. in 0,1,... SCa_{sp} years after) (# years)

ABb_a, number of years before the procurement of aircraft type $a \in A$ in which the aircraft is paid (at once) (# years)

- Ship data

$sinv_s^0$, initial inventory of class $s \in S$ ships (# ships)

$csproc_{sy}$, committed procurement of class $s \in S$ ships in year $y \in Y$ due to production in progress (# ships)

$\overline{sinv}_s$, maximum number of class $s \in S$ ships in inventory (# ships)

$\overline{stot}_{sp}$, maximum number of class $s \in S$ ships to procure from plant $p \in P_s$ (# ships)

$\underline{sproc}_{spy}$, minimum number of class $s \in S$ ships to procure from plant $p \in P_s$ in time period $y \in Y$ (# ships)
Note: $\underline{sproc}_{spy} = 0,\ \forall s \in S, p \in P_s; \forall y \le \max\{SBb_{sp}, SCb_{sp}\} - 1$ and $\underline{sproc}_{spy} = 0,\ \forall s \in S, p \in P_s; \forall y \ge |Y| + 1 - \max\{SBa_{sp}, SCa_{sp}\}$ is required

$\overline{sproc}_{spy}$, maximum number of class $s \in S$ ships to procure from plant $p \in P_s$ in time period $y \in Y$ (# ships)
Note: $\overline{sproc}_{spy} = 0,\ \forall s \in S, p \in P_s; \forall y \le \max\{SBb_{sp}, SCb_{sp}\} - 1$ and $\overline{sproc}_{spy} = 0,\ \forall s \in S, p \in P_s; \forall y \ge |Y| + 1 - \max\{SBa_{sp}, SCa_{sp}\}$ is required

- Aircraft data

$ainv_{at}^0$, initial inventory of type $a \in A$ aircraft that are $t \in T$ years old (# aircraft)

$caproc_{ay}$, committed procurement of type $a \in A$ aircraft in year $y \in Y$ due to production in progress (# aircraft)

$\overline{ainv}_a$, maximum number of type $a \in A$ aircraft in inventory (# aircraft)

$\overline{ainvt}_{at}$, maximum number of type $a \in A$ aircraft in inventory that are $t \in T$ years old (# aircraft)

$\overline{atot}_a$, maximum number of type $a \in A$ aircraft to procure (# aircraft)

$\underline{aproc}_{ay}$, minimum number of type $a \in A$ aircraft to procure during time period $y \in Y$ (# aircraft)

$\overline{aproc}_{ay}$, maximum number of type $a \in A$ aircraft to procure during time period $y \in Y$ (# aircraft)

$\underline{inc}_{ayi}$, increment $i \in I_a$ lower bound for the number of type $a \in A$ aircraft to be procured during year $y \in Y$ (# aircraft)

$\overline{inc}_{ayi}$, increment $i \in I_a$ upper bound for the number of type $a \in A$ aircraft to be procured during year $y \in Y$ (# aircraft)

$asurvive_a$, survival rate of type $a \in A$ aircraft (fraction aircraft)

$\underline{avgage}_{ay}$, minimum average age of type $a \in A$ aircraft at end of year $y \in Y$ (# years of age)

$\overline{avgage}_{ay}$, maximum average age of type $a \in A$ aircraft at end of year $y \in Y$ (# years of age)

$\underline{avgmage}_{my}$, minimum average age of mission $m \in M^A$ aircraft at end of year $y \in Y$ (# years of age)

$\overline{avgmage}_{my}$, maximum average age of mission $m \in M^A$ aircraft at end of year $y \in Y$ (# years of age)

- Retirement data

$\underline{csret}_{sy}$, minimum cumulative number of class $s \in S$ ships to retire by the end of time period $y \in Y$ (# ships)

$\overline{csret}_{sy}$, maximum cumulative number of class $s \in S$ ships to retire by the end of time period $y \in Y$ (# ships)

$\underline{sret}_{sy}$, minimum number of class $s \in S$ ships to retire by the end of time period $y \in Y$ (# ships)

$\overline{sret}_{sy}$, maximum number of class $s \in S$ ships to retire by the end of time period $y \in Y$ (# ships)

$\underline{caret}_{ay}$, minimum cumulative number of type $a \in A$ aircraft to retire by the end of time period $y \in Y$ (# aircraft)

$\overline{caret}_{ay}$, maximum cumulative number of type $a \in A$ aircraft to retire by the end of time period $y \in Y$ (# aircraft)

$\underline{aret}_{sy}$, minimum number of type $a \in A$ aircraft to retire by the end of time period $y \in Y$ (# aircraft)

$\overline{aret}_{sy}$, maximum number of type $a \in A$ aircraft to retire by the end of time period $y \in Y$ (# aircraft)

$arnet_a$ retire no earlier than age for type $a \in A$ aircraft (# years)

- Mission inventory data

$\underline{smreq}_{my}$, number of reference ships required for ship mission $m \in M^S$ in time period $y \in Y$ (# ships)

$\underline{amreq}_{my}$, number of reference aircraft required for air mission $m \in M^A$ in time period $y \in Y$ (# aircraft)

$seffect_s$ effectiveness of type $s \in S$ ship in relation to reference ship (ship per ship)

$aeffect_{at}$ effectiveness of type $a \in A$ aircraft of $t \in T$ years of age in relation to reference aircraft (aircraft per aircraft)

- Budget data

$oscn_y$, fixed SCN cost in year $y \in Y$ ($)

$ocscn_y$, fixed SCN cost in year $y \in Y$ for ships not considered ($)

$frac$, historical fraction of total SCN cost for ship outfitting ($ per $)

$oapn_y$, fixed APN cost in year $y \in Y$ ($)

$ocapn_y$, fixed APN cost in year $y \in Y$ for aircraft not considered in the study ($)

apn_5, historical fraction of total APN categories 1 through 4 required for categories 5 through 7 ($ per $)

oom_y, fixed O&M cost in year $y \in Y$ for maintenance not considered ($)

$scostb_{spql}$, SCN cost incurred *l* years before *q* class-*s* ships are procured from plant p, for $s \in S$, $p \in P_s$, $q \in \bigcup_{y \in Y} Q_{spy}$, $l = \{0,1,\cdots,SBb_{sp} - 1\}$ ($)

$scosta_{spql}$, SCN cost incurred *l* years after *q* class-*s* ships are procured from plant p, for $s \in S$, $p \in P_s$, $q \in \bigcup_{y \in Y} Q_{spy}$, $l = \{1,\cdots,SBa_{sp}\}$ ($)

$aacost_{ayi}$, increment $i \in I_a$ procurement cost for type $a \in A$ aircraft in year $y \in Y$ ($ per aircraft)

$abcost_{ayi}$, increment $i \in I_a$ fixed procurement cost (intercept) for type $a \in A$ aircraft in year $y \in Y$ ($)

$omship_{sy}$, O&M cost for class $s \in S$ ship in year $y \in Y$ ($ per ship)

$omair_{ayt}$, O&M cost for type $a \in A$ aircraft in year $y \in Y$ that are $t \in T$ years old ($ per aircraft)

$csbudget_y$, committed budget in year $y \in Y$ due to ship production in progress ($)

$cabudget_y$, committed budget in year $y \in Y$ due to aircraft production in progress ($)

$\underline{toa}_y$, TOA budget lower limit for year $y \in Y$ ($)

$\overline{toa}_y$, TOA budget upper limit for year $y \in Y$ ($)

$\underline{ctoa}_y$, TOA cumulative budget lower limit for year $y \in Y$ ($)

$\overline{ctoa}_y$, TOA cumulative budget upper limit for year $y \in Y$ ($)

$\underline{airtoa}_y$, aircraft TOA budget lower limit for year $y \in Y$ ($)

$\overline{airtoa}_y$ aircraft TOA budget upper limit for year $y \in Y$ ($)

$\underline{cairtoa}_y$, aircraft TOA cumulative budget lower limit for year $y \in Y$ ($)

$\overline{cairtoa}_y$ aircraft TOA cumulative budget upper limit for year $y \in Y$ ($)

$\underline{airmtoa}_{my}$, aircraft TOA budget lower limit for air mission $m \in M^A$ year $y \in Y$ ($)

$\overline{airmtoa}_{my}$ aircraft TOA budget upper limit for air mission $m \in M^A$ year $y \in Y$ ($)

$\underline{cairmtoa}_{my}$, aircraft TOA cumulative budget lower limit for air mission $m \in M^A$ year $y \in Y$ ($)

$\overline{cairmtoa}_{my}$ aircraft TOA cumulative budget upper limit for air mission $m \in M^A$ year $y \in Y$ ($)

- Labor data

$clabor_{py}$, committed labor in year $y \in Y$ at plant $p \in P$ due to production in progress (# workers)

$sworkb_{spqn}$, required labor *n* years before *q* class-*s* ships are procured from plant p, for $s \in S$, $p \in P_s$, $q \in \bigcup_{y \in Y} Q_{spy}$, $n = \{0,1,\cdots,SCb_{sp}\}$ (# workers)

$sworka_{spqn}$, required labor *n* years after *q* class-*s* ships are procured from plant p, for $s \in S$, $p \in P_s$, $q \in \bigcup_{y \in Y} Q_{spy}$, $n = \{1,\cdots,SCa_{sp}\}$ (# workers)

$\underline{pcap}_{py}$, minimum production capacity at plant $p \in P$ in time period $y \in Y$ (# workers)

$\overline{pcap}_{py}$, maximum production capacity at plant $p \in P$ in time period $y \in Y$ (# workers)

DECISION VARIABLES (and units)

- Variables expressing violations of elastic constraints

F,	objective function value
α_{my}^{AM},	air mission $m \in M^A$ shortage in year $y \in Y$ (# aircraft)
α_{my}^{SM},	ship mission $m \in M^S$ shortage in year $y \in Y$ (# ships)
α_{ay}^{AGE},	aircraft average age excess in year $y \in Y$ (# years of age)
α_{my}^{MAGE},	air mission $m \in M^A$ average age excess in year $y \in Y$ (# years of age)
α_{y}^{B+},	budget excess in year $y \in Y$ ($)
α_{y}^{B-},	budget shortage in year $y \in Y$ ($)
α_{y}^{AB+},	air budget excess in year $y \in Y$ ($)
α_{y}^{AB-},	air budget shortage in year $y \in Y$ ($)
α_{my}^{AMB+},	air mission $m \in M^A$ budget excess in year $y \in Y$ ($)
α_{my}^{AMB-},	air mission $m \in M^A$ budget shortage in year $y \in Y$ ($)
α_{y}^{CB+},	cumulative budget excess in year $y \in Y$ ($)
α_{y}^{CB-},	cumulative budget shortage in year $y \in Y$ ($)
α_{y}^{CAB+},	cumulative air budget excess in year $y \in Y$ ($)
α_{y}^{CAB-},	cumulative air budget shortage in year $y \in Y$ ($)
α_{my}^{CAMB+},	cumulative air mission $m \in M^A$ budget excess in year $y \in Y$ ($)
α_{my}^{CAMB-},	cumulative air mission $m \in M^A$ budget shortage in year $y \in Y$ ($)
α_{y}^{L+},	labor excess in year $y \in Y$ (# workers)
α_{y}^{L-},	labor shortage in year $y \in Y$ (# workers)

- Main decision variables

$APROC_{ayi}$,	number of type $a \in A$ aircraft to procure at the start of year $y \in Y$ in cost increment $i \in I_a$ (# aircraft)
$ARET_{ayt}$,	number of type $a \in A$ aircraft to retire by the end of year $y \in Y$ that are $t \in T$ years old (# aircraft)
$SPROC_{spyq}$,	one if facility $p \in P$ is to deliver $q \in Q_{spy}$ class $s \in S$ ships at the start of year $y \in Y$, and zero otherwise (0-1 variable)
$SRET_{sy}$,	number of class $s \in S$ ships to retire by the end of year $y \in Y$ (# ships)

- Control decision variables

AP_{ayi}, one if aircraft $a \in A$ is procured at the start of year $y \in Y$ in cost increment $i \in I_a$, and zero otherwise (0-1 variable)

$AINV_{ayt}$, inventory of type $a \in A$ aircraft at the start of year $y \in Y$ that are $t \in T$ years old (# aircraft)

$AMINV_{myt}$, inventory for air mission $m \in M^A$ at the start of year $y \in Y$ that are $t \in T$ years old (# aircraft)

$SINV_{sy}$, inventory of class $s \in S$ ships at the start of year $y \in Y$ (# ships)

$SMINV_{my}$, inventory for ship mission $m \in M^S$ at the start of year $y \in Y$ (# ships)

$SBUDGET_y$, amount of SCN money to budget for year $y \in Y$ ($)

$ABUDGET_y$, amount of APN money to budget for year $y \in Y$ ($)

$AMBUDGET_{my}$, amount of APN money to budget for air mission $m \in M^A$ year $y \in Y$ ($)

$OMBUDGET_y$, amount of O&M money to budget for year $y \in Y$ ($)

$BUDGET_y$, total amount of money to budget for year $y \in Y$ ($)

$LABOR_{py}$, amount of labor required in year $y \in Y$ at plant $p \in P$ (# workers)

FORMULATION

$$\min\ F = \sum_{y\in Y}\sum_{m\in M^A} ampen_m\, \alpha_{my}^{AM} + \sum_{y\in Y}\sum_{m\in M^S} smpen_m\, \alpha_{my}^{SM} +$$
$$\sum_{y\in Y}\sum_{a\in A} agepen_a \alpha_{ay}^{AGE} + \sum_{y\in Y}\sum_{m\in M^A} magepen_m \alpha_{my}^{MAGE} +$$
$$\sum_{y\in Y} bpen_y^+\, \alpha_y^{B+} + \sum_{y\in Y} bpen_y^-\, \alpha_y^{B-} + \sum_{y\in Y} cbpen_y^+\, \alpha_y^{CB+} + \sum_{y\in Y} cbpen_y^-\, \alpha_y^{CB-} +$$
$$\sum_{y\in Y} abpen_y^+ \alpha_Y^{AB+} + \sum_{y\in Y} abpen_y^- \alpha_y^{AB-} + \sum_{y\in Y} cabpen_y^+ \alpha_y^{CAB+} + \sum_{y\in Y} cabpen_y^- \alpha_y^{CAB-} +$$
$$\sum_{y\in Y}\sum_{m\in M^A} ambpen_{my}^+ \alpha_{my}^{AMB+} + \sum_{y\in Y}\sum_{m\in M^A} ambpen_{my}^- \alpha_{my}^{AMB-} +$$
$$\sum_{y\in Y}\sum_{m\in M^A} cambpen_{my}^+ \alpha_{my}^{CAMB+} + \sum_{y\in Y}\sum_{m\in M^A} cambpen_{my}^- \alpha_{my}^{CAMB-} +$$
$$\sum_{y\in Y}\sum_{p\in P} lpen_p^+\, \alpha_{py}^{L+} + \sum_{y\in Y}\sum_{p\in P} lpen_p^-\, \alpha_{py}^{L-}$$

subject to:

- Ship

$$\sum_{q\in Q_{spy}} SPROC_{spyq} = 1, \qquad \forall s \in S, p \in P_s; \forall y \in Y \qquad (1)$$

$$SINV_{sy} = sinv_s^0 + \sum_{y' \in Y | y' \le y} csproc_{sy'} + \sum_{p \in P_s} \sum_{y' \le y} \sum_{q \in Q_{spy'}} q\, SPROC_{spy'q} - \sum_{y' \in Y | y' \le y-1} SRET_{sy'}, \quad \forall s \in S; \forall y \in Y \qquad (2)$$

$$\sum_{y \in Y} \sum_{q \in Q_{spy}} q\ SPROC_{spyq} \le \overline{stot}_{sp}, \quad \forall s \in S, p \in P_s \qquad (3)$$

- Aircraft

$$\sum_{i \in I_a} AP_{ayi} \le 1, \quad \forall a \in A; \forall y \in Y \qquad (4)$$

$$\underline{inc}_{ayi}\ AP_{ayi} \le APROC_{ayi} \le \overline{inc}_{ayi}\ AP_{ayi}, \quad \forall a \in A, i \in I_a; \forall y \in Y \qquad (5)$$

$$\underline{aproc}_{ay} \le \sum_{i \in I_a} APROC_{ayi} \le \overline{aproc}_{ay}, \quad \forall a \in A; \forall y \in Y \qquad (6)$$

$$AINV_{ayt} = ainv_{at}^0, \quad \forall a \in A; y = 1; \forall t \in T \qquad (7)$$

$$AINV_{ayt} = asurvive_a * (caproc_{a(y-1)} + \sum_{i \in I_a} APROC_{a(y-1)i}), \quad \forall a \in A; \forall y \in Y | y > 1; t = 1 \qquad (8)$$

$$AINV_{ayt} = asurvive_a * AINV_{a(y-1)(t-1)}, \quad \forall a \in A; \forall y \in Y | y > 1; \forall t \in T | 1 < t \le arnet_a \qquad (9)$$

$$AINV_{ayt} = (asurvive_a * AINV_{a(y-1)(t-1)}) - ARET_{a(y-1)(t-1)}, \quad \forall a \in A; y \in Y | y > 1; \forall t \in T | t > arnet_a \qquad (10)$$

$$\sum_{t \in T} AINV_{ayt} \le \overline{ainv}_a, \quad \forall a \in A; \forall y \in Y \qquad (11)$$

$$\sum_{y \in Y} \sum_{i \in I_a} APROC_{ayi} \le \overline{atot}_a, \quad \forall a \in A \qquad (12)$$

- Age

$$\sum_t (\underline{avgage}_{ay} * AINV_{ayt}) \le \sum_t (t * AINV_{ayt}), \quad \forall a \in A; \forall y \in Y \qquad (13)$$

$$\sum_t (t * AINV_{ayt}) - \alpha_{ay}^{AGE} \le \sum_t (\overline{avgage}_{ay} * AINV_{ayt}), \quad \forall a \in A; \forall y \in Y \qquad (14)$$

$$\sum_{a\in A_m}\sum_{t}(\underline{avgmage_{my}} * aeffect_{at} * AINV_{ayt}) \le \sum_{a\in A_m}\sum_{t}(t * aeffect_{at} * AINV_{ayt}),$$

$$\forall m \in M^A; \forall y \in Y \qquad (15)$$

$$\sum_{a\in A_m}\sum_{t}(t * aeffect_{at} * AINV_{ayt}) - \alpha_{my}^{MAGE} \le \sum_{a\in A_m}\sum_{t}(\overline{avgmage_{my}} * aeffect_{at} * AINV_{ayt}),$$

$$\forall m \in M^A; \forall y \in Y \qquad (16)$$

- Retirements

$$\underline{csret}_{sy} \le \sum_{y'\in Y|y'\le y} SRET_{sy'} \le \overline{csret}_{sy}, \qquad \forall s \in S; \forall y \in Y \qquad (17)$$

$$\underline{caret}_{ay} \le \sum_{t\in T|t\ge arnet_a}\ \sum_{y'\in Y|y'\le y} ARET_{ay't} \le \overline{caret}_{ay}, \qquad \forall a \in A; \forall y \in Y \qquad (18)$$

$$\underline{aret}_{ay} \le \sum_{t\in T|t\ge arnet_a} ARET_{ayt} \le \overline{aret}_{ay}, \qquad \forall a \in A; \forall y \in Y \qquad (19)$$

- Mission Inventory

$$SMINV_{my} = \sum_{s\in S_m}(seffect_s * SINV_{sy}), \qquad \forall m \in M^S; \forall y \in Y \qquad (20)$$

$$SMINV_{my} + \alpha_{my}^{SM} \ge \underline{smreq}_{my}, \qquad \forall m \in M^S; \forall y \in Y \qquad (21)$$

$$\sum_{a\in A_m}\sum_{t}(aeffect_{at} * AINV_{ayt}) + \alpha_{my}^{AM} \ge \underline{amreq}_{my}, \qquad \forall m \in M^A; \forall y \in Y \qquad (22)$$

- Budget

$$\begin{aligned} SBUDGET_y = {} & oscn_y + (1+frac)\Big(ocscn_y + csbudget_y + \\ & \sum_{s\in S}\sum_{p\in P_s}\ \sum_{\substack{y'\in Y| \\ y\le y'\le y+SBb_{sp}}}\ \sum_{q\in Q_{spy'}} scostb_{spq,y'-y}\ SPROC_{spy'q} + \\ & \sum_{s\in S}\sum_{p\in P_s}\ \sum_{y'\in Y|y-SBa_{sp}\le y'\le y-1}\ \sum_{q\in Q_{spy'}} scosta_{spq,y-y'} SPROC_{spy'q}\ \Big), \end{aligned}$$

$$\forall y \in Y \qquad (23)$$

$$AMBUDGET_{my} = \sum_{a \in A_m} \sum_{i \in I_a} (aacost_{a,y+ABb_a,i} * APROC_{a,y+ABb_a,i} + abcost_{a,y+ABb_a,i} * AP_{a,y+ABb_a,i}),$$

$$\forall m \in M^A; \forall y \in Y \qquad (24)$$

$$ABUDGET_y = oapn_y + (1 + apn_5) * (ocapn_y + cabudget_y + \sum_{m \in M^A} AMBUDGET_{my}),$$

$$\forall y \in Y \qquad (25)$$

$$OMBUDGET_y = oom_y + \sum_{s \in S} omship_{sy} * SINV_{sy} + \sum_{a \in A} \sum_{t} omair_{ayt} * AINV_{ayt},$$

$$\forall y \in Y \qquad (26)$$

$$BUDGET_y = SBUDGET_y + ABUDGET_y + OMBUDGET_y, \qquad \forall y \in Y \qquad (27)$$

$$\underline{toa}_y \le \alpha_y^{B-} + BUDGET_y, \qquad \forall y \in Y \qquad (28)$$

$$BUDGET_y - \alpha_y^{B+} \le \overline{toa}_y, \qquad \forall y \in Y \qquad (29)$$

$$\underline{ctoa}_y \le \alpha_y^{CB-} + \sum_{y' \in Y | y' \le y} BUDGET_{y'}, \qquad \forall y \in Y \qquad (30)$$

$$\sum_{y' \in Y | y' \le y} BUDGET_{y'} - \alpha_y^{CB+} \le \overline{ctoa}_y, \qquad \forall y \in Y \qquad (31)$$

$$\underline{airtoa}_y \le \alpha_y^{AB-} + ABUDGET_y, \qquad \forall y \in Y \qquad (32)$$

$$ABUDGET_y - \alpha_y^{AB+} \le \overline{airtoa}_y, \qquad \forall y \in Y \qquad (33)$$

$$\underline{cairtoa}_y \le \alpha_y^{CAB-} + \sum_{y' \in Y | y' \le y} ABUDGET_{y'}, \qquad \forall y \in Y \qquad (34)$$

$$\sum_{y' \in Y | y' \le y} ABUDGET_{y'} - \alpha_y^{CAB+} \le \overline{cairtoa}_y, \qquad \forall y \in Y \qquad (35)$$

$$\underline{airtoa}_{my} \le \alpha_{my}^{AMB-} + AMBUDGET_{my}, \qquad \forall m \in M^A; \forall y \in Y \qquad (36)$$

$$AMBUDGET_{my} - \alpha_{my}^{AMB+} \le \overline{airtoa}_{my}, \qquad \forall m \in M^A; \forall y \in Y \qquad (37)$$

$$\underline{cairtoa}_{my} \le \alpha_{my}^{CAMB-} + \sum_{y' \in Y | y' \le y} AMBUDGET_{my'}, \qquad \forall m \in M^A; \forall y \in Y \qquad (38)$$

$$\sum_{y' \in Y | y' \le y} AMBUDGET_{my'} - \alpha_{my}^{CAMB+} \le \overline{cairtoa}_{my}, \qquad \forall m \in M^A; \forall y \in Y \qquad (39)$$

- Industrial

$$LABOR_{py} = clabor_{py} + \sum_{s \in S | p \in P_s} \sum_{\substack{y' \in Y | \\ y \le y' \le y + SCb_{sp}}} \sum_{q \in Q_{spy'}} sworkb_{spq,y'-y} \, SPROC_{spy'q} + \sum_{s \in S | p \in P_s} \sum_{\substack{y' \in Y | \\ y - SCa_{sp} \le y' \le y-1}} \sum_{q \in Q_{spy'}} sworka_{spq,y-y'} \, SPROC_{spy'q}, \qquad \forall p \in P; \forall y \in Y \qquad (40)$$

$$\underline{pcap}_{py} \le \alpha_{py}^{L-} + LABOR_{py}, \qquad \forall p \in P; \forall y \in Y \qquad (41)$$

$$LABOR_{py} - \alpha_{py}^{L+} \le \overline{pcap}_{py}, \qquad \forall p \in P; \forall y \in Y \qquad (42)$$

- Non-negativity and bounds

$$AINV_{ayt} \ge 0, \qquad \forall a \in A; \forall y \in Y; \forall t \in T \qquad (43)$$

$$AINV_{ayt} \le \overline{ainvt}_{at}, \qquad \forall a \in A; \forall y \in Y; \forall t \in T \qquad (44)$$

$$0 \le SINV_{sy} \le \overline{sinv}_{s}, \qquad \forall s \in S; \forall y \in Y \qquad (45)$$

$$SMINV_{my} \ge 0, \qquad \forall m \in M^s; \forall y \in Y \qquad (46)$$

$$\underline{sret}_{sy} \le SRET_{sy} \le \overline{sret}_{sy}, \qquad \forall s \in S; \forall y \in Y \qquad (47)$$

$$SBUDGET_y \ge 0, \qquad \forall y \in Y \qquad (48)$$

$$ABUDGET_y \ge 0, \qquad \forall y \in Y \qquad (49)$$

$$AMBUDGET_{my} \ge 0, \qquad \forall m \in M^A; \forall y \in Y \qquad (50)$$

$$OMBUDGET_y \ge 0, \qquad \forall y \in Y \qquad (51)$$

$$BUDGET_y \ge 0, \qquad \forall y \in Y \qquad (52)$$

$$LABOR_{py} \geq 0, \qquad \forall p \in P; \forall y \in Y \qquad (53)$$

$$\boldsymbol{\alpha} \geq \mathbf{0} \qquad (54)$$

- Fixed variables

$$APROC_{ayi} = 0, \qquad \forall a \in A, i \in I_a; \forall y \in Y \mid y \leq ABb_a \qquad (55)$$

$$SPROC_{spy0} = 1, \qquad \forall s \in S, p \in P_s; \forall y \in Y \mid y \leq max\{SBb_{sp}, SCb_{sp}\} - 1 \qquad (56)$$

$$SPROC_{spy0} = 1, \qquad \forall s \in S, p \in P_s; \forall y \in Y \mid y \geq |Y| + 1 - \max\{SBa_{sp}, SCa_{sp}\} \qquad (57)$$

- Binary/Integer variables

$$APROC_{ayi} \in Z^+, \qquad \forall a \in A, i \in I_a; \forall y \in Y \qquad (58)$$

$$ARET_{ayt} \in Z^+, \qquad \forall a \in A; \forall y \in Y; t \in T \qquad (59)$$

$$AP_{ayi} \in \{0,1\}, \qquad \forall a \in A, i \in I_a; \forall y \in Y \qquad (60)$$

$$SPROC_{spyq} \in \{0,1\}, \qquad \forall s \in S, p \in P_s; \forall y \in Y; \forall q \in Q_{spy} \qquad (61)$$

$$SRET_{sy} \in Z^+, \qquad \forall s \in S; \forall y \in Y \qquad (62)$$

EQUATION DISCUSSION

The above equations (1) Enforce exactly one quantity of ships is procured for delivery in a given year; (2) Calculate ship inventory; (3) Limit the number of ships per plant over the horizon; (4) Procure aircraft in no more than one cost segment; (5) Limit aircraft procurement each year in the chosen cost segment; (6) Limit aircraft procurement in all cost segments; (7) Set the first year inventory equal to starting values; (8) Calculate age 1 aircraft inventory after first year; (9) Calculate pre-retirement age aircraft inventory after first year; (10) Calculate retirement age aircraft inventory after first year; (11) Limit maximum aircraft inventory; (12) Limit the number of aircraft procured over the horizon; (13) Limit minimum aircraft inventory average age; (14) Limit maximum aircraft inventory average age (elastic); (15) Limit minimum mission inventory average age; (16)

Limit maximum mission inventory average age (elastic); (17) Limit cumulative ship retirements; (18) Limit cumulative aircraft retirements; (19) Limit aircraft retirements; (20) Calculate ship mission inventory; (21) Limit minimum ship mission inventory (elastic); (22) Limit minimum air mission inventory (elastic); (23) Calculate ship budget (SCN); (24) Calculate air mission budget (APN); (25) Calculate aircraft budget (APN); (26) Calculate O&M budget; (27) Calculate total budget; (28) Limit minimum budget (elastic); (29) Limit maximum budget (elastic); (30) Limit minimum cumulative budget (elastic); (31) Limit maximum cumulative budget (elastic); (32) Limit minimum air budget (elastic); (33) Limit maximum air budget (elastic); (34) Limit minimum cumulative air budget (elastic); (35) Limit maximum cumulative air budget (elastic); (36) Limit minimum air mission budget (elastic); (37) Limit maximum air mission budget (elastic); (38) Limit minimum cumulative air mission budget (elastic); (39) Limit maximum cumulative air mission budget (elastic); (40) Calculate labor per plant; (41) Limit minimum labor (elastic); (42) Limit maximum labor (elastic). Equations (43) through (54) are non-negativity constraints and bounds for inventories, retirements, budgets, labor, and elastic variables. Equations (55) through (57) fix to zero, deliveries of ships and aircraft for those years that require production and payment schedules before the first year of the planning horizon. Equations (58) through (62) define procurement and retirement binary and integer variables.

Equations (14), (16), (21), (22), (28) through (39), (41) and (42) use elastic variables. The elastic variables take on a continuous non-negative value as each associated constraint is violated. The CIPA APU objective function minimizes penalties associated with violating the respective budget, mission inventory, average age, and labor constraints.

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