# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**A SYSTEMS ENGINEERING APPROACH TO OPTIMIZING PROJECT SELECTION FOR PORTFOLIO-TYPE RESEARCH AND DEVELOPMENT PROGRAMS: A CASE STUDY OF NAVFAC EXWC'S NAVAL INNOVATIVE SCIENCE AND ENGINEERING PROGRAM**

by

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September 2018

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This thesis applies systems engineering principles to improve project selection in portfolio-type research and development programs using the Naval Innovative Science and Engineering program as a case study. Qualitative and quantitative value modeling and integer linear programming optimization aided in the selection process. The resulting optimized portfolio increased the number of funded projects by 20 percent in comparison to the non-optimized portfolio. In addition, it has a 13.9 percent increase in value in comparison to the non-optimized portfolio. The primary stakeholders were engaged throughout the process and concurred with the results not only due to the merit of the findings, but also because the process created is defendable and repeatable.

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# ABSTRACT

This thesis applies systems engineering principles to improve project selection in portfolio-type research and development programs using the Naval Innovative Science and Engineering program as a case study. Qualitative and quantitative value modeling and integer linear programming optimization aided in the selection process. The resulting optimized portfolio increased the number of funded projects by 20 percent in comparison to the non-optimized portfolio. In addition, it has a 13.9 percent increase in value in comparison to the non-optimized portfolio. The primary stakeholders were engaged throughout the process and concurred with the results not only due to the merit of the findings, but also because the process created is defendable and repeatable.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AHP | analytical hierarchy process |
| DASN | Deputy Assistant Secretary of the Navy |
| DoD | Department of Defense |
| DoN | Department of Navy |
| GNP | gross national product |
| ILP | integer linear programming |
| MAUT | multi-attribute utility theory |
| MOP | multiple objective programming |
| NAVFAC EXWC | Naval Facilities Engineering and Expeditionary Warfare Center |
| NISE | Naval Innovative Science and Engineering |
| NR&DE | Naval Research and Development Establishment |
| ROI | return on investment |
| R&D | research and development |
| RDT&E | research, development, test, and evaluation |
| SMART | simple multi-attribute rating technique |
| TGB | Technology Governance Board |
| TRL | technology readiness level |

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# EXECUTIVE SUMMARY

Currently, industry outspends the Department of Defense (DoD) two to one in research and development (R&D) (Fabey 2017). Results of industry R&D often become commercial products available to our adversaries. We must optimize the relatively small U.S. Navy R&D budget and ensure alignment to top Navy priorities. This thesis applies systems engineering principles to improve project selection in portfolio-type R&D programs using the Naval Innovative Science and Engineering (NISE) program at Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) as a case study.

The thesis methodology is based on theory from *Decision Making with Multiple Objectives* (Keeney and Raffia 1976). The resulting process is four steps: create a qualitative value model, create a quantitative value model, implement the model, and verify the results.

As the first step in creating the qualitative value model, the fundamental objective is determined through researching U.S. Navy strategic guidance and discussion with NAVFAC EXWC NISE program stakeholders, specifically the Technology Governance Board (TGB). The fundamental objective of Navy R&D is to maintain technological superiority. The fundamental objective is decomposed down to five selection criteria and three screening criteria.

To create the quantitative value model, a brainstorming session is conducted with the TGB to define values for the selection criteria, creating value scales. Next, using the swing weight matrix technique (Ewing, Tarantino, and Parnell 2006), weights are defined for each of the selection criteria. The multi-attribute utility theory (MAUT) additive model is used as the basis for the objective function with the goal to maximize the total value to the portfolio. Budget and portfolio balancing constraints are developed.

Twenty-three R&D proposals totaling $1,517,000 are received as a result of the NISE program solicitation. The allocated budget for the portfolio is $1,000,000. The TGB evaluated all of the proposals according to the developed criteria. The data is then run

through an optimization model using Microsoft Excel and the Solver add-in using integer linear programming. The optimized portfolio is then compared to a portfolio selected based on top score alone. The optimized portfolio has a 13.9 percent increase in total value compared to the non-optimized portfolio. In addition, the optimized portfolio utilizes 99.5 percent of the allocated budget compared to only 94.5 percent in the non-optimized portfolio. The optimized portfolio selects 18 projects and the non-optimized portfolio selects only 15 projects, a 20 percent increase. The optimized portfolio outperforms the non-optimized portfolio.

After the projects are completed (at the end of FY 19), they will be analyzed based on technology transition, cost, schedule and performance to determine if the most successful projects were rated higher according to the criteria and whether the model is a good predictor for project success. The model will then be adjusted accordingly.

As expected, the projects with the highest value are selected while adhering to budget, and portfolio balancing constraints. The TGB, the primary stakeholders for the project, were engaged throughout the whole process and are pleased with the results. The created process is defendable and repeatable.

**References**

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# I. INTRODUCTION

> Maritime superiority for America's Navy and Marine Corps is enabled by technological superiority. However, our once-dominant technological edge is at risk of being overtaken due to the accumulated friction of complexity and bureaucracy in our system of research, development and acquisition. Lasting strategic advantage comes from institutional capacity to develop and field new capabilities faster than our adversaries. (Office of Naval Research 2017, 3)

The above quote from *Naval Research and Development: A Framework for Accelerating to the Navy and Marine Corps after Next* challenges the Naval Research and Development Establishment (NR&DE) to maintain our technological superiority through aligning, allocating, and accelerating the Navy's research and development (R&D). Currently, industry out spends the Department of Defense (DoD) two to one in research and development (Fabey 2017). Results of industry R&D often become commercial products accessible to our adversaries. We must optimize the relatively small U.S. Navy R&D budget and ensure alignment to top Navy priorities.

This thesis applies systems engineering principles to improve project selection in portfolio-type research and development programs using the Naval Innovative Science and Engineering (NISE) program at Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) as a case study.

## A. BACKGROUND

> NAVFAC EXWC is a command of approximately 1,100 employees who provide specialized facilities engineering, technology solutions, and life-cycle management of expeditionary equipment to the Navy, Marine Corps, federal agencies, and other Department of Defense supported commands. NAVFAC EXWC was established in 2012 and represents the consolidation of several commands: NAVFAC Engineering Service Center, NAVFAC Expeditionary Logistics Center, and the Specialty Center Acquisitions. (NAVFAC EXWC 2018, 1)

NAVFAC EXWC develops and supports advanced facility and expeditionary technologies to enable U.S. Navy operating forces. As NAVFAC's only warfare center, NAVFAC is charged with R&D in these areas. In 2017, EXWC was designated a Science

Technology Reinvention Laboratory. This designation authorizes NAVFAC EXWC to pursue an official Naval Innovative Science and Engineering (NISE) program. The NISE program, authorized by public law 110–417 section 219 and public law 111–84 section 2801, enables the director of department of defense warfare center and laboratories to utilize between 2 percent–4 percent of all funds for the purpose of basic and applied research, technology transition, lab revitalization, and workforce development. The NISE program is also known as the 219 program due to its section number in the legislation (United States Congress 2009). Per NISE program policy, the goals of the NISE program are to:

- Maintain the scientific and technical vitality of naval in-house laboratories and centers;
- Increase the rate of recruitment and retention of laboratory and center personnel in critical areas of science and engineering;
- Foster creativity and stimulate exploration of cutting edge science and technology;
- Serve as a proving ground for new concepts in research and development;
- Support high value, potentially high-risk research and development; and
- Provide for the maturation and transition of technologies beneficial to the Navy, Marine Corps, and the military forces of the other Services.
- Enhance the laboratories' ability to address future military and Department of Navy (DoN) and Department of Defense (DoD) missions (Thomsen 2009, 2).

NAVFAC EXWC began implementing a pilot version of the NISE program in fiscal year (FY) 2016. The process for project selection was based on heuristics and other warfare center's current practices. Projects are submitted and ranked by NAVFAC EXWC's technology governance board (TGB), which consist of the command's technical leadership. In FY18, projects were ranked based on six criteria:

1. Alignment to one or more of NAVFAC EXWC's technical capabilities
2. Technical merit of the project
3. Potential for the project to produce patents and publications
4. Potential internal and Navy benefit of the project
5. Innovation
6. Collaboration (NAVFAC EXWC 2016, 2)

NAVFAC EXWC's TGB expressed concern that the selection criteria may not be optimal for project selection and requested analysis and recommendation of optimal selection criteria.

## B. PROBLEM STATEMENT

The Navy's R&D budget is limited, and we want to ensure that our investment is optimized. In portfolio-type R&D programs such as NISE, there are multiple projects competing for a limited budget. How can we ensure that we are selecting the best projects? Although there is not one answer to guarantee success, a clear and repeatable systems engineering approach to selecting R&D projects will enable Navy and DoD organizations to better manage portfolio-type R&D programs.

## C. RESEARCH OBJECTIVES

The objective of this research is to apply systems engineering techniques in order to improve NAVFAC EXWC's NISE project selection. The research methodology applies systems engineering principles as part of a case study analysis using research and stakeholder analysis. Research is conducted to identify Navy R&D strategic objectives and a qualitative and quantitative value model is created and implemented as part of the research design and approach. Functional and requirement analysis is done to align these strategic objectives to fundamental objectives, and then decomposed to value measures creating a qualitative value model. Stakeholder analysis involving surveys and focus groups of NAVFAC EXWC's technical leaders provides feedback on the qualitative value model. The technical leaders are then asked to rank the value measures. This is the data that is used to create the additive quantitative value model.

## D. CHAPTER CONCLUSION

This thesis discusses utilizing systems engineering principles to create an R&D project selection methodology and applies it to the NISE program. The goal is to optimize the research and development portfolio and ensure it aligns with Navy R&D priorities. The chapters that follow provide the details on the research and implementation.

Chapter II discusses the methodology beginning with a brief literature review and theory behind qualitative and quantitative value analysis and concluding with a case study analysis of the NISE program. Chapter III discusses the data and results. Chapter IV summarizes the research and findings.

# II. LITERATURE REVIEW AND METHODOLOGY

Much work has been done researching the best ways to manage R&D portfolios specifically in the private industry where return on investment (ROI) is the primary motivating factor such as "Portfolio Management for New Products" (Cooper and Edgett 2014) and "Rapid System Development Methodologies: Proposing a Selection Framework" (Jain and Chandrasekaran 2009). ROI and risk are two common selection criteria. A Naval Postgraduate School (NPS) thesis by Schwarz (2016) discusses the unique aspects to managing R&D in the public sector and recommends a model for portfolio section based on Dr. Johnathan Mun's Integrated Risk Management approach. The focus of his approach is a five-step process including qualitative management screening, valuation, risk assessment, portfolio optimization and reporting, and update analysis. This thesis differs from Schwartz's in that it focuses on ranking criteria development and ensuring project alignment to end user needs, which are two of NAVFAC EXWC's strategic objectives. In addition, focusing on risk would not be appropriate, as one of the NISE program goals is to support potentially high-risk, high-value research projects. The criteria development model is based on theory from *Decision Making with Multiple Objectives* (Keeney and Raffia 1976). However, the primary reference sources used are *Value Focused Thinking* (Keeney 1992), a more recent version of the same concepts; "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis" (Ewing, Tarantino, and Parnell 2006) a case study using Keeney and other experts in the field theory in application; and *Decision Making in Systems Engineering* (Trainor and Parnell 2011) a text citing Ewing and other experts in the field.

Ralph Keeney describes decision analysis as "a formalization of common sense for decision problems that are too complex for informal use of common sense" (quoted in Parnell et al. 2013, 3). Decision analysis is chosen for this reason; it is simple, makes sense, and the process is easy to replicate. Many decision analysis experts debate whether multi-attribute utility theory (MAUT) or analytical hierarchy process (AHP) is the better decision analysis method to aid decision makers in multi-criteria problems. Many argue that because AHP is not based in "normative utility theory as incorporated in MAUT" that AHP is technically unsound. Other criticisms of AHP include “its measurement scale, rank reversal, and transitivity of preferences.” Forman and Gass, as cited by Gass, argue that AHP is theoretically sound and tested in industry and because “AHP is not an extension of MAUT,” it should not have to conform to utility theory; AHP is an independent theory of decision-making (quoted in Gass 2005, 308-310). MAUT is chosen not because of the arguments against AHP, but because, in the authors opinion it is easier for the non-systems engineer/operations research scientist to understand. Many of the stakeholders in the TGB do not have a background in systems engineering or operations research but as scientists and engineers, they want to understand the theory behind the process. MAUT was chosen because it “is a structured methodology designed to handle tradeoffs among multiple objectives” that is easy to explain and repeat (Chelst and Edwards n.d., 1).

Figure 1 depicts the proposed process to develop R&D project selection criteria using qualitative value analysis, developing a model to quantify and rank projects using quantitative value analysis with the final steps implementing and verifying results. Figures 1–3 were developed using SPEC Innovation’s Innoslate, a systems engineering modeling tool (SPEC Innovations 2017). Hierarchy charts, Figures 7–9, were also developed in Innoslate.

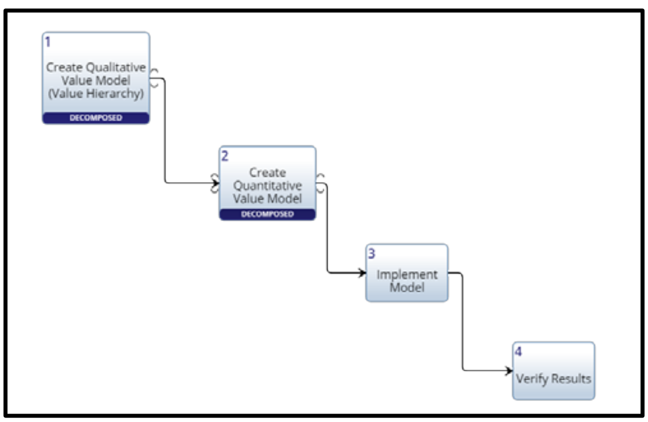


Figure 1. R&D selection criteria model

Figure 2 decomposes the qualitative value analysis into the following steps: determine the fundamental objective, identify functions that provide value, identify objectives that provide value, and identify value measures (selection criteria). The qualitative value model theory is described in Section A of this chapter.

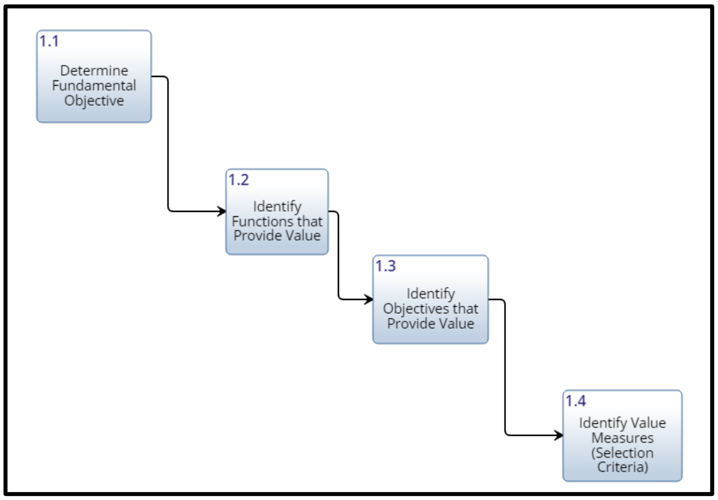


Figure 2. Create qualitative value model (decomposed)

Figure 3 decomposes the quantitative value analysis into the following steps: define values for value measures, define weights for value measures using swing weighting, define the value model objective function, and define the value model constraints. The qualitative value model implementation is described in Section B of this chapter.

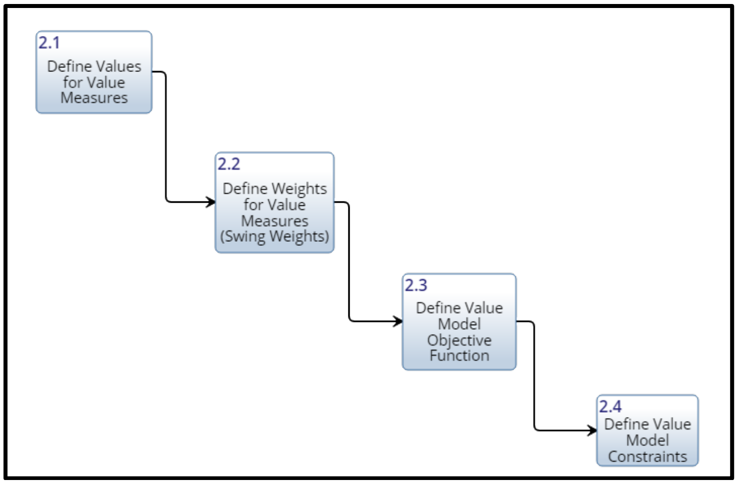


Figure 3. Create quantitative value model (decomposed)

## A. QUALITATIVE VALUE MODEL THEORY

One way to create a qualitative value model is through the use of a value hierarchy. *Decision Making in Systems Engineering Management* by Trainor and Parnell describes the process in detail. The first step in creating the value hierarchy is identifying the fundamental objective. The fundamental objective "is a clear, concise statement of the primary reason we are undertaking the decision problem" (Trainor and Parnell 2011). The fundamental objective should be confirmed through stakeholder involvement. The next step is to decompose this fundamental objective into functions that provide value. The next step is to decompose further into objectives that define value. The objective provides preference such as "maximize efficiency" or "minimize cost" (Trainor and Parnell 2011). A value measure is then identified for each objective. The value measures, in this case are synonomous with selection criteria. They determine how well a project meets the objective. Throughout the process of creating the value hierarchy it is very important to socialize the results with key stakeholders, especially those that have approval authority. Selection criteria should be measurable, operational, and understandable. A criteria is measureable if it defines the associated objective in more detail than that provided by the objective alone. A criteria is operational if it shows preference for different levels of achievement. A criteria is understandable if it is clearly defined and unambigous (Keeney 1992). Figure 4 depicts an example of a value hierarchy for a rocket. The example shows how the fundamental objective is decomposed down to functions which are further decomposed into objectives, and finally down to the value measures. Each value measure can be traced up to the fundamental objective demonstrating alignment.

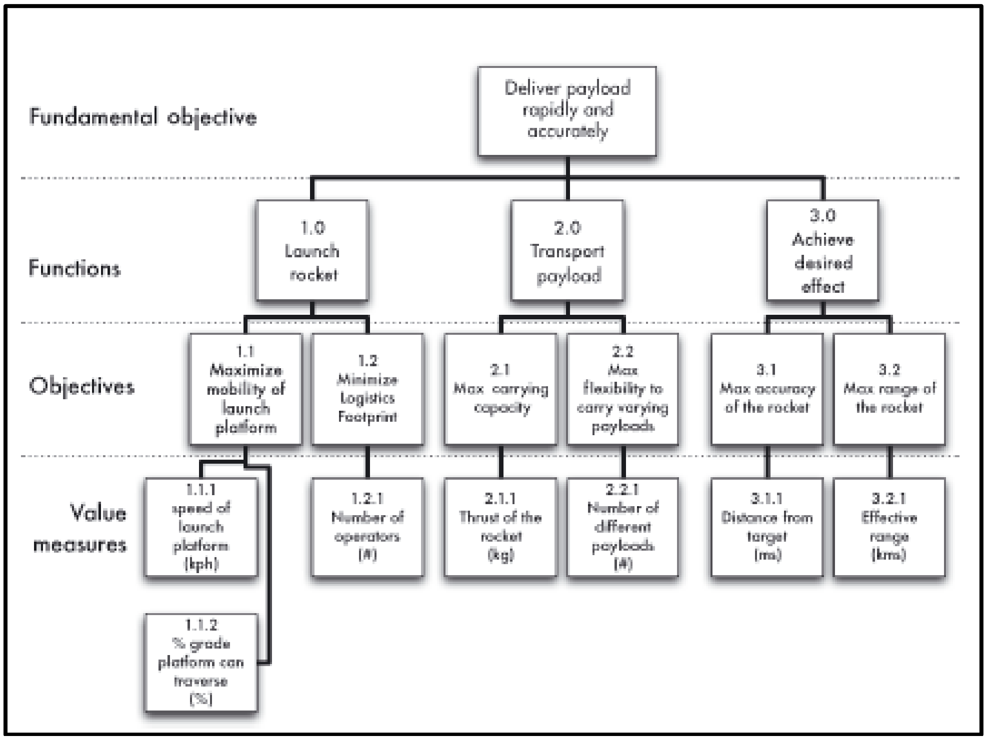


Figure 4. Value hierarchy of a rocket. Source: Trainor and Parnell (2011).

## B. QUALITATIVE VALUE MODEL IMPLEMENTATION

The NISE program has four pillars: basic and applied research, technology transition, lab revitalization and workforce development. One value hierarchy is created for each pillar except basic and applied research is combined with technology transition because they are similar in that they are all research projects at various technology readiness levels (TRLs), basic research being the lowest, and technology transition being the highest. Lab revitalization focuses on improving the warfare center's technical equipment and facilities. Workforce development focuses on developing employees technical skills through technical training, advanced education, and strategic rotations.

Although the selection criterion varies for the different pillars, the fundamental objective remains constant.

The first step in developing the value hierarchy is determining the fundamental objective. This is done through researching Navy R&D strategy and discussions with the primary stakeholders, EXWC's technology governance board (TGB). The primary strategic documents utilized are the *Naval Research and Development: A Framework for Accelerating to the Navy and Marine Corps after Next* (Office of Naval Research 2017) and The Department of the Navy Research, Development, Test and Evaluation 30 Year Strategic Plan (DASN RDT&E and Chief of Naval Research 2016), and NISE program policy and guidance (Burrow 2017). All three documents highlight the importance of maintaining technological superiority through strategic investment. The stakeholders agree that "Maintaining Technological Superiority" is the fundamental objective, the reason we conduct R&D.

The next step is to identify functions that provide value to the fundamental objective. The value hierarchy for basic and applied research and technology transition is shown in Figure 5. The functions are identified through functional decomposition. We need to maintain technological superiority so that we can 1.0 Develop/utilize the best technology, 2.0 Develop the right technology, 3.0 Ensure our sailors get the technology first, and with limited budgets 4.0 Leverage others technology development. The next step is to identify objectives that provide value to the functions. For example, 1.1 Maximize added Navy benefit is the objective to the goal 1.0 Develop/utilize the best technology. The final step is to identify value measure (selection criteria). The selection criteria measure the value of the objective. For example, 1.1.1. Benefit added provides a way to measure, the objective 1.1 Maximize added Navy benefit.

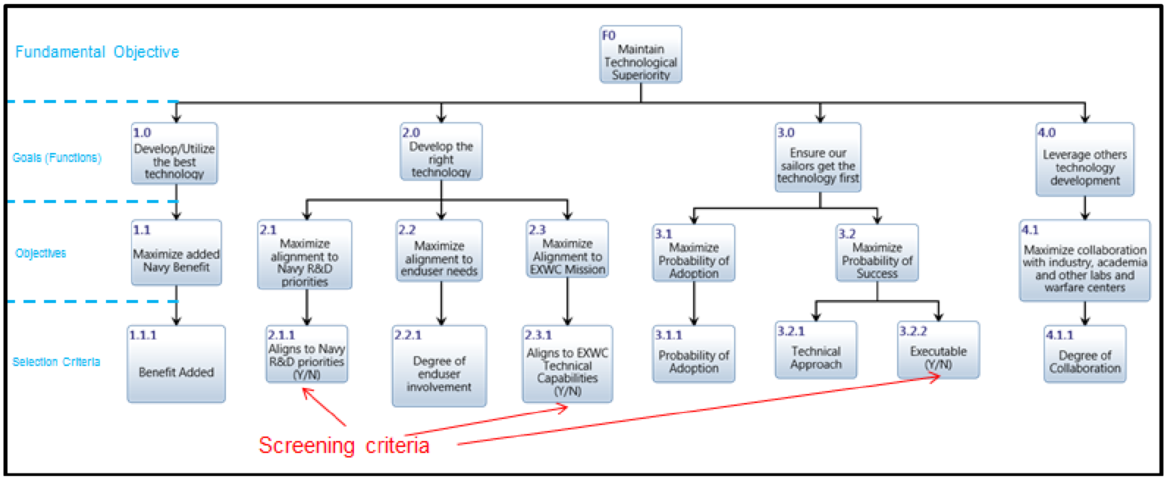


Figure 5. Value hierarchy for NISE program (basic research, applied research and technology transition)

Figures 6 and 7 portray the value hierarchies for the lab revitalization pillar and workforce development respectively. The same process is followed as described above. After the initial hierarchy is developed, a stakeholder meeting is held to gain feedback and consensus. Several changes are made during the meeting to ensure stakeholder buy in and consensus. Figures 5, 6, 7 are the final versions of the hierarchies.

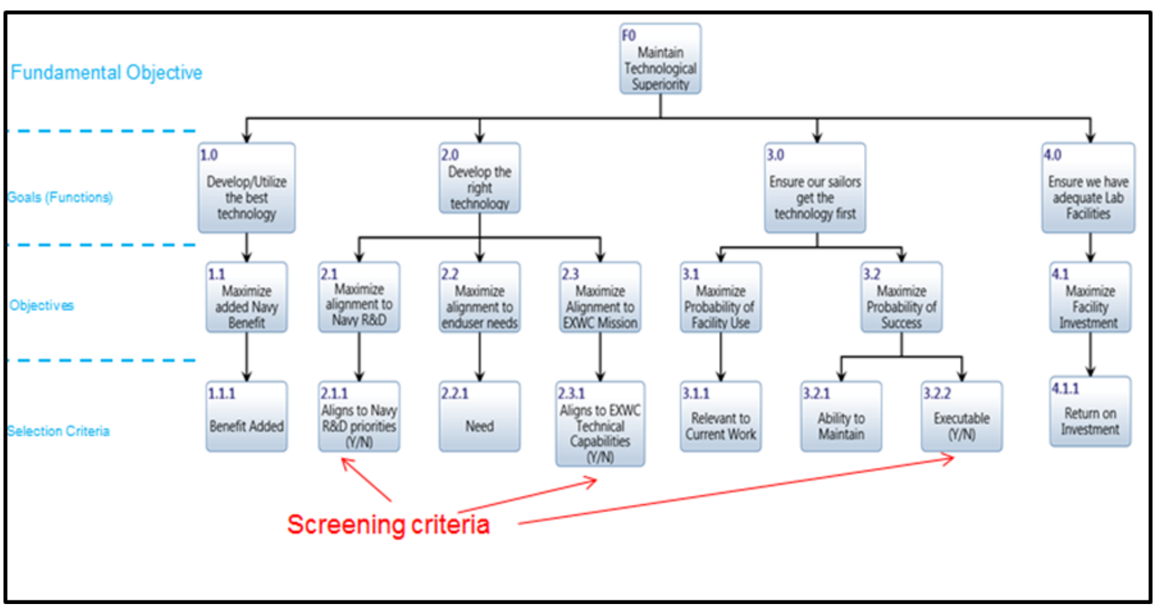


Figure 6. Value hierarchy for NISE program (lab revitalization)

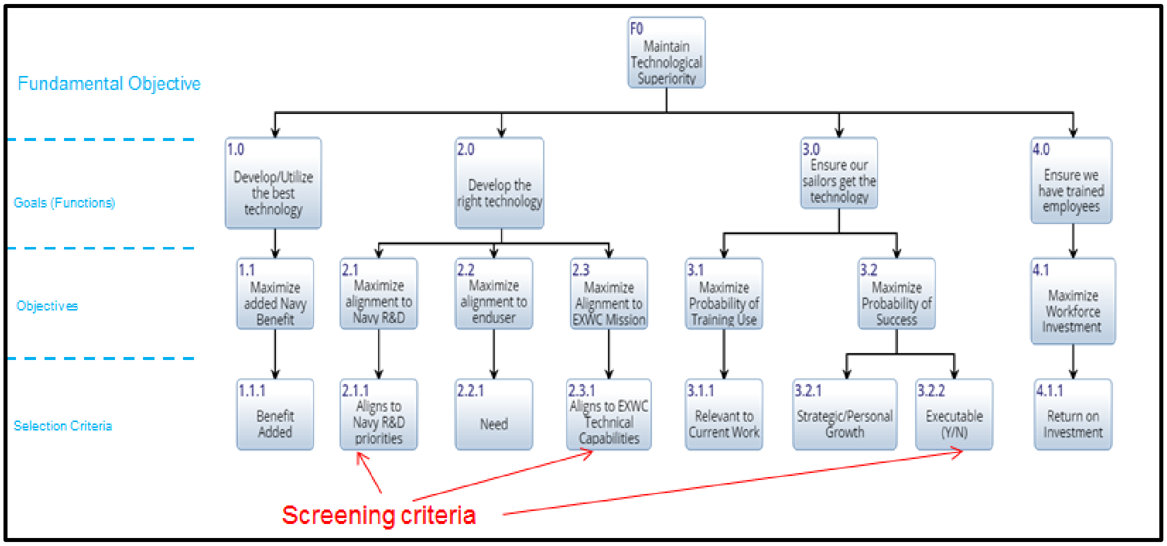


Figure 7. Value hierarchy for NISE program (workforce development)

Three screening criteria are included in the value hierarchy. They are better suited as screening criteria than selection criteria because the measurement is a binary, yes or no, versus an actual numerical value. The selection criteria are assigned values of 1, 3, 5, which will be discussed in the quantitative value analysis section. Alignment to Navy priorities is determined by comparing the project's focus to the Navy R&D focus areas in Tables 1 and 2. Stakeholders determined that there is no additional value to aligning to more than one priority versus to only one; therefore, if a project aligns to at least one of the priorities it moves on to be ranked. During the second screening, the alignment to EXWC technical capabilities is determined by comparing the project's focus area to EXWC's technical capabilities in Table 3. If the project aligns to at least one of the priorities, it moves on to be ranked. The third criteria measures the ability for the project to be executed, e.g., assume that there is no acquisition method available then it is given a No, and the project will not move on to be ranked. If there are no known barriers for a program, it is given a Yes during this last screening and moves on to be ranked.

Table 1. Navy R&D priorities. Source: Office of Naval Research (2017).

| Navy R&D Priorities (Naval Research and Development Framework) | Description |
|---|---|
| Augmented Warfighter | • Enhance decision-making speed and quality<br>• Improve human-machine interfaces and teaming<br>• Mitigate tactical-level risk to our people and command, control and communications degradation |
| Integrated & Distributed Forces | • Enhance dynamic, synchronized actions across forces<br>• Support collaboration spanning geography, domains, platforms, and joint partners; leverage satellite and Precision Navigation and Timing advancements<br>• Increase flexibility and reach of the naval force through incorporation of autonomous and disaggregated systems |
| Operational Endurance | • Enable maneuverability, efficiency, and resiliency for sustained operations by warfighters, systems and platforms (regardless of the threat or operating environment)<br>• Improve platform-level energy storage/efficiency for propulsion and weapons systems<br>• Develop wide-are and force wide disinformation deception and decoys |
| Sensing & Sense-making | • Transform vast data into timely knowledge<br>• Enable persistent awareness and understanding, and optimized operation (regardless of the threat or operating environment)<br>• Integrate artificial intelligence into C4ISR networks and scalable to theater wide |
| Scalable Lethality | • Enable offensive and defensive actions that are multi-domain, integrated, cost-effective, and kinetic and non-kinetic<br>• Deliver directed energy and low cost, high probability of kill standoff strike |

Table 2. Navy R&D strategic thrusts. Source DASN RDT&E and Chief of Naval Research (2016).

| Navy R&D 30yr Strategic Thrusts | Description |
|---|---|
| Advanced Autonomous Systems | • Network Optional Warfighting (NOW) capabilities coupled with robust assured point-to-point LPI/LPD/LPE (Laser/Optical/EM)<br>• Advanced scalable swarm & micro-autonomous systems technologies, Agile and Reconfigurable Systems<br>• Non-deterministic systems test and evaluation technologies and certification methodologies<br>• Unmanned Surface, Air, and Subsurface Vessels providing persistent, organic ISR & OTH targeting capabilities to maritime/expeditionary forces |
| Advanced Computing and Sensing | • Ubiquitous Internet of Things (IoT) hyper-spectral sensing<br>• Data analytics, fusion, visualization and dynamic sensemaking<br>• Nanotechnology and quantum-based sensing<br>• Cognitive computing/machine learning/artificial intelligence, optical and quantum computing<br>• Neuromorphic Chip Technologies, BRAIN-inspired algorithm computational development, genetic algorithms<br>• Computational model-based design and systems evaluation with high representational fidelity<br>• Human performance enhancement including 3D virtualized immersive technologies, training and series games<br>• Live, virtual, constructive test and training environments |
| Advanced Materials and Manufacturing Technologies | • Bio-mimic design and development technologies, synthetic biology and energetics<br>• Nanotechnology and meta-materials for enhanced functionality, affordability and sustainment<br>• 3-D Additive Manufacturing – exploit extensive materials/design variability opportunities from micro to macro applications |
| Advanced EMW & Cyber | • Low cost deployable decoys and confusion generation/obfuscation "Off-Set" technologies – high bang for the buck<br>• High powered microwave vacuum tube & Digital Radio Frequency Memory (DRFM) technologies<br>• Technology to protect the Information Technology (IT) systems, infrastructure and data against advanced adversarial cyber threats |
| Advanced Weapons & Systems Technologies | • Micro/nano satellite technology for on-demand communication, ISR and PNT constellations<br>• Affordable Maritime-suitable next generation Stealth<br>• Directed Energy Weapons (DEW)/Counter-DEW technologies, hypersonics and countermeasure technologies<br>• Longer Range Energetic Weapons for Enhanced Effects in the Integrated Battlespace<br>• Undersea weapons with salvo and collaborative capabilities<br>• Anti-tamper RADHARD electronics miniaturization<br>• Integrated and interoperable systems technologies |
| Advanced Energy Technologies | • Energy Harvesting<br>• Energy Storage<br>• Autonomous, reconfigurable power transmission<br>• Advanced Power and Energy Management<br>• Improved wireless energy transfer at-a-distance |

Table 3. NAVFAC EXWC's technical capabilities

| NAVFAC EXWC's Technical Capabilities |
|---|
| Cyber Security and Cyber Defense RDT&E and S&T for Navy Facilities, Construction, Property, Environmental, Energy and Expeditionary Systems |
| Energy Savings Performance Contracts and RDT&E Acquisitions |
| Expeditionary Systems S&T, RDT&E, ISE, Procurement, Fielding, and Sustainment |
| Operational Technology RDT&E, S&T for Navy Facilities, Construction, Property, Environmental, Energy and Expeditionary Systems |
| Petroleum, Oil, and Lubricants Facilities Systems S&T, RDT&E, ISE |
| Potable Water Systems and Resiliency S&T, RDT&E, ISE, and Sustainment |
| Physical Security S&T, RDT&E, ISE, and Sustainment |
| Restoration and Conservation S&T, RDT&E, ISE |
| Shore Energy Technology and Integration, S&T, RDT&E, ISE, and Sustainment |
| Shore Environmental Compliance S&T, RDT&E, ISE |
| Shore Facilities S&T, RDT&E, ISE, and Sustainment |
| Shore Waste Systems S&T, RDT&E, ISE, and Sustainment |
| Undersea Cable Facilities S&T, RDT&E, ISE, and Sustainment |
| Waterfront Facilities S&T, RDT&E, ISE, and Sustainment |

In summary, key stakeholders are engaged throughout the process of creating the value hierarchy. Selection criteria are developed while keeping in mind that selection critieria should be measurable, operational, and understandable. Final consensus is gained from the stakeholders.

## C. QUANTITATIVE VALUE MODEL THEORY

The quantitative value model determines how well each project compares in regards to the stakeholders' values, the qualitative value model. The first step is to define the scale for the selection criteria. The scales of the selection criteria are either natural (preferred) or constructed. An example of a natural scale is dollars to measure cost. "A constructed attribute is developed specifically for a given decision context." An example of a constructed scale is the Gross National Product (GNP) to indicate economic health (Keeney 1992, 103). The next step is to weight the individual selection criteria to account for stakeholders' preferences. The use of a swing weight matrix is chosen to aide with stakeholder ranking of the selection criteria because of its simplicity in relation to the other common weighting approaches such as Simple Multi-attribute Rating Technique (SMART) and analytic hierarchy process (AHP) (Ewing, Tarantino and Parnell 2006). The

Swing Weight Matrix method was developed by Trainor et al. (2004) and then refined by Ewing et al. (2006). An example of a swing weight matrix is shown in Figure 8.

Ability to change →

Variation of scale ↓

| Mission immutable (very difficult to change) | | Mission support (difficult to change without external support) | | Mission enablers (change with army dollars) | |
|---|---|---|---|---|---|
| **Heavy mnvr area<br>Direct fire<br>Brigade capacity<br>100** | **Light mnvr area<br>Indirect fire<br>90** | **Int/partnering<br>Area cost factor<br>75** | *Housing avail.<br>Crime index<br>Maint./manuf.<br>50* | *RDTE diversity<br>20* | Supply & storage<br>Ops/admin<br>Ammo storage<br>10 |
| **Force deploy<br>Materiel deploy<br>Airspace<br>90** | **Critical infrastr.<br>Proximity<br>Test ranges<br>Mob. history<br>75** | *Munitions prod.<br>Accessibility<br>Urban sprawl<br>50* | *Connectivity<br>Work force<br>Availability<br>20* | MOUT<br>10 | Applied instructional<br>General instructional<br>5 |
| **Buildable acres<br>75** | *Soil resiliency<br>Joint facilities<br>50* | *Employment op.<br>Water quantity<br>Inst unit cost<br>ENV. elasticity<br>20* | Medical avail.<br>Noise contours<br>Air quality<br>In-state tuition<br>10 | C2 TGT facility<br>5 | 1 |

| Level of importance | | |
|---|---|---|
| **HIGH** | *MEDIUM* | LOW |

Figure 8. Swing weight matrix of army base realignment and closure military value analysis. Source: Ewing, Tarantino, and Parnell (2006).

According to Ewing et al. (2006), the first step in creating a swing weight matrix is to define the importance and variance dimensions, which make up the x and y axis of the matrix, respectively. The second step is to place the value measures (selection criteria) in the matrix based on relative importance. This is best done as an interactive exercise with the stakeholders in the room making the determination rather than trying to get concurrence after the fact. The third step is to assess the swing weights. Figure 9 shows the mathematical relationships that must hold in the swing weight matrix. No other strict relationships apply. It is important to have sufficient range of weights between the highest and lowest ranked value measure. In Ewing et al.'s example (Figure 8), the box in the upper left is given a weight of 100 and the box in the lower right a 1. The final step is to calculate the global weights. The global weights are determined by Equation 1:

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \qquad \textit{Equation 1}$$

where $f_i$ = the matrix swing weight, corresponding to value measure $i$.

| | | Level of importance of the value measure | | |
|---|---|---|---|---|
| | | Very important | Important | Less important |
| Variation in measure range | High | $A$ | $B_2$ | $C_3$ |
| | Medium | $B_1$ | $C_2$ | $D_2$ |
| | Low | $C_1$ | $D_1$ | $E$ |

*Where:*

$A >$ all other cells

$B_1 > C_1, C_2, D_1, D_2, E$

$B_2 > C_2, C_3, D_1, D_2, E$

$C_1 > D_1, E$

$C_2 > D_1, D_2, E$

$C_3 > D_2, E$

$D_1 > E$

$D_2 > E$

Figure 9. Swing weight assessment mathematical relationships.
Source: Trainor and Parnell (2011).

The next step after determining the individual criteria weighting is to define the value model objective function. Multi-attribute utility theory (MAUT) additive model is used as the theory behind the objective function. This is used because the selection criteria have multiple, sometimes conflicting objectives and this method allows for quantifying these differing objectives. The additive model can only be used if the value measures (selection criteria) are mutually preferentially independent. According to Ehrgott et al. (2009, 35), “this means that the conditional preferences of one attribute given the second attribute do not depend on the value of the second attribute.”

The NISE portfolio model considers several criteria, which are discussed in the next section, “Quantitative Value Model Implementation.” Because the criteria “consider more than expected return and variance… they are harder to solve than the quadratic mean variance problem” (Ehrgott et al. 2009, 31). Two recommended optimization approaches are using MAUT to construct a “utility function based on investor preferences and an optimization problem is solved to find a portfolio that maximizes the utility function” or use a multiple objective programming (MOP) approach to find “a set of efficient portfolios by optimizing a scalarized objective function. The investor then chooses a portfolio from an efficient set” (Ehrgott, et al. 2009, 31). The efficient set is sometimes referred to as the “efficient frontier” and all of the optimal solutions in this efficient set are Pareto optimal, i.e., mathematically equivalent. MAUT in combination with finding the optimal solutions to an integer linear program (ILP) is used. Integer linear programming is a type of mathematical optimization in which the decision variable is restricted to integer values (Ragsdale 2017). The former technique ensures that the stakeholders incorporate their preferences for a multiple objective problem, and by solving multiple ILPs, the latter technique allows the analysist to explore the efficient frontier of the multiple objective problem.

The individual project value model is shown below:

$$v_j = \sum_{i=1}^{n} w_i x_{ij} \quad \forall j \quad j \in \{1, 2, 3 \ldots n\} \qquad \textit{Equation 2}$$

where $v_j$ is the value of project *j*, $w_i$ is the weight of criteria *i*, *x* is the score of project *j* for criteria *i*.

The overall portfolio value model is shown in Equation 3, where, $V_k$ is the value of portfolio *k* and $Y_j$ is a binary variable, with the value of 1 if project *j* is present in the portfolio and 0 otherwise. The objective is to maximize total portfolio value.

$$V_k = \sum_{j=1}^{n} v_j Y_j \ \forall k \quad Y_j \in \{0, 1\} \qquad \textit{Equation 3}$$

Equation 4 represents the optimization model constraint in standard form and is used to ensure that the overall program budget is met along with other factors such as portfolio area balancing, where $a_{ij}$ and $b_i$ are the parameters associated with the resource constraints, such as the individual pillar budget and the overall program budget respectively. Equation 4 is explicitly defined in Chapter III in Equations 5 and 6. There are *m* constraints and *n* projects in the portfolio.

$$b_i = \sum_{j=1}^{n} a_{ij} Y_j \ \forall i \ \ i \in \{1, 2, 3 \ldots m\} \qquad \textit{Equation 4}$$

## D. QUANTITATIVE VALUE MODEL IMPLEMENTATION

The first step in developing the quantitative value model is defining the values for the value measures (selection criteria). This is done through conducting a brainstorming session with the key stakeholders (the Technology Governance Board) and gaining consensus on the final value scales shown in Tables 4, 5, and 6. Three value scales were constructed aligning to the three value hierarchies.

Table 4. Value Scale for Naval Innovation Science and Engineering program basic research, applied research, and technology transition pillar created from value hierarchy after brainstorming session with stakeholders

| Criteria # | Criteria | Value Scale |
|---|---|---|
| 1 | Overall Benefit to the Navy | 5 points: Improves safety or lethality |
| | | 3 points: Improves efficiency or total ownership cost |
| | | 1 point: Improves quality of life, innovative approach |
| | | |
| 2 | Degree of End User Involvement | 5 points: End user requested project/technology |
| | | 3 points: End user is aware of project but uncommitted |
| | | 1 point: End user is not aware of project or is aware and does not support |
| | | |
| 3 | Probability of Adoption | 5 points: High. Resource sponsor is identified and has budgeted to implement technology if successful. |
| | | 3 points: Medium. Resource sponsor is aware and supportive. |
| | | 1 point: Low. Resource sponsor is not aware of project or is aware and does not support |
| | | |
| 4 | Degree of Collaboration | 5 points: Collaborator is on board and will provide additional funds. |
| | | 3 points: Collaborator is on board but will not provide any funds. |
| | | 1 point: No collaboration. |
| | | |
| 5 | Technical Approach | 5 points: Follows scientific method and other logical methodology. |
| | | 3 points: Follows scientific method and other logical methodology but some reservations exist. |
| | | 1 point: Technical approach is flawed. |

Table 5. Value scale for Naval Innovative Science and Engineering program lab revitalization pillar created from value hierarchy after brainstorming session with stakeholders

| Criteria # | Criteria | Value Scale |
|---|---|---|
| 1 | Overall Benefit to the Navy | 5 points: Improves safety or lethality |
| | | 3 points: Improves efficiency or total ownership cost |
| | | 1 point: Improves quality of life, innovative |
| | | |
| 2 | Ability to Maintain | 5 points: High. Sustainment sponsor is identified and has budgeted to implement technology if successful. |
| | | 3 points: Medium. Sustainment sponsor is aware and supportive. |
| | | 1 point: Low. Sustainment sponsor is not aware of project or is aware and does not support |
| | | |
| 3 | Need | 5 points: High. Capability is needed for an active project. |
| | | 3 points: Medium. Capability is needed for future projects that sponsors have already requested. |
| | | 1 point: Low. Capability would give us the ability to go after new work. |
| | | |
| 4 | Relevant to current work | 5 points: Will directly impact/benefit current work |
| | | 3 points: Will indirectly impact/benefit current work |
| | | 1 point: No impact |
| | | |
| 5 | Return on Investment | 5 points: High. Higher than .2 |
| | | 3 points: Medium. Return of up to .2 |
| | | 1 point: Low. No tangible return |

Table 6. Value scale for Naval Innovative Science and Engineering program workforce development pillar created from value hierarchy after brainstorming session with stakeholders

| Criteria # | Criteria | Value Scale |
|---|---|---|
| 1 | Overall Benefit to the Navy | 5 points: Improves safety or lethality |
| | | 3 points: Improves efficiency or total ownership cost |
| | | 1 point: Improves quality of life, innovative |
| 2 | Strategic/Personal Growth | 5 points: High. High impact of both personal career growth and strategic growth benefiting the command with future work |
| | | 3 points: Medium. Potential for either personal career growth or strategic growth benefiting the command. |
| | | 1 point: Low. No impact |
| 3 | Need | 5 points: High. Capability is needed for an active project. |
| | | 3 points: Medium. Capability is needed for future projects that sponsors have already requested. |
| | | 1 point: Low. Capability would give us the ability to go after new work. |
| 4 | Relevant to current work | 5 points: Will directly impact/benefit current work |
| | | 3 points: Will indirectly impact/benefit current work |
| | | 1 point: No impact |
| 5 | Return on Investment | 5 points: High. Higher than .2 |
| | | 3 points: Medium. Return of up to .2 |
| | | 1 point: Low. No tangible return |

The next step is to define weights for the value measures. The swing weight matrix technique was used. A blank version of the matrix in Figure 10 was put on the screen and stakeholders were asked to place the selection criteria on the matrix based on relative level of importance and impact. The different NISE program pillars have different selection criteria so a separate matrix was created for each pillar: 1. Basic and Applied Research and Technology Transition, 2. Lab Revitalization, 3. Workforce Development. The results are shown in Figures 10, 11 and 12 for the different pillars of the NISE program. On the left of the figures, the equation used to determine the individual weights, $w_i$ is shown as well as the final weights of all selection criteria.

$$w_i = f_i \div \sum_{i=1}^{5} f_i$$

| | i | $f_i$ | $w_i$ |
|---|---|---|---|
| Technical Approach | 1 | 100 | 0.32 |
| Probability of Adoption | 2 | 75 | 0.24 |
| Benefit Added | 3 | 50 | 0.16 |
| Degree of End User Involvement | 4 | 50 | 0.16 |
| Degree of Collaboration | 5 | 40 | 0.12 |
| | Total | 315 | 1 |

**Basic and Applied Research, and Technology Transition**

| Impact to Individual Project Success | Level of Importance: High Impact on Technology Superiority | Medium Impact on Technology Superiority | Low Impact on Technology Superiority |
|---|---|---|---|
| High | Technical Approach 100 | 75 | Degree of End User Involvement 50 |
| Medium | Probability of Adopt 75 | Degree of Collaboration 40 | 30 |
| Low | Benefit Added 50 | 30 | 1 |

Figure 10. Swing weight matrix for NISE program basic research, applied research, and technology transition pillar created during a stakeholder focus group

$$w_i = f_i \div \sum_{i=1}^{5} f_i$$

| | i | $f_i$ | $w_i$ |
|---|---|---|---|
| Need | 1 | 100 | 0.34 |
| Relevant to Current Work | 2 | 75 | 0.26 |
| Benefit Added | 3 | 50 | 0.17 |
| Ability to Maintain | 4 | 40 | 0.14 |
| ROI | 5 | 25 | 0.09 |
| | Total | 290 | 1 |

**Lab Revitalization**

| Impact to Individual Project Success | Level of Importance: High Impact on Technology Superiority | Medium Impact on Technology Superiority | Low Impact on Technology Superiority |
|---|---|---|---|
| High | Need 100 | 75 | 50 |
| Medium | Relevant to Current Work 75 | Ability to Maintain 40 | 25 |
| Low | Benefit Added 50 | ROI 25 | 1 |

Figure 11. Swing weight matrix for NISE program lab revitalization pillar created during a stakeholder focus group

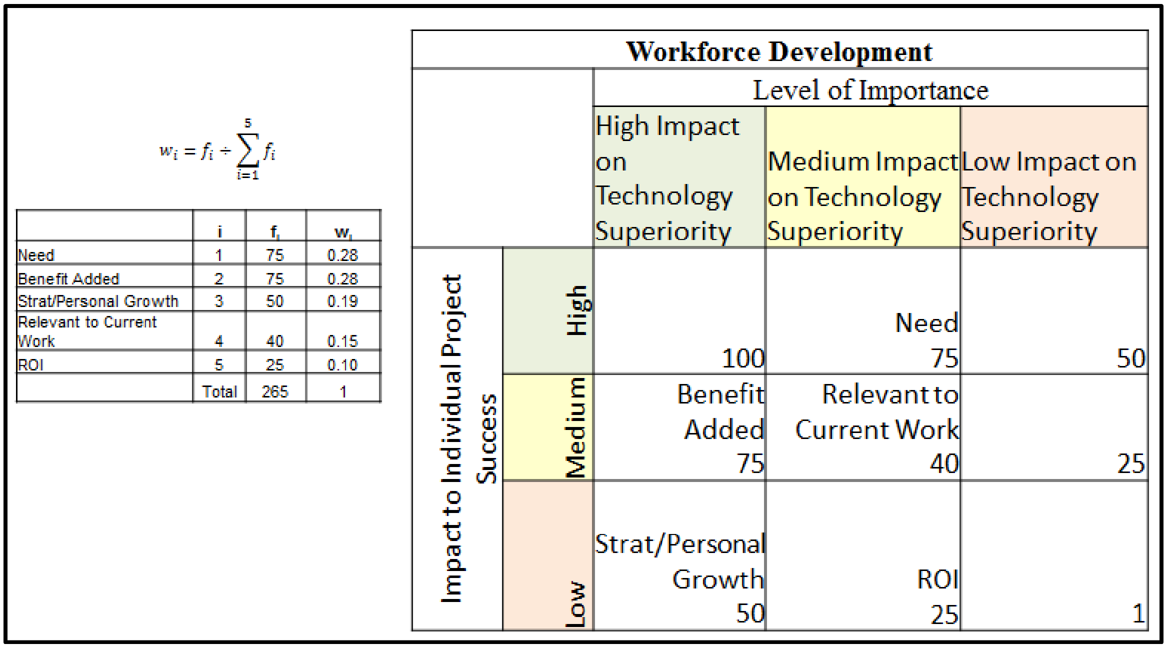


Figure 12. Swing weight matrix for NISE program workforce development pillar created during a stakeholder focus group

The next step is to determine the value model objective function. As mentioned earlier in the chapter, the MAUT additive model is used because the selection criteria have sometimes conflicting objectives and this method provides a transparent and operation model that is defendable with repeatable results. The model and specific constraints are discussed in Chapter III.

# III. DATA PRESENTATION, ANALYSIS, AND RESULTS

The individual project value model is presented in Chapter II as Equation 2 The overall portfolio value model, or objective function, is presented in Chapter II as Equation 3, and the generalized constraints are given in Equation 4. The objective is to maximize the total portfolio value within given constraints.

To implement the ILP, the generalized constraints of Equation 4 need to be explicitly defined. Equation 5 constrains the numbers of projects selected to be less than or equal to the overall program budget and Equation 6 constrains the budgets of the individual program pillars to ensure a balanced portfolio. Table 7 shows the constraint parameter used to constrain the budget for the different pillars. The parameters are percentages of the budget based on NAVFAC EXWC's emphasis for the year and may change year to year. The percentages this year are based on other warfare centers investment portfolio that was approved by DASN RDT&E.

$$B \geq \sum_{j=1}^{n} c_{pj} Y_j \quad \forall p \quad p \in \{1, 2, \ldots, 5\} \qquad \textit{Equation 5}$$

$$B * D_p \leq \sum_{j=1}^{n} c_{pj} Y_j \leq B * E_p \qquad \textit{Equation 6}$$

where $B$ is the total program budget, $c$ is the cost of project $j$, and $p$ is the individual program pillar defined in Table 7. The percentage ranges of the individual program pillars were determined discussing with the key stakeholders (TGB).

Table 7. Budget constraint parameters for NISE pillars corresponding to Equation 5. $D_p$ and $E_p$ are the lower and upper bound percentages, respectively

| NISE Program Pillar | *p* | $D_p$ | $E_p$ |
|---|---|---|---|
| Basic Research | 1 | 0.1 | 0.4 |
| Applied Research | 2 | 0.1 | 0.4 |
| Technology Transition | 3 | 0.03 | 0.2 |
| Lab Revitalization | 4 | 0.05 | 0.2 |
| Workforce Development | 5 | 0.03 | 0.1 |

Once the model is created it is important to test the model in order to work out any bugs. This model was created in Excel and the ILP solved using the Solver add-in.

## A. DATA PRESENTATION

A project solicitation for NISE proposals was released in early March 2018 and closed 27 April 2018. Twenty-three proposals were received, totaling $1,517,000. The budget allocation for these projects is $1,000,000. The current Excel implementation will solve for optimal portfolios exceeding NAVFAC EXWC leadership expectations of 50 proposals in the future. The project data is shown in Table 8. Project titles and principle investigator names are removed and general project identifiers are added in their place.

Table 8. NISE project selection data

| Project Identifier | Category | FY19 Project Cost |
|---|---|---|
| B1 | Basic Research | $115,000 |
| B2 | Basic Research | $100,000 |
| B3 | Basic Research | $100,000 |
| B4 | Basic Research | $100,000 |
| A1 | Applied Research | $100,000 |
| A2 | Applied Research | $75,000 |
| A3 | Applied Research | $100,000 |
| A4 | Applied Research | $100,000 |
| A5 | Applied Research | $150,000 |
| A6 | Applied Research | $100,000 |
| T1 | Technology Transition | $40,000 |
| T2 | Technology Transition | $50,000 |
| T3 | Technology Transition | $50,000 |
| L1 | Lab Revitalization | $72,000 |
| L2 | Lab Revitalization | $50,000 |
| L3 | Lab Revitalization | $50,000 |
| L4 | Lab Revitalization | $40,000 |
| L5 | Lab Revitalization | $50,000 |
| W1 | Workforce Development | $25,000 |
| W2 | Workforce Development | $5,500 |
| W3 | Workforce Development | $13,100 |
| W4 | Workforce Development | $16,400 |
| W5 | Workforce Development | $15,000 |

| Project Identifier | Category | FY19 Project Cost |
|---|---|---|
| **Totals** | | **Total** |
| **23** | | **$1,517,000** |

The TGB provided input on each proposal evaluating them according to the criteria listed in Chapter II. All eight members evaluated each proposal and aggregate scores and rankings are displayed in Table 9. Total score is determined using Equation 2.

Table 9. NISE project data with TGB evaluations, total score determined using Equation 2

| Project Identifier | Category | Total Score | Overall Rank | Rank in Category | FY19 Project Cost |
|---|---|---|---|---|---|
| B1 | Basic Research | 26.44 | 11 | 1 | $115,000 |
| B2 | Basic Research | 25.33 | 14 | 2 | $100,000 |
| B3 | Basic Research | 23.02 | 18 | 3 | $100,000 |
| B4 | Basic Research | 19.75 | 22 | 4 | $100,000 |
| A1 | Applied Research | 29.17 | 5 | 2 | $100,000 |
| A2 | Applied Research | 33.56 | 1 | 1 | $75,000 |
| A3 | Applied Research | 24.13 | 16 | 5 | $100,000 |
| A4 | Applied Research | 28.10 | 9 | 3 | $100,000 |
| A5 | Applied Research | 22.16 | 21 | 6 | $150,000 |
| A6 | Applied Research | 26.19 | 12 | 4 | $100,000 |
| T1 | Technology Transition | 31.05 | 2 | 1 | $40,000 |
| T2 | Technology Transition | 23.87 | 17 | 2 | $50,000 |
| T3 | Technology Transition | 22.89 | 19 | 3 | $50,000 |
| L1 | Lab Revitalization | 25.78 | 13 | 5 | $72,000 |
| L2 | Lab Revitalization | 29.95 | 4 | 1 | $50,000 |
| L3 | Lab Revitalization | 29.08 | 6 | 2 | $50,000 |
| L4 | Lab Revitalization | 28.57 | 8 | 4 | $40,000 |
| L5 | Lab Revitalization | 28.60 | 7 | 3 | $50,000 |
| W1 | Workforce Development | 26.75 | 10 | 2 | $25,000 |
| W2 | Workforce Development | 15.73 | 23 | 5 | $5,500 |
| W3 | Workforce Development | 30.48 | 3 | 1 | $13,100 |
| W4 | Workforce Development | 22.38 | 20 | 4 | $16,400 |
| W5 | Workforce Development | 24.94 | 15 | 3 | $15,000 |

## B. RESULTS

The optimal portfolio is found by solving an integer linear program (ILP) and implemented using Excel Solver. The objective function (Equation 2) and constraints (Equations 4 and 5) are implemented in Excel and the ILP solved using the Excel Solver. Table 10 compares the optimization method to an alternative method previously used by the command, sorting in order of rank and funding all projects that fall under $1,000,000.

The optimized portfolio utilizes 99.5 percent of the available budget where the non-optimized portfolio utilizes only 94.5 percent. In addition, the optimized portfolio funds 18 projects where as the non-optimized portfolio funds only 15 projects which is a 20 percent increase in funded projects. The total value of the optimized portfolio is 483. The total value for the non-optimized portfolio is 424. The optimized portfolio has a 13.9 percent increase in value. The optimized portfolio out performs the non-optimized portfolio specifically adding three additional projects within the original budget constraint and additional value according to the selection criteria.

Table 10. NISE project ranking comparing optimization method to an alternative method, sorting in order of rank and funding all projects that fall under $1,000,000 in the running total column

| Project Identifier | Category | Total Score | Overall Rank | Rank in Category | FY19 Project Cost | Selected in Optimized Portfolio (0= No; 1= Yes) | Running Total Budget |
|---|---|---|---|---|---|---|---|
| A2 | Applied Research | 33.56 | 1 | 1 | $75,000 | 1 | $75,000 |
| T1 | Technology Transition | 31.05 | 2 | 1 | $40,000 | 1 | $115,000 |
| W3 | Workforce Development | 30.48 | 3 | 1 | $13,100 | 1 | $128,100 |
| L2 | Lab Revitalization | 29.95 | 4 | 1 | $50,000 | 1 | $178,100 |
| A1 | Applied Research | 29.17 | 5 | 2 | $100,000 | 1 | $278,100 |
| L3 | Lab Revitalization | 29.08 | 6 | 2 | $50,000 | 1 | $328,100 |
| L5 | Lab Revitalization | 28.60 | 7 | 3 | $50,000 | 1 | $378,100 |
| L4 | Lab Revitalization | 28.57 | 8 | 4 | $40,000 | 1 | $418,100 |

| Project Identifier | Category | Total Score | Overall Rank | Rank in Category | FY19 Project Cost | Selected in Optimized Portfolio (0= No; 1= Yes) | Running Total Budget |
|---|---|---|---|---|---|---|---|
| A4 | Applied Research | 28.10 | 9 | 3 | $100,000 | 1 | $518,100 |
| W1 | Workforce Development | 26.75 | 10 | 2 | $25,000 | 1 | $543,100 |
| B1 | Basic Research | 26.44 | 11 | 1 | $115,000 | 1 | $658,100 |
| A6 | Applied Research | 26.19 | 12 | 4 | $100,000 | 1 | $758,100 |
| L1 | Lab Revitalization | 25.78 | 13 | 5 | $72,000 | 0 | $830,100 |
| B2 | Basic Research | 25.33 | 14 | 2 | $100,000 | 1 | $930,100 |
| W5 | Workforce Development | 24.94 | 15 | 3 | $15,000 | 1 | $945,100 |
| A3 | Applied Research | 24.13 | 16 | 5 | $100,000 | 0 | $1,045,100 |
| T2 | Technology Transition | 23.87 | 17 | 2 | $50,000 | 1 | $1,095,100 |
| B3 | Basic Research | 23.02 | 18 | 3 | $100,000 | 0 | $1,195,100 |
| T3 | Technology Transition | 22.89 | 19 | 3 | $50,000 | 1 | $1,245,100 |
| W4 | Workforce Development | 22.38 | 20 | 4 | $16,400 | 1 | $1,261,500 |
| A5 | Applied Research | 22.16 | 21 | 6 | $150,000 | 0 | $1,411,500 |
| B4 | Basic Research | 19.75 | 22 | 4 | $100,000 | 0 | $1,511,500 |
| W2 | Workforce Development | 15.73 | 23 | 5 | $5,500 | 1 | $1,517,000 |

The binary variable indicates whether the project was selected in the optimized portfolio, 1 if selected, 0 if not. The projects highlighted in green are funded in the non-optimized portfolio. Projects highlighted in yellow indicate differences between the portfolios.

## C. ANALYSIS

It is important to analyze the results and update the model to reflect any necessary updates. As projects complete at the end of FY 19, success of the projects will be tracked. Success criteria includes technology transition, cost, schedule and performance. Technology transition will be measured as to whether a project transitions to the fleet or to another program. The actual cost, schedule and performance of projects will be compared to the project proposal. Projects will then be compared to total value ranking to see if the model is a good predictor for project success and will be adjusted accordingly.

A sensitivity analysis is used to generate some solutions of the efficient frontier using the ILP by changing the parameters of the budget constraint. The results of the analysis are seen in Tables 11 and 12. This tool is used to help the stakeholders determine if a small increase or decrease in the budget would create major changes in the portfolio. Increasing the original $1,000,000 budget by $50,000 increases the overall portfolio value by .12 but decreases the value to budget ratio. Increasing by $100,000 does add an additional project but also decreases the value to budget ratio. The $1,000,000 budget seems to be the ideal budget in the range from $900,000–$1,100,000. In general, as the portfolio budget is decreased, a project is removed from the portfolio and as the portfolio budget is increased, a project is added to the portfolio highlighted in Table 12. However, in certain cases ($900K and $1050K) additional projects are swapped. This is due to the model selecting the projects with the highest value that fit within the budget range. For example, in the $1050K portfolio, B3 was swapped for T3. B3 has a higher total score but also a higher cost and therefore would not fit in the $1000K budget.

Table 11. Sensitivity analysis showing the effects a change in budget has on the number of projects funded and the total portfolio value

| Program Budget | Number of Projects Funded in Portfolio | Total Portfolio Value | Value to Budget Ratio |
|---|---|---|---|
| $900,000 | 16 | 428.42 | 0.00048 |
| $950,000 | 17 | 460.2 | 0.00048 |
| $1,000,000 | 18 | 483.09 | 0.00048 |
| $1,050,000 | 18 | 483.21 | 0.00046 |
| $1,100,000 | 19 | 506.1 | 0.00046 |

Table 12. Sensitivity analysis showing the effects a change in budget has on the selected portfolio

| | Portfolio Budget | | | | |
|---|---|---|---|---|---|
| **Project Identifier** | **900K** | **950K** | **1000K** | **1050K** | **1100K** |
| B1 | 1 | 1 | 1 | 1 | 1 |
| B2 | 1 | 1 | 1 | 1 | 1 |
| B3 | 1 | 0 | 0 | 1 | 1 |
| B4 | 0 | 0 | 0 | 0 | 0 |
| A1 | 1 | 1 | 1 | 1 | 1 |
| A2 | 1 | 1 | 1 | 1 | 1 |
| A3 | 0 | 0 | 0 | 0 | 0 |
| A4 | 1 | 1 | 1 | 1 | 1 |
| A5 | 0 | 0 | 0 | 0 | 0 |
| A6 | 0 | 1 | 1 | 1 | 1 |
| T1 | 1 | 1 | 1 | 1 | 1 |
| T2 | 1 | 1 | 1 | 1 | 1 |
| T3 | 0 | 0 | 1 | 0 | 1 |
| L1 | 0 | 0 | 0 | 0 | 0 |
| L2 | 1 | 1 | 1 | 1 | 1 |
| L3 | 1 | 1 | 1 | 1 | 1 |
| L4 | 1 | 1 | 1 | 1 | 1 |
| L5 | 0 | 1 | 1 | 1 | 1 |
| W1 | 1 | 1 | 1 | 1 | 1 |
| W2 | 1 | 1 | 1 | 1 | 1 |
| W3 | 1 | 1 | 1 | 1 | 1 |
| W4 | 1 | 1 | 1 | 1 | 1 |
| W5 | 1 | 1 | 1 | 1 | 1 |
| **Totals** | **16** | **17** | **18** | **18** | **19** |

Original portfolio highlighted in green, changes highlighted in yellow. 1’s indicate selection in portfolio, 0’s otherwise.

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# IV. CONCLUSION

## A. FINDINGS AND RECOMMENDATIONS FOR R&D PROJECT SELECTION

In order to maintain the Navy's technological superiority, we must optimize our research and development budgets. Using systems engineering principles, this thesis recommends one approach to do so using the NISE program as a case study. Both qualitative and quantitative value models were developed, and projects were then rated by NAVFAC EXWC's technical leadership, the TGB. These projects were then run through an optimization model to aid with selection. As expected, the projects with highest value were selected while adhering to budget and program pillar minimum and maximum constraints.

The optimized portfolio increased the number of funded projects by 20 percent in comparison to the non-optimized portfolio. In addition, the optimized portfolio has a 13.9 percent increase in value compared to the non-optimized portfolio. The TGB, the primary stakeholders for the project, were engaged throughout the entire process and as a whole were pleased with the results. The process created is defendable and repeatable.

## B. FUTURE WORK

Future work will include analyzing the success of the selected individual projects and comparing them to their rankings to determine if the model is a good predictor for project success. The model will be adjusted accordingly.

In addition, future research could include applying this methodology to other DoD portfolio-type R&D programs and analyzing the results.

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