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Flexible and Adaptable Ship Options: Assessing the Future Value of Incorporating Flexible Ships Design Features Into New Navy Ship Concepts

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Abstract

To successfully implement the Surface Navy's Flexible Ships concept, PEO-SHIPS requires a new methodology that assesses the total future value of various combinations of Flexible Ships design features and how they will enable affordable warfighting value over the ship's full service life. Examples of Flexible Ships design features include decoupling payloads from platforms, standardizing platform-to-payload interfaces, allowance for rapid reconfiguration of onboard electronics and weapons systems, preplanned access routes for mission bays and mission decks, and allowance for sufficient growth margins for various distributed systems. The current research analyzes the application of strategic Real Options Valuation methodology within the Integrated Risk Management process to assess the total future value of Flexible Ship design feature options. This approach can be used to support the Future Surface Combatant Analysis of Alternatives technique. The current research has the explicit goal of proposing a reusable, extensible, adaptable, and comprehensive advanced analytical modeling process. This methodology is designed to help U.S. Navy decision-makers in quantifying, modeling, valuing, and optimizing a set of ship design options to support a business case for making strategic acquisition decisions in the context of various quantifiable uncertainties.

Introduction

The U.S. Navy is tasked with fulfilling its missions globally in environments with rapidly changing threats using an equally rapidly evolving technological base of ship platform, mission, electronic, and weapon systems. The challenge the U.S. Navy faces is to retain and maintain sufficient military capabilities during wartime as well as a deterrent during peacetime, with the added goal of minimizing major intrusive, time-consuming, and costly modernization throughout a ship's service life by incorporating Modular Adaptable Ships (MAS) and Flexible and Adaptable Ship Options (FASO) in the ship design. Pursuing this goal has the added benefit of allowing the Navy to affordably and quickly transform a ship's mission systems over its service life to ensure it maintains its required military capabilities (Doerry, 2012).

Historically, naval ship design includes robust fixed structural features that limit the ability to include options for any future capabilities that may require design changes. For instance, any major requirement changes needed to meet critical operational tasks during wartime would necessitate a major modernization effort or decommissioning the existing ship prior to the end of its service life and replacing it with a newly commissioned ship. The concept of MAS and FASO, if applied correctly, with the optimal options implemented, would reduce the need for costly and lengthy major mid-service-life intrusive modernizations, as well as increase the existing platform's flexibility to adapt to new requirements utilizing a faster and cheaper alternative.

The concept of FASO is not new to the Navy. In fact, benefits of MAS/FASO concepts have previously been detailed by Jolliff (1974), Simmons (1975), Drewry (1975), and others. Even as recently as 2015, the Naval Sea Systems Command's (NAVSEA) PEO SHIPS released a presentation on Flexible Ships, detailing its *Affordable Relevance Over the Ship's Life Cycle* (Sturtevant, 2015). In it, Director of Science and Technology, Glen Sturtevant, noted that the current and future main challenges confronting Surface Navy include unknown but evolving global threats while having to manage an accelerated pace of technological changes, coupled with rising costs and declining budgets. The analysis found that ships currently cost too much to build and sustain; the ships (Platforms) are too tightly coupled with their capabilities (Payloads); and inflexible and fixed architectures of legacy ships limit growth and capability upgrades or result in lengthy and costly upgrades. The effects of these issues, of course, are compounded by ever-evolving global threats that introduce significant uncertainty.

ADM Greenert (Chief of Naval Operations) and VADM Rowden (Commander of Naval Surface Forces) in past speeches echoed the idea that the ability to quickly change payloads and having modularity on ships would maximize the service life of ships and allow faster and more affordable upgrades to combat systems and equipment.

Some examples of MAS and FASO that had been espoused in Navy ship design research literature, such as in Sturtevant (2015), Doerry (2012), Koenig (2009), Koenig, Czapiewski, and Hootman (2008), and others, include Decoupling of Payloads from Platforms, Standardizing Platform-to-Payload Interfaces, Rapid Reconfiguration, Preplanned Access Routes, and Sufficient Service Life Allowance for Growth. These FASO areas can be applied to a whole host of systems such as weapons, sensors, aircraft, unmanned vehicles, combat systems, C4I, flexible infrastructure, flexible mission bays and mission decks, vertical launch systems (VLS) for various multiple missile types, future high-powered surface weapons (laser weapon systems and electromagnetic railguns), and modular payloads (e.g., anti-submarine warfare, special operations, mine warfare, intelligence gathering, close-in weapon systems, harpoon launchers, rigid hull inflatable boats, gun systems, etc.).

The concepts of Adaptability and Flexibility (plug-and-play concepts of rapidly removing and replacing mission systems and equipment pier-side or at sea), Modularity (common design interface and modular components that will greatly simplify adding, adapting, modifying, or modernizing a ship's capabilities), and Commonality/Scalability (capabilities that are built independently of a ship by using standardized design specifications that allow similar systems to be placed across multiple ship platforms) are concepts that can take advantage of the capabilities of strategic Real Options Valuation (ROV) analytical methodologies. ROV has been used in a variety of settings in Navy ship maintenance, signal intelligence, and shipbuilding contexts, as well as being widely used in various industries including pharmaceutical drug development, oil and gas exploration and production, manufacturing, start-up valuation, venture capital investment, information technology infrastructure, research and development, mergers and acquisitions, intangible asset valuation, and others. The current project applies the same flexibility modeling empowered by Real Options Valuation methods to identify the optimal ship design alternatives.

This current research acknowledges that the U.S. Navy has attempted to incorporate FASO and MAS capabilities in its ship design of Future Surface Combatants (FSC). Further, the Navy acknowledges that there is significant value in terms of being able to rapidly upgrade FASO ships at a lower cost, while extending the ships' service life, all the while being able to quickly adapt to changes in both external threats and internal new technologies. As such, this current research is not meant to identify said FASO/MAS platforms or payloads per se. Rather, this research is designed to examine previously identified platforms such as the DDG 51 Flight III where there are opportunities to insert flexible ship features. This analysis is limited to the context of the domain of Anti-Submarine Warfare (AWS).

The current research reviews a series of quantitative tools and techniques that may be useful in developing a Business Model or Business Case Analysis to support strategic decision-making, under uncertainty. Specifically, it will identify, model, value, and optimize the various strategic real options in flexible ship designs. Currently, there is only a limited set of real-life applications of FASO/MAS in ship design and they are classified; therefore, actual empirical data is not used in this research. In addition, because the objective of this research is to illustrate, in detail, a potential business case modeling process and analytical methodology (such that the method and process can be replicated and used in all future FASO/MAS design decisions), subject matter expert (SME) opinions, publicly available information, and certain basic assumptions or rough order of magnitude (ROM) estimates were used. The use of said ROM or SME inputs does not detract from the analytical power, efficacy, or applicability of these methods.

In summary, the process will:

- Identify which FASO/MAS options have a positive return on investment (i.e., the benefits outweigh the costs).
- Model Uncertainty and Risks (i.e., Monte Carlo Risk Simulations will be applied to simulate hundreds of thousands of possible scenarios and outcomes to model the volatility and ever-changing global threat matrix).
- Frame and Value the Ship Design Options (i.e., each design option will be vetted and modeled, where the options will be framed in context and valued using cost savings for rapid upgrades at lower costs, costs to design and implement these FASO/MAS options, and estimate potential military value using the Knowledge Value Added method to monetize expected military value).
- Optimize the Portfolio of Options (i.e., in the context of a given a set of FASO/MAS design options with different costs, benefits, capabilities, and uncertainties, given constraints in budget, schedule, and requirements).

The Real Options Solution in a Nutshell

Simply defined, real options is a systematic approach and integrated approach for valuing real options (e.g., ship design options). This approach employs financial theory, economic analysis, management science, decision sciences, statistics, and econometric modeling in applying options theory to value real physical assets (e.g., options for weapons insertion on a ship platform). It is not designed for valuing financial options (e.g., calls, puts in the stock market context). It is appropriate for a dynamic and uncertain environment where decisions have the possibility of being flexible in the context of strategic acquisition investments by, valuing investment opportunities, and projecting required capital expenditures. Real options are crucial in:

- Identifying different acquisition investment decision pathways or projects that management can navigate given highly uncertain conditions (e.g., new enemies, new technologies).
- Valuing each of the strategic decision pathways and what they represent in terms of financial viability and feasibility.
- Prioritizing these pathways or projects based on a series of qualitative and quantitative metrics.
- Optimizing the value of strategic investment decisions by evaluating different decision paths under certain conditions or using a different sequence of pathways that can lead to the optimal acquisition strategy.
- Timing the effective execution of acquisition investments and finding the optimal trigger values and cost or value drivers.
- Managing existing or developing new optionalities and strategic decision pathways for future opportunities (e.g., technology or weapon insertions).

ROV is useful for valuing a project, alternative path, implementation option, or ship design through its strategic options especially in capital-intensive investment decisions under uncertainty. In a traditional cost-benefit and cash flow model, the ROI or cost-benefit question, is presumed to be an accurate, but static, representation of the potential future value of acquisition options. In fact, some of the answers generated through the use of traditional cash flow models are flawed because the model assumes a static, one-time decision-making process with no recourse to choose other pathways or options in the future. In contrast, the real options approach takes into consideration the strategic managerial acquisition options certain projects create, under uncertainty, and the decision-makers' flexibility in exercising or abandoning these ship design options at different points in time, when the quantitative level of uncertainty has decreased or has become known over time.

Real Options Valuation Applications in the U.S. Department of Defense

This section provides a quick snapshot of the various ROV option types and their relevance to the DoD in general, as well as applications within the scope of the current research.

Option to Wait and Defer (Ability to Wait Before Executing)

An option to defer allows the holder the option, but not the obligation, to execute a certain strategy when situations make it optimal to do so. An option to wait and defer provides the holder with the following advantages:

- A portfolio of capabilities and readiness for immediate deployment can be created and maintained with the use of options to defer. If the predeveloped payload or platform options exist, they will allow rapid change out of equipment and integration of new weapons or electronics systems, without the excessive schedule and cost penalties.
- Options to defer allow ship designers to incorporate modernization and upgrade options into the ship design early on, and to defer the exact configuration of the ship until a future date when uncertainties on capability requirements are resolved over the passage of time (midlife of the ship's lifespan), actions (new missions), and events (wartime, peacetime).

- By creating design options and design flexibility specifically for mission and weapon systems that are anticipated to have the maximum change over the lifespan of a ship, and at the same time, using common bow and stern configurations, any changes in future capability requirements can be accommodated quickly and cheaply.
- Other applications within the DoD include the following:
    - Build or Buy Options (Buy versus Lease Options). That is, should a technology be developed internally, or should commercially available off-the-shelf applications be used?
    - Multiple Contracts and Vendors. Having multiple vendors or contracts in place that may or not be executed increases the chances of corporate survivorship and an existing military industrial base to ensure future uncertain demands are met.
    - Capitalizing on other opportunities while reducing large-scale implementation risks, and determining the value of P3I and R&D (parallel implementation of alternatives while waiting on technical success of the main project, and no need to delay the project because of one bad component in the project).
    - Low-rate initial production (LRIP), advanced weapons R&D, advanced technology demonstrations, and weapons and systems prototyping. Provide the right of first refusal to test and see the results (deferring the final decision) until the outcomes of said trials are evident.
    - There is significant Value of Information in forecasting cost inputs, capability requirements, schedule risks, and other key decision metrics by deferring decisions until a later date, but having the option ready to be triggered at a moment's notice.
    - Military intervention strategies include the naval option, the air option, go-long versus go-deep versus go-home option, first strike option, surge option, force mix option, and deterrent options.

Option to Switch (Ability to Switch Applications)

An option to switch allows the holder the right, but not the requirement or obligation, to maintain the current status quo or to switch among a variety of predetermined options. The decision on which option to execute is deferred until a future date when exact needs and specifications are known, and the optimal option is then executed.

- Standardization and Modularity. By incorporating options to ensure ISO standards for containers, tie-down systems, mission bays, and support structures, ships can take on multi-mission payloads quickly and efficiently.
- Flexible infrastructure options within a ship, such as open power, open HVAC, open data cabling, open outfitting, and open structure, allow ships to be adaptable and reconfigured for different missions quickly without major rework such as stripping and welding.
- Other applications within the DoD include, but are not limited to:
    - Switching vendors in Open Architecture (OA) and modular concepts allows the U.S. Navy to use multiple vendors for similar parts, ensuring healthy price and quality competition sustainment in the industry, as well as existing parts suppliers for the future.

    - Readiness and capability risk mitigation can be obtained through ensuring multiple vendors and a strong military industrial base.

Simultaneous Compound Option (Parallel Development)

Simultaneous and parallel development efforts are sometimes used to reduce critical path and schedule risks. The risk of technical failures during development or schedule delays, especially when speed is critical, are mitigated with this simultaneous option where multiple systems are designed in parallel.

- By designing multiple payloads (combat subsystems or electronic subsystems) in parallel with the platform (ship design), newer weapons systems may be ready for integration into the platform years earlier.
- Other applications within the DoD include:
    - Simultaneous test programs (aircraft flight demonstrations and contract competitions).
    - Development of multiple and simultaneous weapons systems.

Portfolio Option (Basket of Options to Execute)

A portfolio of options provides the holder a variety or basket of possible option paths to execute. Some of these options may be too expensive, consistently be dominated by other options, take too long to execute, or simply be nonviable options. Determining the optimal portfolio of warfighter capabilities to develop and field within budgetary and time constraints is key to solving and modeling a portfolio optimization problem.

- Determine the optimal portfolios that provide the maximum capability, flexibility, and cost effectiveness with minimal risks given budget, schedule, wartime, and other scenarios. For instance, if Congress authorizes additional funding or cuts existing funding to certain programs, which capabilities or features should be added or cut?
- Helps to model and determine how much flexibility in design options should be incorporated into an MAS/FASO ship. Investing too little in flexibility will result in excessive modernization costs and increased downtime of the ship or its early retirement before the end of the design service life. Investing too much will create excess flexibility that will not be used, and create a higher up-front cost to obtain these flexibility options.
- Allows for different flexible pathways: Mutually Exclusive (C1 or C2 but not both), Platform Technology (C3 requires C2, but C2 can be standalone; expensive and worth less if considered by itself without accounting for flexibility downstream options it provides for the next phase), expansion options, abandonment options, and parallel development or simultaneous compound options.
- Other applications within the DoD include, but are not limited to:
    - Determining testing required in modular systems, mean-time-to-failure estimates, and replacement and redundancy requirements to maintain desired readiness and availability levels.
    - Maintaining capability and readiness at various levels.
    - Force mix options.
    - Capability selection and sourcing across a spectrum of vendors.

Sequential Compound Option (Proof of Concept, Milestones, and Stage-Gate Development)

The DoD has a requirement for an advanced technology to meet warfighter needs, but the technologies needed are in an early stage of maturity, and it is highly risky whether the technology will be available or work. There are limited vendors/activities capable of undertaking the development, so the program office may mitigate downside risks to the program through a phased approach to the acquisition. For instance, in the first phase, the vendor develops the underlying technology and presents the results to the PEO with a preliminary design. At the end of this phase, the government can either choose to continue through development of a prototype system or harvest the Science and Technology work for later use and abandon the effort. On delivery of a working prototype, the government will conduct tests for performance, evaluate total life-cycle cost, and decide whether to continue to full-scale system development or to abandon the effort, salvaging the knowledge from the prototyping effort for later use.

As an example, an acquisition program manager recognizes that multiple approaches to the problem are possible and decides to pursue a course of parallel development in which a variety of vendors and government labs undertake work to propose a technology solution, which creates a Multiple Activity or Multiple Vendor development of a system or technology. At option points (generally one to two years after contract award), the various solutions will be evaluated for performance, technical merit, and cost, and the universe of participants reduced through a down-select process. After two (or pick a number) rounds, the two most promising approaches are selected for advanced development and prototyping. From those, the best (evaluated in terms of performance, risk, and cost) will be selected for final development and fielding.

The U.S. Navy is currently pursuing the applications of new 3D scanning technology on board a ship to streamline the planning process for depot-level repair work. If the technology works after any technical problems have been ironed out, the scope can be expanded to implement online collaborative tools (requires additional investment) to implement additional process efficiencies for the management of depot-level ship repairs. Expansions across the population of Naval Shipyards will extend the savings/return on investment.

In pursuing Open Architecture (OA) over multiple stages, a proof of concept stage is performed first, and then several small-scale implementations and a final larger-scale implementation are executed. For instance, try OA modular development on a shore-based test system to see if it works before fielding on all units of that Class in the fleet once all the bugs are worked out and only if the proof of concept results are encouraging, thereby reducing the risk while at the same time obtaining the additional upside potential of going to OA (lower downtime, reduced cycle-time, reduced cost, interchangeable parts, at-sea repairs, multiple vendor parts for one system instead of relying only on a single vendor for the entire system, etc.). Successful implementation of a component or technology in one ship Class also provides the opportunity in an OA environment to expand to integrate the capability/technology into other open architected systems for other ship Classes.

A PM in charge of a large spiral development may need to determine the value of various items to release in each spiral. For example, the USAF logistics modernization program (called the Enterprise Resource Planning [ERP] System) has a goal to replace 250 separate legacy systems. A single release would likely be a huge failure. Developing various sequential strategies would show how to capture the most savings during each spiral release of the ERP system while minimizing risks as the system matures. The Army is also adopting the spiral development process for its logistics modernization program. Other examples of spiral development include the U.S. Air Force Air Theater Battle Management System and the Army's Future Combat Systems program, a system of systems development.

- Other applications within the DoD include, but are not limited to:
    - Stage-gate implementation of high-risk project development, prototyping, low-rate initial production (LRIP), technical feasibility tests, and technology demonstration competitions.
    - Government contracts with multiple stages with the option to abandon at any time and valuing Termination for Convenience (T-for-C), and built-in flexibility to execute different courses of action at specific stages of development.
    - P3I, Milestones, R&D, and Phased Options.
    - Platform technology development.

Expansion Option (Platform Technology With Spinoff Capabilities)

The C-17 Globemaster III is a long-range cargo/transport aircraft operated by the USAF since 1993. Full-scale development of the C-17 got underway in 1986, but technical problems and funding shortfalls delayed the program. Despite those difficulties, the C-17 retained broad support from Congress. In April 1990, Defense Secretary Cheney reduced the projected buy from 210 to 120 planes, exercising a contraction option. By the mid-1990s, the program's difficulties had been largely resolved. In 1996, the DoD approved plans for more C-17s and planned to end the production at 180 aircraft in FY2007. Congress then approved another $2 billion for 10 additional C-17 aircraft in FY2008. Expansion options put in place would allow the smooth addition of aircraft as needed, including foreign military sales. Other applications within the DoD include Platform Technologies, Acquisitions, ACTD Follow-on, Foreign Military Sales (FMS), Reusability and Scalability Options, and so forth.

Abandonment Option (Salvage and Walk Away)

A DoD research and development organization in conjunction with a military contractor decides to enter into a joint-testing agreement to test a satellite-based voice recognition intelligence gathering hardware-software product combination currently in its infancy stage of development that, if successful, could potentially be very useful in the fight against terrorism. The DoD can hedge its risks (i.e., the risk is the potential that the hardware-software combination will not work as required) and invest a small sum to buy the right of first refusal for a future investment, for some prespecified amount that is agreed upon now. This way, the U.S. Navy gets to participate in the technology if it is successful, but yet risks only a little if unsuccessful. In deciding whether to purchase the intelligence gathering equipment, a military analyst values the potential to abandon and sell off or divest the assets of the company in the future should there be no further use of the technology or if a newer and much more potent technology arrives on the market. The ability to do so will, in fact, reduce the risk on what the military has to spend on the technology and allows it to recoup some of its potential losses. Other applications within the DoD include Exit and Salvage (cutting losses), Stop before executing the next phase, Termination for Convenience (T-for-C), and so forth.

Contraction Option (Partnerships and Cost/Risk Reduction Strategy)

A contraction option allows two parties to create a joint venture or partnership (e.g., DoD and military vendor partnership) whereby the DoD agrees to purchase certain quantities of a product while holding partial intellectual property rights to the new development. Risks of failure are shared between the two parties, and no single party will bear all the risks (the DoD hedges its downside risks of the product failing, and the vendor hedges its risks of the DoD being not interested in its product). Other applications within the DoD include Outsourcing, Alliances, Contractors, Joint Inter-Service Venture, Foreign Partnerships, and so forth.

FASO/MAS at PEO-Ships: Flexibility Options for Guided Missile Destroyers

The Arleigh Burke class of Guided Missile Destroyers (DDG) is the U.S. Navy's first class of destroyer built around the Aegis Combat System and the SPY-1D multi-function passive electronically scanned array radar. The class is named for Admiral Arleigh Burke, the most famous American destroyer officer of World War II, and later Chief of Naval Operations. The class leader, USS *Arleigh Burke*, was commissioned during Admiral Burke's lifetime (Navy Programs, 2013).

The DDG class ships were designed as multi-mission destroyers to fit the Anti-Aircraft Warfare (AAW) role with their powerful Aegis radar and surface-to-air missiles; Anti-Submarine Warfare (ASW) with their towed sonar array, bow sonar, anti-submarine rockets, and ASW helicopter; Anti-Surface Warfare (ASUW) with their Harpoon missile launcher; and strategic land strike role with their Tomahawk missiles. With upgrades to AN/SPY-1 phased radar systems and their associated missile payloads as part of the Aegis Ballistic Missile Defense System, members of this class have also begun to demonstrate some promise as mobile anti-ballistic missile and anti-satellite weaponry platforms. Some versions of the class no longer have the towed sonar or Harpoon missile launcher (Navy Programs, 2013).

The DDG 51 class destroyers have been designed to support carrier strike groups, surface action groups, amphibious groups, and replenishment groups. They perform primarily AAW with secondary land attack, ASW, and ASUW capabilities. The Mk 41 vertical launch system has expanded the role of the destroyers in strike warfare, as well as their overall performance. The U.S. Navy will use the DDG 51 Flight III Destroyer equipped with the Aegis Modernization program and AMDR to provide joint battlespace threat awareness and defense capability to counter current and future threats in support of joint forces ashore and afloat. The following provides two high-level examples of identifying and framing strategic flexibility options in the DDG51 and DDG1000 environments. These are only notional examples with rough order magnitude values to illustrate the options framing approach.

Power Plant Options

This real options example illustrates the implications of the standard LM2500 GE Marine Gas Turbines for DDG51 FLT III ships versus the Rolls-Royce MT30 Marine Gas Turbine Engines for the Zumwalt DDG 1000, where the latter can satisfy large power requirements in warships. The LM2500 provides 105,000 shaft hp for a four-engine plant. In comparison, the MT30 can generate upwards of 35.4MW, and its auxiliary RR4500 Rolls-Royce turbine generators can produce an added 3.8MW, and each DDG1000 carries two MT30s and two RR4500s. This means that the combined energy output from the Zumwalt can fulfil the electricity demands in a small- to medium-size city. Manufacturer specifications indicate that the LM2500 has an associated Cost/kW of energy of $0.34 and the MT30 Cost/kW is $0.37. In addition, the MT30 prevents warships from running off balance when an engine cannot be restarted until it has cooled down, as is the case in the LM2500.

Figure 1 illustrates a real options strategy tree with four mutually exclusive paths. Additional strategies and pathways can similarly be created, but these initial strategies are sufficient to illustrate the options framing approach. Path 1 shows the As-Is strategy where no additional higher capacity power plant is used, that is, only two standard LM2500 units are deployed, maintain zero design margins for growth, and only what is required for the current ship configuration is designed and built. Medium and large upgrades will require major ship alterations, with high cost and delayed schedule. Path 2 implements the two required LM2500 units with additional and sufficient growth margins for one MT30 power plant but currently only with a smaller power plant incorporated into the design. Sufficient area or modularity is available where parts of the machinery can be removed and replaced with the higher energy production unit if needed. Upfront cost is reduced, and future cost and schedule delays are also reduced. Path 3 is to have two prebuilt MT30s and RR4500s initially. While providing the fastest implementation pathway, the cost is higher in the beginning, but total cost is lower if indeed higher energy weapons will be implemented. Path 4 is an option to switch whereby one LM2500 is built with one MT30 unit. Depending on conditions, either the LM2500 or MT30 will be used (switched between units). When higher-powered future weapons are required such as electromagnetic railguns (E.M. Rail Guns) or high-intensity lasers (H. I. Lasers) as well as other similarly futuristic weapons and systems, the MT30 can be turned on.

Having a warship flexibility with two LM2500s (As-Is base case), allows the Navy a savings of $31.76 million by deferring the option of the other two additional LM2500s. Therefore, having a flexible ship, the Navy can invest later in one LM2500 and attach another MT30 (preventing any engine off-balance effects when the engines cannot be restarted due to excessive heat), can save $34.58 million. The usage of options to defer/invest that combine gas turbine specifications allows the Navy to prevent high sunk costs, properly adjusting the true kW requirements, and allows different combinations of propulsion and energy plants. This analysis can be further extended into any direction as needed based on ship designs and Navy requirements.

The true competitor for MT-30 is LM2500+, as installed in LHD8, LHA6, and the trimaran/even-hull LCS. As an integrated electric plant, the analysis can also factor in ancillary generators (diesel or gas turbine) in addition to the main gas turbines to get an idea of total load capacity since loads can be shifted between propulsion and other uses. In contrast, our legacy plants can’t do that, although there is a move afoot to install auxiliary electric motors onto the reduction gears of the DDGs so they can slow-speed steam on electric power with mains offline.

Vertical Launch System

Another concern of the DoD is the large capital investments required in Vertical Launch Systems (VLS) in U.S. Navy ships. VLS need to be developed and integrated per Navy requirements, which are constrained by rapid technological change and high uncertainties in costs. The usage of strategic real options aims to assess whether the Navy can *keep the option open* to defer the large investments to help avoid high sunk costs and quick technological obsolescence, or whether the Navy should pre-invest in a new VLS. Consequently, flexibility and uncertainty create the right environment to model VLS using a real option framework. According to DGG 51 (Flight II and Flight III) specifications, the estimated cost of a single VLS is approximately $228 million. The most expensive subarea is the MK41 subsystem (DDG 51 contains two MK41s). This current example is developed based on the assumptions of a rapid technological obsolescence, high integration costs, time delays, and reduced capability, which can jeopardize investments in VLS.

In addition, using a real options framework to possibly defer the implementation of MK41 would allow ship designers and engineers to incorporate modernization and upgrade margins in the VLS within the ship design early on, and to defer the exact configuration of the VLS until a future date when uncertainties on capability requirements (i.e., integration, upgrades, changes, new technology, new requirements, updated military warfighter needs) are resolved over the passage of time, action, and events. Also, we can evaluate the option to invest in the second or third MK41 as the situational needs arise. Figure 2 shows the two simple option paths, in which the first path indicates immediate execution where two MK41s are implemented immediately, not knowing if both are actually needed, as opposed to the second strategic path where the VLS is designed such that either two MK41s can be implemented or only one. Therefore, one MK41 can be first inserted and the second added on later only when required, where the VLS has design growth margins to adapt to slightly different technological configurations. The question, of course, is which strategic pathway makes most sense, as computed using strategic real options value.

When the flexibility value is added into the mix, the expected total cost is reduced from $110.10 million to $98.51 million. Finally, wartime scenarios can be incorporated into the analysis whereby if there is a higher probability of conflict where the VLS is required, the value to keep open the option to defer is reduced, and the Navy is better off executing the option immediately and having the required VLS in place.

The project with flexibility is $118.22 million (flexible VLS warship open to integrate another MK41 in the future as and when needed) against $228.34 million (base case DDG 51 with no flexibility options, where the VLS is already built in). The Navy can save or delay the usage of $110.10 million in cost by holding on to the option of deferring the second MK41. In addition, in the near future, the cost to implement the second MK41 can be reduced due to a flatter learning curve, economies of scale, and the specific technology becoming more readily available, less complex, and easier to implement, or can be more expensive because the technology experiences new updates, higher performance, and greater efficiency. If cost volatility is the main variable for the Navy, we contrast differing the second MK41 against the base case. It means that we compare the VLS system with no flexibility ($228.32 million) against the cost changes in the second MK41 (assuming Navy engineers develop a plug-and-play structure to integrate the next MK41 quickly). This assumption can be relaxed using cost and schedule modeling and Monte Carlo simulation methods. In terms of the options valuation, the option to defer for the Navy follows cost comparisons. It other words, it reduces the cost exposure for the second MK41 from $110.10 million to an expected value of $69.89 million. In addition, decision-makers observe in the options strategy tree and decision tree where they can keep the option to defer open and under what conditions the Navy should execute and invest in the second MK41. One likely extension is where the decision-maker can introduce probabilities or expectations of Navy actions (new missions and new requirements) or events (wartime, peacetime). This affects the flexibility of the second MK41 by constraining the option’s flexibility to defer. For instance, if the Navy has strong expectations of requiring the second MK1 (wartime probability is higher than 30%), it reduces the value of the option to defer and accelerates the availability and execution of the second MK41 option earlier. In peacetime, the Navy has more flexibility in terms of how it implements or assesses its real options to wait and defer. Additional MK57 Peripheral VLS in use on DDG1000 or the MK48 family of self-defense VLS for ESSM can of course be additional considered.

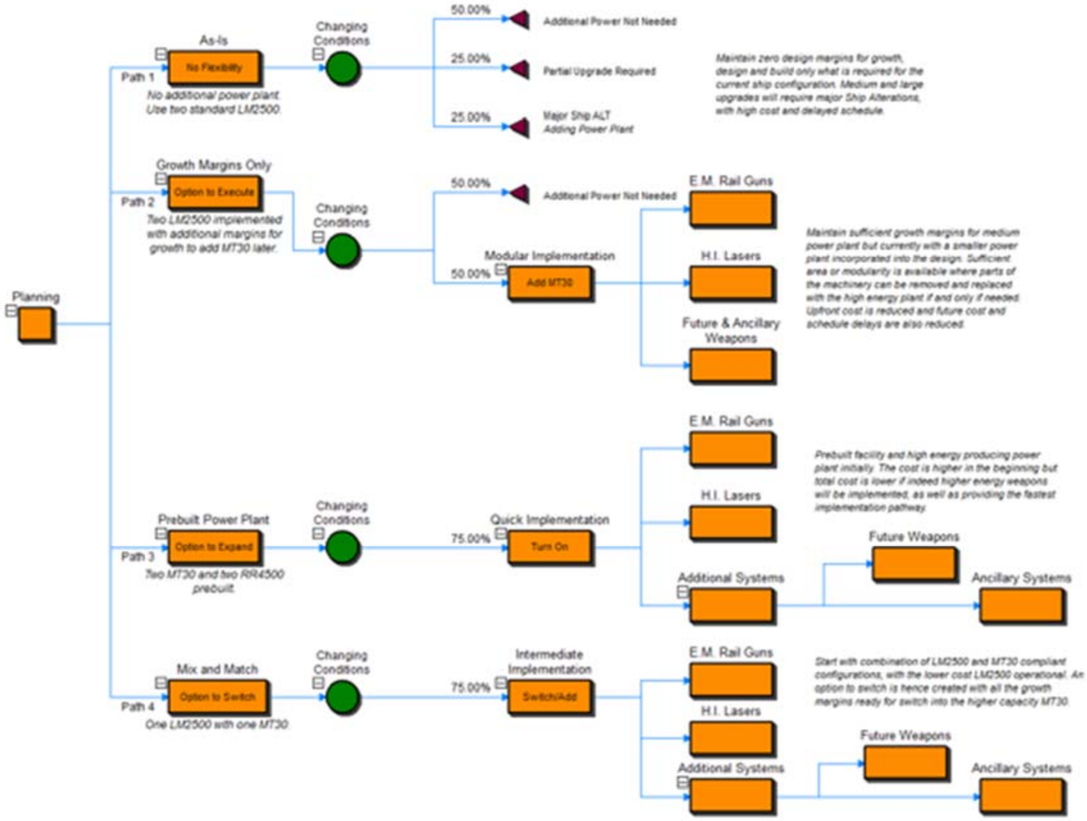

Figure 1. Options Framing on Power Generation

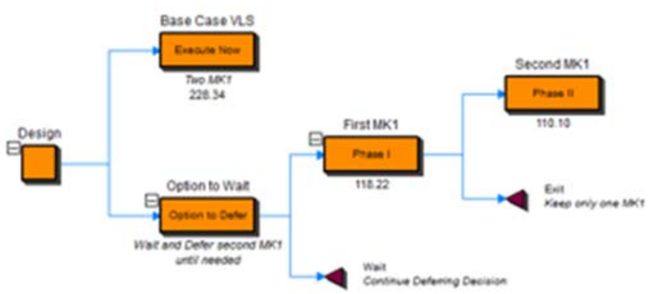

Figure 2. Options Framing on Vertical Launch Systems

The strategic real options analysis is solved employing various methodologies, including the use of binomial lattices with a market-replicating portfolios approach, and backed up using a modified closed-form sequential compound option model. The value of a compound option is based on the value of another option. That is, the underlying variable for the compound option is another option, and the compound option can be either sequential in nature or simultaneous. Solving such a model requires programming capabilities. This subsection is meant as a quick peek into the math underlying a very basic closed-form compound option. This section is only a preview of the detailed modeling techniques used in the current analysis and should not be assumed to be the final word. For instance, we first start by solving for the critical value of I, an iterative component in the model, using (Mun, 2016):

$$X_2 = Ie^{-q(T_2-t_1)}\Phi\left(\frac{\ln(I/X_1)+(r-q+\sigma^2/2)(T_2-t_1)}{\sigma\sqrt{(T_2-t_1)}}\right)$$
$$-X_1e^{-r(T_2-t_1)}\Phi\left(\frac{\ln(I/X_1)+(r-q-\sigma^2/2)(T_2-t_1)}{\sigma\sqrt{(T_2-t_1)}}\right)$$

Then, solve recursively for the value I above and input it into the model:

$$Compound\ Option = Se^{-qT_2}\Omega\left[\frac{\ln(S/X_1)+(r-q+\sigma^2/2)T_2}{\sigma\sqrt{T_2}};\ \frac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}};\ \sqrt{t_1/T_2}\right]$$
$$-X_1e^{-rT_2}\Omega\left[\frac{\ln(S/X_1)+(r-q+\sigma^2/2)T_2}{\sigma\sqrt{T_2}}-\sigma\sqrt{T_2};\ \frac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}}-\sigma\sqrt{t_1};\ \sqrt{t_1/T_2}\right]$$
$$-X_2e^{-rt_1}\Phi\left[\frac{\ln(S/I)+(r-q+\sigma^2/2)t_1}{\sigma\sqrt{t_1}}-\sigma\sqrt{t_1}\right]$$

The model is then applied to a sequential problem where future phase options depend on previous phase options (e.g., Phase II depends on Phase I's successful implementation).

Definitions of Variables

S	present value of future cash flows ($)	r	risk-free rate (%)
σ	volatility (%)	Φ	cumulative standard-normal
q	continuous dividend payout (%)	I	critical value solved recursively
Ω	cumulative bivariate-normal	X_1	strike for the underlying ($)
X_2	strike for the option on the option ($)	t_1	expiration date for the option on the option
T_2	expiration date for the underlying option		

The preceding closed-form differential equation models are then verified using the risk-neutral market-replicating portfolio approach assuming a sequential compound option. In solving the market-replicating approach, we use the following functional forms (Mun, 2016):

- Hedge ratio (h):
  $$h_{i-1} = \frac{C_{up} - C_{down}}{S_{up} - S_{down}}$$
- Debt load *(D)*
  $$D_{i-1} = S_i(h_{i-1}) - C_i$$
- Call value *(C)* at node *i:*
  $$C_i = S_i(h_i) - D_i e^{-rf(\delta t)}$$
- Risk-adjusted probability (q):
  $q_i = \frac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$ obtained assuming
  $$S_{i-1} = q_i S_{up} + (1-q_i)S_{down}$$

- This means that
  $S_{i-1} = q_i S_{up} + S_{down} - q_i S_{down}$ and $q_i[S_{up} - S_{down}] = S_{i-1} - S_{down}$
  so we get $q_i = \frac{S_{i-1} - S_{down}}{S_{up} - S_{down}}$

Additional methods using closed-form solutions, binomial and trinomial lattices, and simulation approaches as well as dynamic simulated decision trees that are used in computing the relevant option values of each strategic pathways as previously indicated. Fortunately, Navy analysts do not have to be experts in advanced mathematics to run these models, as they have all been preprogrammed in PEAT, as illustrated in Figure 15.

Cost Analysis and Data Gathering

Once the various FASO/MASO options are framed and modeled as shown in the previous step, the modeling process continues with additional data gathering activities. The following are some sample parameters of the Surface Warfare program under consideration, and we use the generic terms Option 1, Option 2, and so forth, for generalization purposes.

- For all models, we can assume a 15% discount rate, 35% tax rate, and a 10-year time horizon for the cost savings (all future savings past Year 10 after discounting will be assumed to be negligible). The discounting base year is 2017 (Year 0 and Capital Investment is required in 2017) whereas immediate savings and short-term benefits and maintenance savings start in Year 1 (2018). This means Year 10 is 2027. These rates are applied only to monetary values and can be changed to whatever appropriate values as required.
- The following table shows the remaining relevant information you will need to run your models. All monetary values are in thousands of dollars ($000). Remember to save your models and settings.

Capability Options	Savings Now	Short-Term Benefits	Maintenance Savings	Capital Cost	Fixed Cost	Operating Cost	OPNAV Value	Command Value	KVA Value
Option 1	$550	$30	$60	$400	$3	$2	8.1	1.2	8.1
Option 2	$650	$5	$10	$300	$3	$2	1.27	2.5	1.27
Option 3	$700	$35	$10	$350	$3	$2	5.02	7.5	5.02
Option 4	$1,000	$50	$20	$600	$3	$2	8.83	4.5	8.83
Option 5	$2,000	$100	$20	$1,000	$3	$2	9.88	9.7	9.88
Option 6	$1,000	$10	$20	$550	$3	$2	3.64	7.4	3.64
Option 7	$2,000	$100	$20	$750	$3	$2	5.27	4.5	5.27
Option 8	$850	$75	$20	$550	$3	$2	9.8	7.5	9.8
Option 9	$1,500	$125	$20	$750	$3	$2	5.68	7.5	5.68
Option 10	$1,000	$125	$20	$550	$3	$2	8.29	8.5	8.29

- "Savings Now" is the immediate monetary cost savings benefits obtained by implementing the new upgraded system (e.g., lower overhead requirements, reduced parts and labor requirements). This amount is applied in the first year of the cash flow stream only (Year 1 or 2016) as its effects are deemed as immediate.
- "Short-Term Benefits" is the savings per year for the first 5 years, stemming from reduction in staffing requirements, but these savings are deemed to be reabsorbed later on. Savings apply from 2016 to 2020.
- "Maintenance Savings" is the savings each year for all 10 years starting in 2016 where system maintenance cost is reduced and saved.
- "Capital Cost" is applied in Year 0 or 2015 as a one-time capital expenditure.
- Assume a "Fixed Direct Cost" and constant "Indirect Operating Cost" per year for all 10 years starting in 2016. The new equipment upgrades will require

some fixed overhead cost and operating expenses to maintain. The idea is these will be less than the total sum of benefits obtained by implementing the capability.

- “OPNAV” and “Command” are average values of multiple subject matter experts’ estimates of the criticality (1–10, with 10 being the highest) of each capability. “KVA” is unit equivalence (this can be multiplied by any market price comparable such as $1 million per unit or used as-is in the optimization model). These will be used later in the optimization section.

Financial Modeling

The *Discounted Cash Flow* section shown in Figure 3 is at the heart of the analysis’s input assumptions. Users would enter their input assumptions—such as starting and ending years of the analysis, the discount rate to use, and the marginal tax rate—and set up the project economics model (adding or deleting rows in each subcategory of the financial model). Additional time-series inputs are entered in the data grid as required, while some elements of this grid are intermediate computed values. The entire grid can be copied and pasted into another software application such as Microsoft Excel, Microsoft Word, or other third-party software applications, or can be viewed in its entirety as a full screen pop-up.

Users can also identify and create the various options, and compute the economic and financial results such as net present value (NPV), internal rate of return (IRR), modified internal rate of return (MIRR), profitability index (PI), return on investment (ROI), payback period (PP), and discounted payback (DPP). This section will also auto-generate various charts, cash flow ratios and models, intermediate calculations, and comparisons of the options within a portfolio view, as illustrated in the next few figures. As a side note, the term *Project* is used in PEAT’s DCF module to represent a generic analysis option, where each project can be a different asset, project, acquisition, investment, research and development, or simply variations of the same investment (e.g., different financing methods when acquiring the same firm, different market conditions and outcomes, or different scenarios or implementation paths). Therefore, the more flexible terminology of *Project* is adopted instead.

Figure 4 illustrates the *Economic Results* of each project. This Level 3 subtab shows the results from the chosen project and returns the NPV, IRR, MIRR, PI, ROI, PP, and DPP. These computed results are based on the user’s selection of the discounting convention, if there is a constant terminal growth rate, and the cash flow to use (e.g., net cash flow versus net income or operating cash flow). An *NPV Profile* table and chart are also provided, where different discount rates and their respective NPV results are shown and charted. Users can change the range of the discount rates to show/compute by entering the From/To percent, copy the results, and copy the profile chart, as well as use any of the chart icons to manipulate the chart’s look and feel (e.g., change the chart’s line/background color, chart type, chart view, or add/remove gridlines, show/hide labels, and show/hide legend). Users can also change the variable to display in the chart. For instance, users can change the chart from displaying the NPV profile to the time-series charts of net cash flows, taxable income, operating cash flows, cumulative final cash flows, present value of the final cash flows, and so forth.

The *Economic Results* subtabs are for each individual project, whereas *the Portfolio Analysis* tab (which is shown later as Figure 5) compares the economic results of all projects at once. The *Terminal Value Annualized Growth Rate* is applied to the last year’s cash flow to account for a perpetual constant growth rate cash flow model, and these future cash flows, depending on which cash flow type chosen, are discounted back to the base year and added to the NPV to arrive at the perpetual valuation.

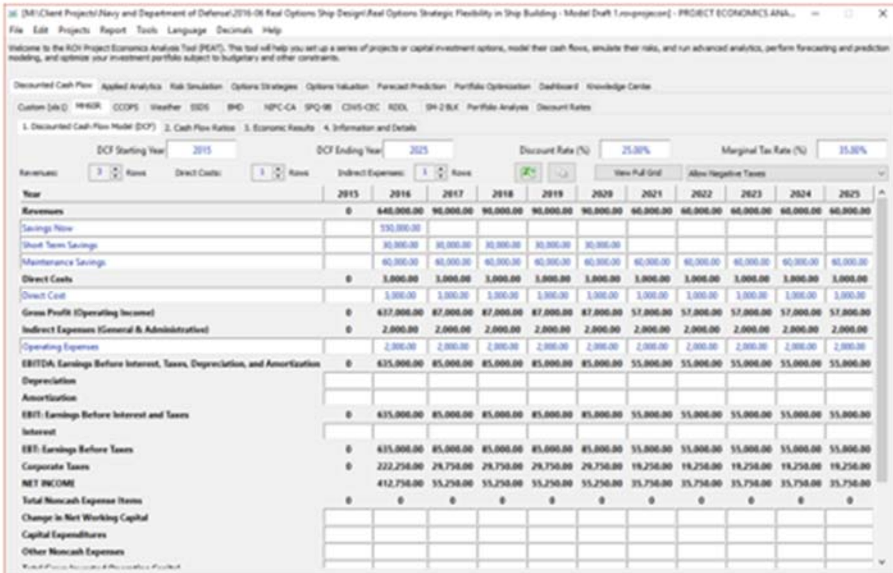

Figure 3. PEAT Discounted Cash Flow Module

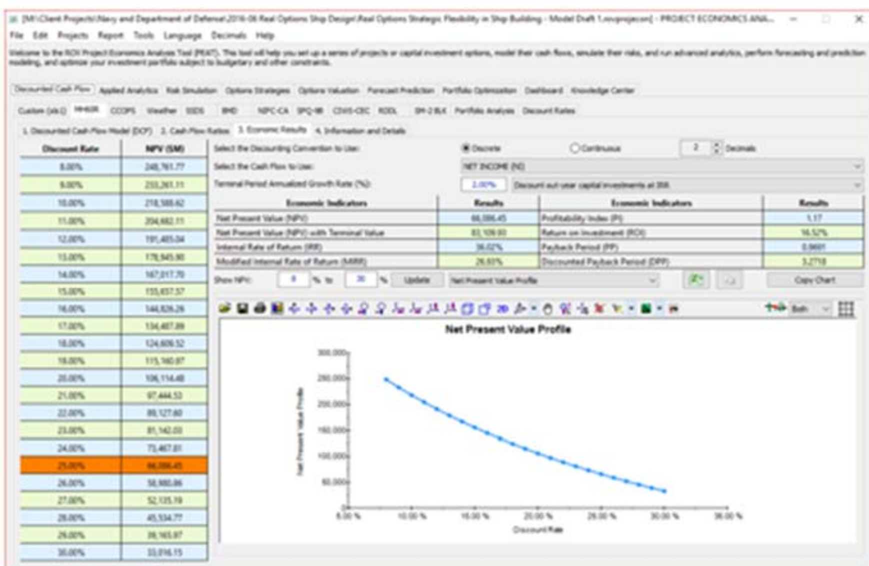

Figure 4. Economic Results

Static Portfolio Analysis and Comparisons of Multiple Projects

Figure 5 illustrates the *Portfolio Analysis* of multiple *Projects*. This Portfolio Analysis tab returns the computed economic and financial indicators such as NPV, IRR, MIRR, PI, ROI, PP, and DPP for all the projects combined into a portfolio view (these results can be stand-alone with no base case or computed as incremental values above and beyond the chosen base case). The *Economic Results* (Level 3) subtabs show the individual project's economic and financial indicators, whereas this Level 2 *Portfolio Analysis* view shows the results of all projects' indicators and compares them side by side. There are also two charts available for comparing these individual projects' results. The *Portfolio Analysis* tab is used to obtain a side-by-side comparison of all the main economic and financial indicators of all the projects at once. For instance, users can compare all the NPVs from each project in a single results grid. The bubble chart on the left provides a visual representation of up to three chosen variables at once (e.g., the y-axis shows the IRR, the x-axis represents the NPV, and the size of the bubble may represent the capital investment; in such a situation, one would prefer a smaller bubble that is in the top right quadrant of the chart). These charts have associated icons that can be used to modify their settings (chart type, color, legend, etc.).

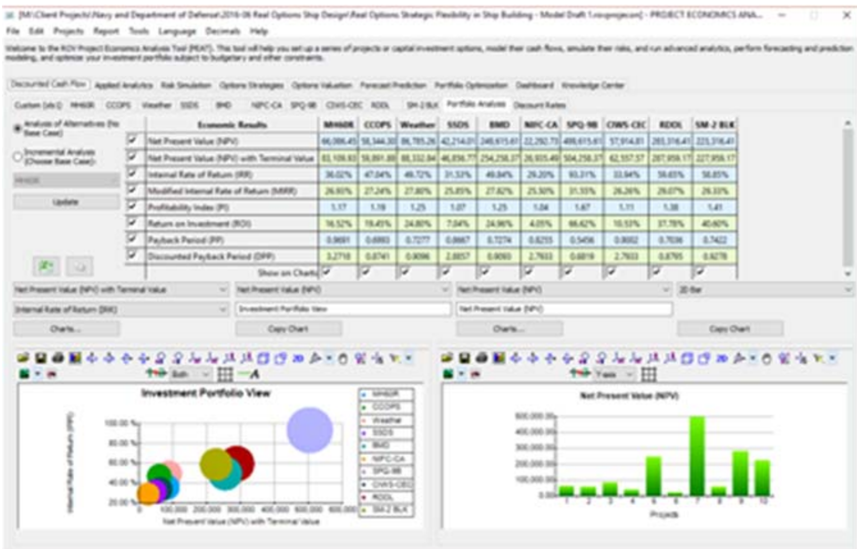

Figure 5. Static Portfolio Analysis

Tornado and Sensitivity Analytics

Figure 6 illustrates the *Applied Analytics* section, which allows users to run *Tornado Analysis* and *Scenario Analysis* on any one of the projects previously modeled—this analytics tab is on Level 1, which means it covers all of the various projects on Level 2. Users can, therefore, run tornado or scenario analyses on any one of the projects. Tornado analysis, as we already know, is a static sensitivity analysis of the selected model's output to each input assumption, performed one at a time, and ranked from most impactful to the least. Users start the analysis by first choosing the output variable to test from the droplist.

Users can change the default sensitivity settings of each input assumption to test and decide how many input variables to chart (large models with many inputs may generate unsightly and less useful charts, whereas showing just the top variables reveals more information through a more elegant chart). Users can also choose to run the input assumptions as unique inputs, group them as a line item (all individual inputs on a single line item are assumed to be one variable), or run as variable groups (e.g., all line items under Revenue will be assumed to be a single variable). Users will need to remember to click Update to run the analysis if they make any changes to any of the settings. The sensitivity results are also shown as a table grid at the bottom of the screen (e.g., the initial base value of the chosen output variable, the input assumption changes, and the resulting output variable's sensitivity results). The following summarizes the tornado analysis chart's main characteristics:

- Each horizontal bar indicates a unique input assumption that constitutes a precedent to the selected output variable.
- The x-axis represents the values of the selected output variable. The wider the bar chart, the greater the impact/swing the input assumption has on the output.
- A green bar on the right indicates that the input assumption has a positive effect on the selected output (conversely, a red bar on the right indicates a negative effect).
- Each of the precedent or input assumptions that directly affect the NPV with Terminal Value is tested ±10% by default (this setting can be changed); the top 10 variables are shown on the chart by default (this setting can be changed), with a 2-decimal precision setting; and each unique input is tested individually.
- The default sensitivity is globally ±10% of each input variable but each of these inputs can be individually modified in the data grid. Note that a larger percentage variation will test for nonlinear effects as well.
- The model's granularity can be set (e.g., Variable Groups look at an entire variable group such as all revenues or direct costs will be modified at once; Line Items change the entire row for multiple years at once; and Individual Unique Inputs look at modifying each input cell).

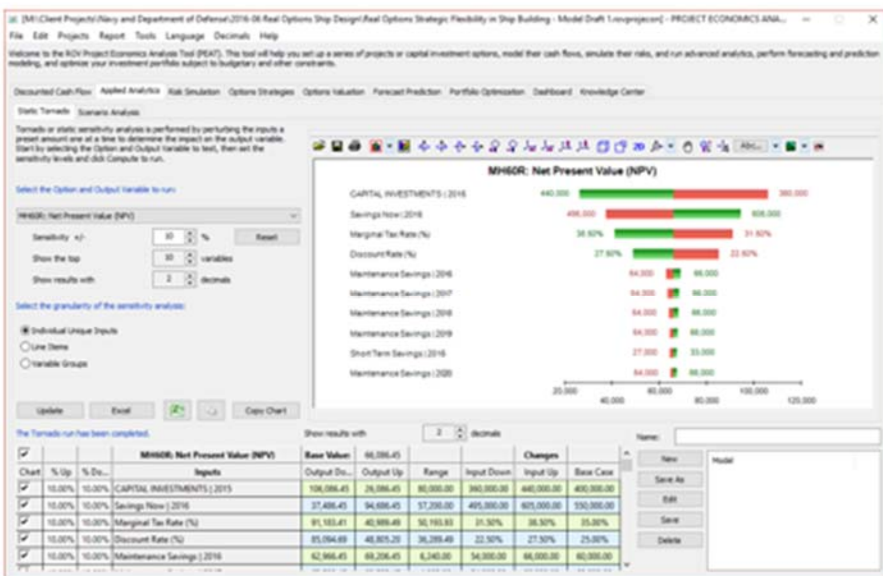

Figure 6. Applied Analytics: Tornado

Figure 7 illustrates the *Scenario Analysis* tab, where the scenario analysis can be easily performed through a two-step process: identify the model input settings and run the model to obtain scenario output tables. In the *Scenario Input Settings* subtab, users start by selecting the output variable they wish to test from the droplist. Then, based on the selection, the precedents of the output will be listed under two categories (*Line Item*, which will change all input assumptions in the entire line item in the model simultaneously, and *Single Item*, which will change individual input assumption items). Users select one or two checkboxes at a time and the inputs they wish to run scenarios on, and enter the plus/minus percentage and the number of steps between these two values to test. Users can also add color coding of sweetspots or hotspots in the scenario analysis (values falling within different ranges have unique colors). Users can create multiple scenarios and *Save As* each one (enter a name and model notes for each saved scenario).

Scenario analyses can sometimes be used as heat maps to identify the combinations of input parameter conditions whereby the calculated outputs will be above or below certain thresholds. A visual heat map can be created by adding color thresholds in the scenario results table. Figure 8 illustrates the *Scenario Output Tables* to run the saved *Scenario Analysis* models.

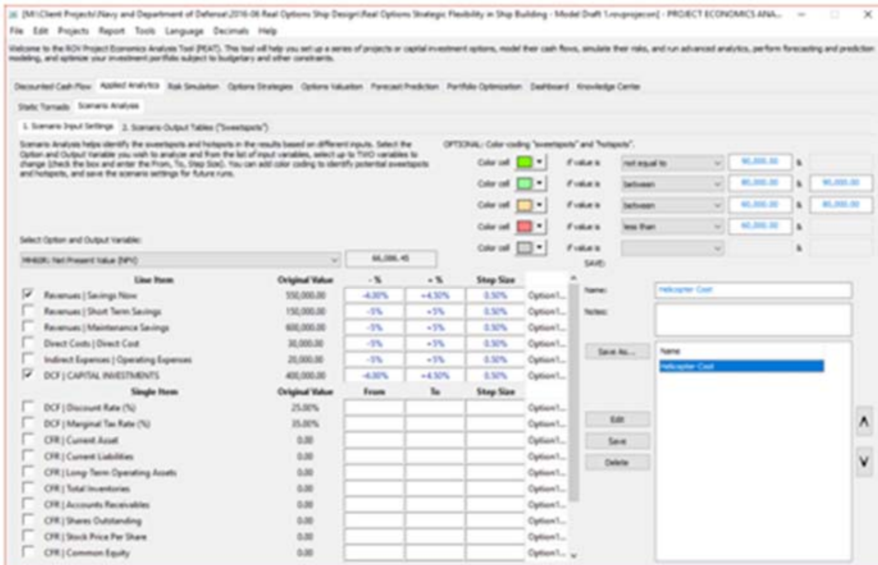

Figure 7. Applied Analytics: Scenario Analysis Input

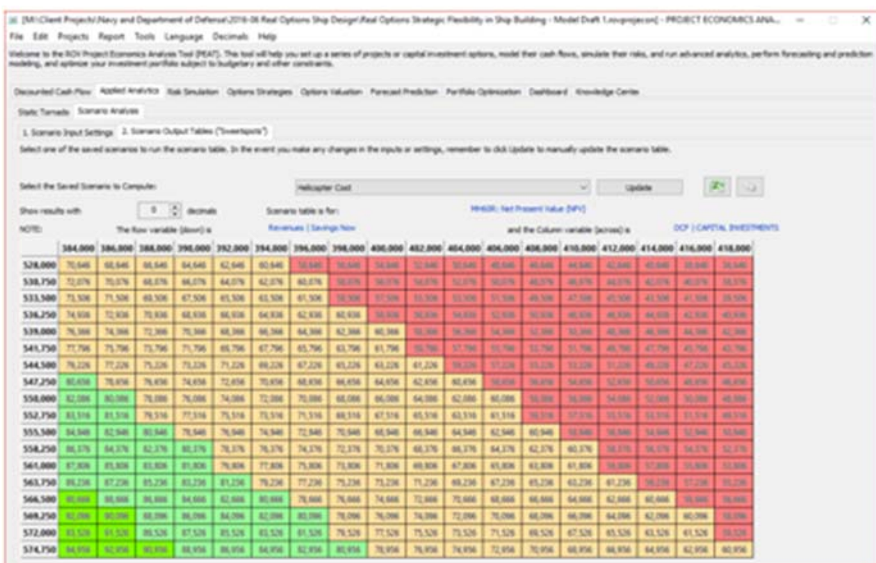

Figure 8. Applied Analytics: Scenario Tables

Monte Carlo Risk Simulation

Figure 9 illustrates the *Risk Simulation* section, where Monte Carlo risk simulations can be set up and run. Users can set up probability distribution assumptions on any combinations of inputs, run a risk simulation tens to hundreds of thousands of trials, and retrieve the simulated forecast outputs as charts, statistics, probabilities, and confidence intervals in order to develop comprehensive risk profiles of the projects.

Simulation Results, Confidence Intervals, and Probabilities

Figure 10 illustrates the Risk Simulation results. After the simulation completes its run, the utility will automatically take the user to the *Simulation Results* tab. The user selects the output variable to display using the droplist. The simulation forecast chart is shown on the left, while percentiles and simulation statistics are presented on the right.

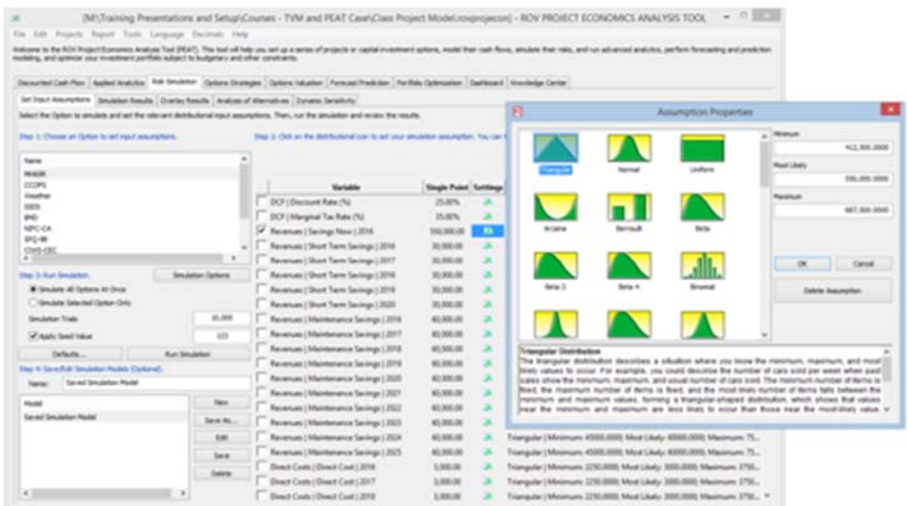

Figure 9. Risk Simulation Input Assumptions

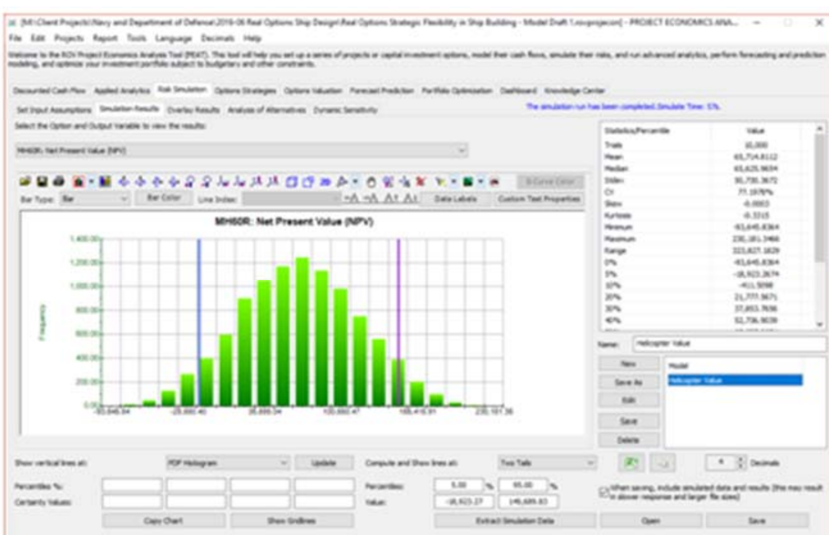

Figure 10. Risk Simulation Results

Probability Distribution Overlay Charts

Figure 11 illustrates the Overlay Results tab. Multiple simulation output variables can be compared at once using the overlay charts. Users simply check/uncheck the simulated outputs they wish to compare and select the chart type to show (e.g., S-Curves, CDF, PDF). Users can also add percentile or certainty lines by first selecting the output chart, entering the relevant values, and clicking the *Update* button. As usual, the generated charts are highly flexible in that users can modify them using the included chart icons (as well as whether to show or hide gridlines), and the chart can be copied into the Microsoft Windows clipboard for pasting into another software application. Typically, S-curves of CDF curves are used in overlay analysis when comparing the risk profile of multiple simulated forecast results.

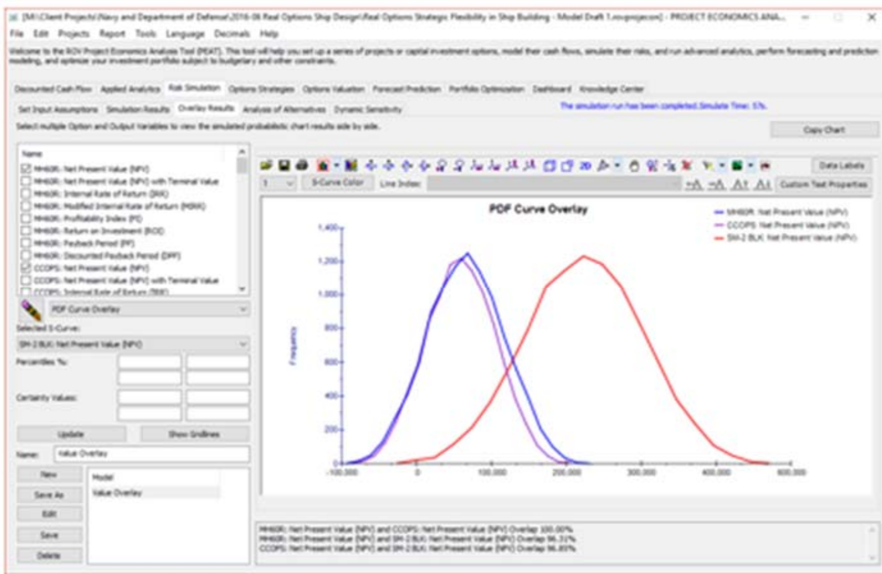

Figure 11. Simulated Overlay Results

Analysis of Alternatives

Figure 12 illustrates the *Analysis of Alternatives* subtab. Whereas the *Overlay Results* subtab shows the simulated results as charts (PDF/CDF), the *Analysis of Alternatives* subtab shows the results of the simulation statistics in a table format as well as a chart of the statistics such that one project can be compared against another. The default is to run an analysis of alternatives to compare one project versus another, but users can also choose the *Incremental Analysis* project (remembering to choose the desired economic metric to show, its precision in terms of decimals, the *Base Case* project to compare the results to, and the chart display type).

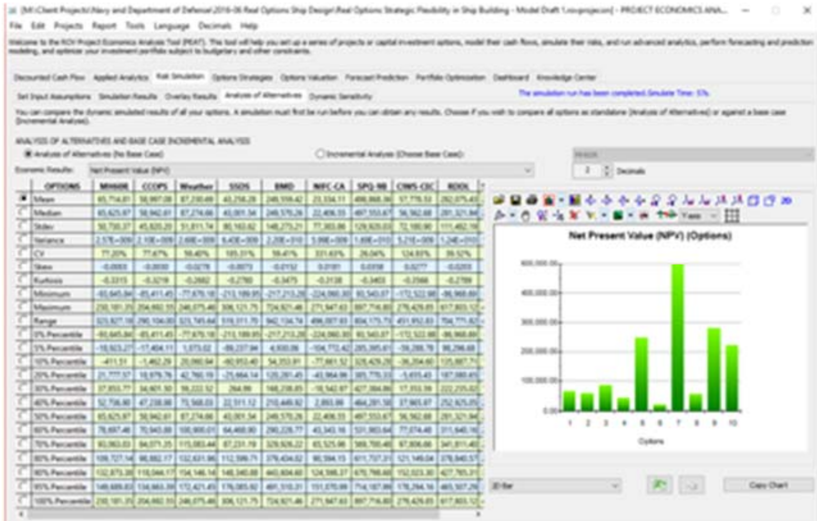

Figure 12. Simulated Analysis of Alternatives

Dynamic Sensitivity Analysis

Figure 13 illustrates the *Dynamic Sensitivity Analysis* computations. Tornado analysis and scenario analysis are both static calculations. Dynamic sensitivity, in contrast, is a dynamic analysis, which can only be performed after a simulation is run. Users start by selecting the desired project's economic output. Red bars on the *Rank Correlation* chart indicate negative correlations and green bars indicate positive correlations for the left chart. The correlations' absolute values are used to rank the variables from the highest relationship to the lowest, for all simulation input assumptions. The *Contribution to Variance* computations and chart indicate the percentage fluctuation in the output variable that can be statistically explained by the fluctuations in each of the input variables. As usual, these charts can be copied and pasted into another software application.

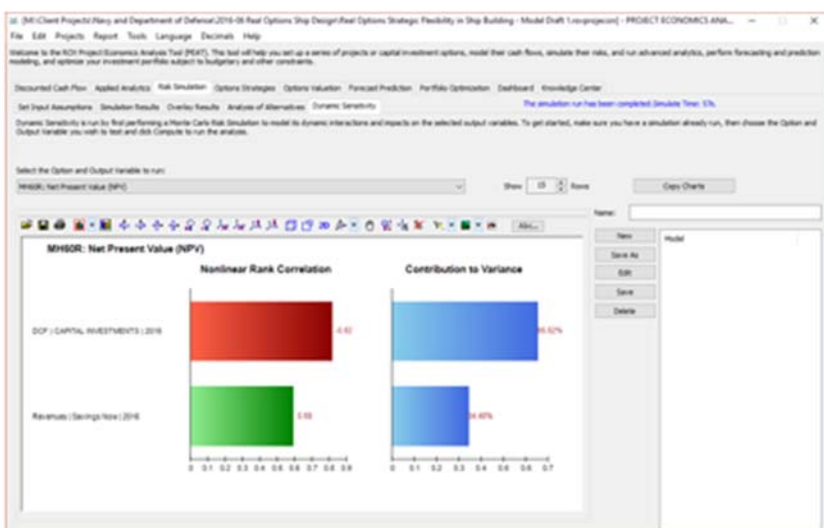

Figure 13. Simulated Dynamic Sensitivity Analysis

Strategic Real Options Valuation Modeling

Figure 14 illustrates the Options Strategies tab. Options Strategies is where users can draw their own custom strategic maps, and each map can have multiple strategic real options paths. This section allows users to draw and visualize these strategic pathways and does not perform any computations.

Real Options Valuation Modeling

Figure 15 illustrates the *Options Valuation* tab and the *Strategy View*. This section performs the calculations of real options valuation models. Users must understand the basic concepts of real options before proceeding. This *Options Valuation* tab internalizes the more sophisticated Real Options SLS. Instead of requiring more advanced knowledge of real options analysis and modeling, users can simply choose the real option types, and the required inputs will be displayed for entry. Users can compute and obtain the real options value quickly and efficiently, as well as run the subsequent tornado, sensitivity, and scenario analyses.

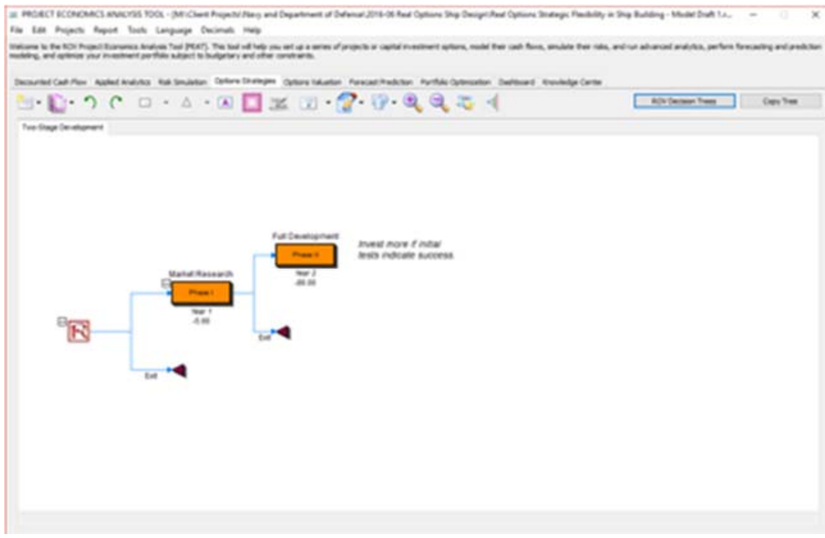

Figure 14. Options Strategies

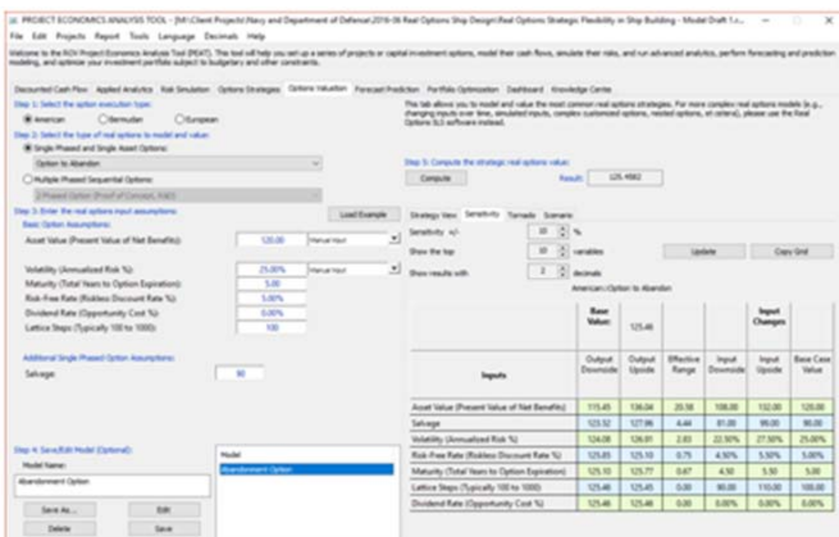

Figure 15. Options Valuation

Portfolio Optimization

Figure 16 illustrates the *Portfolio Optimization's Optimization Settings* subtab. In the Portfolio Optimization section, the individual projects can be modeled as a portfolio and optimized to determine the best combination of projects for the portfolio. In today's competitive global economy, companies are faced with many difficult decisions. These decisions include allocating financial resources, building or expanding facilities, managing inventories, and determining product-mix strategies. Such decisions might involve thousands or millions of potential alternatives. Considering and evaluating each of them would be impractical or even impossible. A model can provide valuable assistance in incorporating relevant variables when analyzing decisions and in finding the best solutions for making decisions. Models capture the most important features of a problem and present them in a form that is easy to interpret. Models often provide insights that intuition alone cannot. An optimization model has three major elements: decision variables, constraints, and an objective. In short, the optimization methodology finds the best combination or permutation of decision variables (e.g., which products to sell or which projects to execute) in every conceivable way such that the objective is maximized (e.g., revenues and net income) or minimized (e.g., risk and costs) while still satisfying the constraints (e.g., budget and resources).

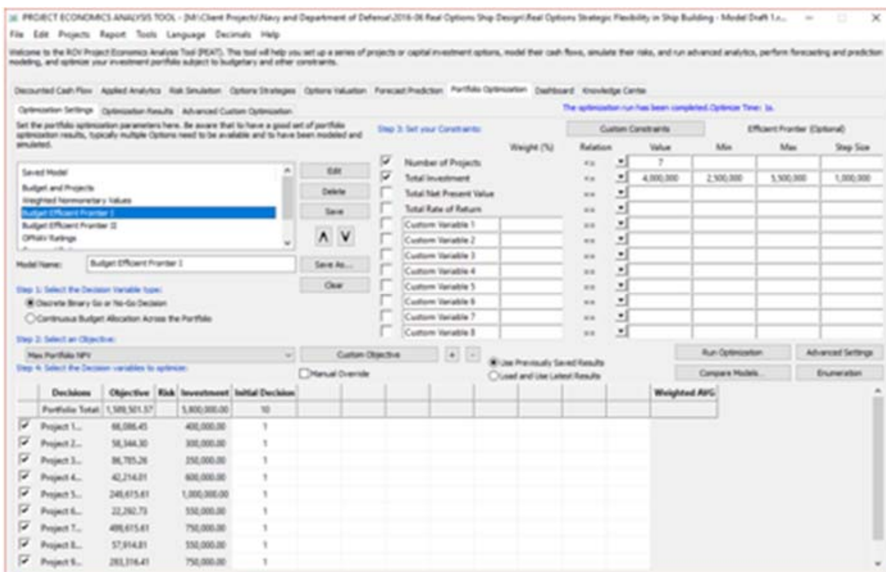

Figure 16. Portfolio Optimization Settings

The projects can be modeled as a portfolio and optimized to determine the best combination of projects for the portfolio in the *Optimization Settings* subtab. Users start by selecting the optimization method (Static or Dynamic Optimization). Then they select the decision variable type of *Discrete Binary* (choose which Project or Options to execute with a Go/No-Go Binary 1/0 decision) or *Continuous Budget Allocation* (returns % of budget to allocate to each option or project as long as the total portfolio is 100%); select the *Objective* (Max NPV, Min Risk, etc.); set up any *Constraints* (e.g., budget restrictions, number of projects restrictions, or create customized restrictions); select the options or projects to optimize/allocate/choose (default selection is *all options*); and when completed, click *Run Optimization.*

Figure 17 illustrates the *Optimization Results* tab, which returns the results from the portfolio optimization analysis. The main results are provided in the data grid, showing the final Objective Function results, final *Optimized Constraints*, and the allocation, selection, or optimization across all individual options or projects within this optimized portfolio. The top left portion of the screen shows the textual details and results of the optimization algorithms applied, and the chart illustrates the final objective function. The chart will only show a single point for regular optimizations, whereas it will return an investment efficient frontier curve if the optional *Efficient Frontier* settings are set (min, max, step size) in the tab.

Figures 17 and 18 are critical results for decision-makers as they allow flexibility in designing their own portfolio of options. For instance, Figure 17 shows an efficient frontier of portfolios, where each of the points along the curve are optimized portfolios subject to a certain set of constraints. In this example, the constraints were the number of options that can be selected in a ship and the total cost of obtaining these options are subject to a budget constraint. The colored columns on the right in Figure 17 show the various combinations of budget limits and maximum number of options allowed. For instance, if a program office in the Navy only allocates $2.5 million (see the Frontier Variable located on the second row) and no more than four options per ship, then only options 3, 7, 9, and 10 are feasible, and this portfolio combination would generate the highest bang for the buck while simultaneously satisfying the budgetary and number of options constraints. If the constraints were relaxed to, say, five options and $3.5 million budget, then option 5 is added to the mix. Finally, at $4.5 million and no more than seven options per ship, options 1 and 2 should be added to the mix. Interestingly, even with a higher budget of $5.5 million, the same portfolio of seven options is selected. In fact, the Optimized Constraint 2 shows that only $4.1 million is used. Therefore, as a decision-making tool for the budget-setting officials, the maximum budget that should be set for this portfolio of options should be $4.1 million. Similarly, the decision-maker can move backwards, where say, if the original budget of $4.5 million was slashed by the U.S. Congress to $3.5 million, then the options that should be eliminated would be options 1 and 2.

While Figure 17 shows the efficient frontier where the constraints such as number of options allowed and budget were varied to determine the efficient portfolio selection, Figure 18 shows multiple portfolios with different objectives. For instance, the five models shown were to maximize the financial bang for the buck (minimizing cost and maximizing value while simultaneously minimizing risk), maximizing OPNAV value, maximizing KVA value, maximizing Command value, and maximizing a Weighted Average of all objectives. This capability is important because depending on who is doing the analysis, their objectives and decisions will differ based on different perspectives. Using a multiple criteria optimization approach allows us to see the scoring from all perspectives. Options with the highest count (e.g., 5) would receive the highest priority in the final portfolio, because it satisfies all stakeholders' perspectives, and would hence be considered first, followed by options with counts of 4, 3, 2, and 1.

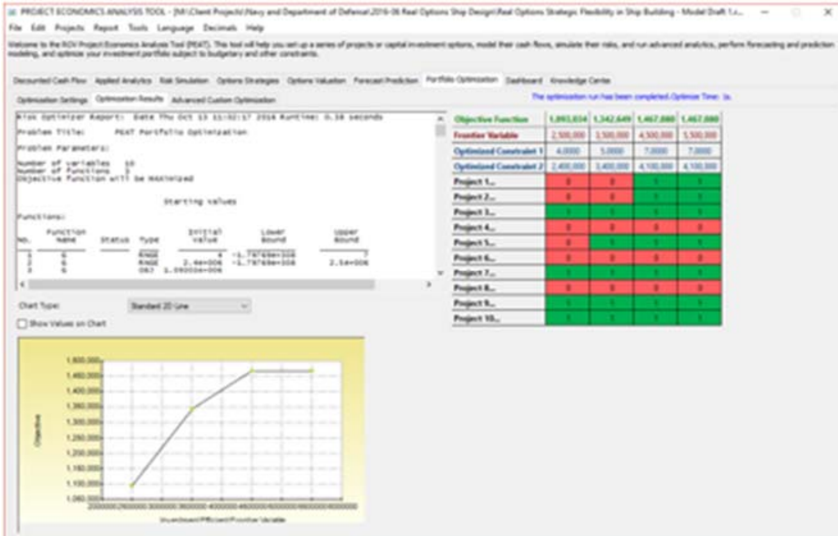

Figure 17. Portfolio Optimization Results

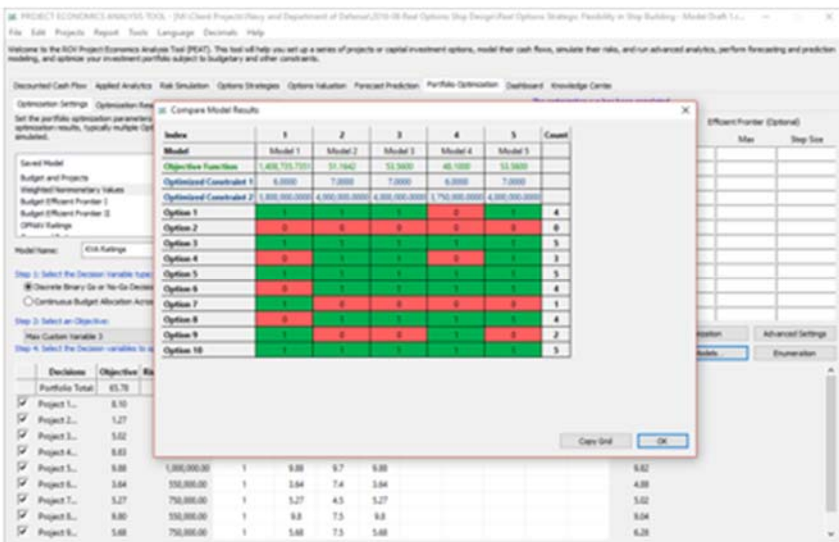

Figure 18. Multicriteria Portfolio Optimization Results

Analytics

As a side note and for the purposes of being comprehensive and inclusive, we point out that multiple types of algorithms have been developed over the years to find the solutions of an optimization problem, from basic linear optimization using the simplex model and solving first partial differential equations. However, when more and more complex real-life problems are assumed, these basic methods tend to break down, and more advanced algorithms are required. In solving our efficient frontier problem, we utilized a combination of genetic algorithm, Lagrange multipliers, and taboo-based reduced gradient search methodologies.

Simplistically, the Lagrange multiplier solution assumes some nonlinear problem of:

$$\min or \max f(x)$$

$$s.t. \quad g_i(x) = b_i \;\; \forall\, i = 1, \dots, m$$

where the equality is oftentimes replaced by some inequality values indicating a ceiling or floor constraint.

From this functional form, we first derive the Lagrange multiplier v for all i values:

$$L(x, v) \triangleq f(x) + \sum_{i=1}^{m} v_i [b_i - g_i(x)]$$

$$s.t. constraints\; g_i(x) = b_1, \dots, g_m(x) = b_m$$

The solution $(x*, v*)$ is a set of points along the Lagrange function $L(x, v)$ if it satisfies the condition:

$$\sum_i \nabla g_i(x^*) v^* = f(x^*) \; which\; requires \; \sum_i \frac{\partial g_i}{\partial x_j} v_i = \frac{\partial f}{\partial x_j} \forall j \; and \;\; g_i(x^*) = b_i$$

This approach is simple and elegant but limited to linear and quasi-linear as well as some simple nonlinear functional forms of $f(x)$. In order to be able to extend the functional form to generalized nonlinear applications, we need to add additional conditions to the solution set and apply some search algorithms to cover a large (and oftentimes unlimited set of optimal allocations). One limitation is the requirement that the Kuhn-Tucker condition is satisfied where the nonlinear problems have a differentiable general form:

$$\min or \max f(x)$$

$$\begin{aligned} s.t. \quad & g_i(x) \geq b_i \;\; \forall\, i \in Feasible\ Set \\ & g_i(x) \leq b_i \;\; \forall\, i \in Feasible\ Set \\ & g_i(x) = b_i \;\; \forall\, i \in Feasible\ Set \end{aligned}$$

and the inequality constraints will need to be active at a local optimum or when the Lagrange variable is set to null:

$$v_i[b_i - g_i(x)] = 0$$

In addition, mathematical algorithms will have to be developed to perform both an ad-hoc and systematic search of the optimal solution set. Using an enumeration method will take even a supercomputer close to an infinite number of years to delineate all possible permutations. Therefore, search algorithms are typically used in generating an efficient frontier using optimization. One simple approach is the use of a reduced gradient search method. To summarize the approach, we assume

$$\nabla f(x) \cdot \Delta x$$

where the functional form $f(x)$ is the objective function and is divided into two parts, a basic (B) and non-basic portion (N) is multiplied by the change in vector direction x. Using a Taylor expansion, we obtain:

$$\nabla f(x) \cdot \Delta x = \nabla f(x)^B \cdot \Delta x^B + \nabla f(x)^N \cdot \Delta x^N$$

$$= \nabla f(x)^B \cdot (-B^{-1} N \Delta x^N) + \nabla f(x)^N \cdot \Delta x^N$$
$$= (\nabla f(x)^N - \nabla f(x)^B B^{-1} N) \Delta x^N$$

The reduced gradient with respect to the solution matrix B is:

$$r \triangleq (r^B, r^N)$$

where

$$r^B \triangleq 0$$
$$r^N \triangleq \nabla f(x)^N - \nabla f(x)^B B^{-1} N$$

Solving for this solution set is manually possible when the number of decision variables is small (typically less than four or five), but once the number of decision variables is large, as in all real-life situations, the manual solution is intractable and computer search algorithms have to be employed.

Conclusions and Recommendations

First, it is vital to understand that real options analysis is *not* a simple set of equations or models. It is an *entire decision-making process* that enhances the traditional decision analysis approaches. It takes what has been tried-and-true financial analytics and evolves it to the next step by pushing the envelope of analytical techniques. In addition, it is vital to understand that 50% of the value in real options analysis is simply thinking about it. Another 25% of the value comes from the number crunching activities, while the final 25% comes from the results interpretation and explanation to management. Several issues should be considered when attempting to implement real options analysis:

- **Tools**—The correct tools are important. These tools must be more comprehensive than initially required because analysts will grow into them over time. Do not be restrictive in choosing the relevant tools. Always provide room for expansion. Advanced tools will relieve the analyst of detailed model-building and let him or her focus instead on 75% of the value—thinking about the problem and interpreting the results.
- **Resources**—The best tools in the world are useless without the relevant human resources to back them up. Tools do not eliminate the analyst but enhance the analyst's ability to effectively and efficiently execute the analysis. The right people with the right tools will go a long way. Because there are only a few true real options experts in the world who truly understand the theoretical underpinnings of the models as well the practical applications, care should be taken in choosing the correct team. A team of real options experts is vital in the success of the initiative. A company should consider building a team of in-house experts to implement real options analysis and to maintain the ability for continuity, training, and knowledge transfer over time. Knowledge and experience in the theories, implementation, training, and consulting are the core requirements of this team of individuals. This is why training is vital. For instance, the CRM/CQRM certification program provides analysts and managers the opportunity to immerse themselves into the theoretical and real-life applications of simulation, forecasting, optimization, and real options (for details, please see www.realoptionsvaluation.com).
- **Senior Decision-Maker Buy-in**—The analysis buy-in has to be top-down where senior management drives the real options analysis initiative. A bottom-up approach where a few inexperienced junior analysts try to impress the powers that be will fail miserably.

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