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Risk-Based Modeling of Life-Cycle and Total Ownership Cost

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Risk-Based Modeling of Life-Cycle and Total Ownership Cost

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Abstract

In this research, we answer the following primary question: Would an advanced analytical model be a more effective metric to estimate total ownership cost (TOC) with life-cycle cost under uncertainty and risk than the current method of life-cycle cost estimates for surface electro-optical infrared (EO/IR) sensors? To accomplish this, we developed and analyzed a computational model for Total Ownership with Life-Cycle Cost Model Under Uncertainty for Surface Electro-Optical Infrared Sensors. During the development of the model, we identified the required data and examined the current Department of Defense (DoD) method for determining system life-cycle costs for defense systems and determined that the proposed model is a useful alternative to the current method of determining the life-cycle costs for EO/IR sensors on surface ships. Finally, we concluded that the developed model can be applied to cost estimating in other sectors of DoD cost projections.

Introduction

Research Purpose

The purpose of this research is to develop a model to estimate total ownership with life-cycle costs under uncertainty associated with surface electro-optical infrared (EO/IR) sensors. We examine the basics of total ownership cost (TOC) modeling over the life cycle of the EO/IR sensors, including the inception phase of acquisition costs, followed by annual operations and maintenance (O&M) expenses, along with a final set of disposition costs at the end of life of the sensor. This model will allow managers to have better decision analytics of the costs of said sensors for use in subsequent cost comparisons across sensor platforms, return on investment analysis, portfolio allocation of resources, and analysis of alternatives.

Research Focus

In this research, we answer the following primary question: Would an advanced analytical model be a more effective metric to estimate TOC with life-cycle cost under uncertainty and risk than the current method of life-cycle cost estimates for surface EO/IR sensors? To accomplish this, we develop and analyze a Total Ownership with Life-Cycle Cost Model Under Uncertainty for surface EO/IR sensors. In the development of the model, we determine what data are required to implement our proposed model for surface ship EO/IR sensors. We also examine the current Department of Defense (DoD) method for determining system life-cycle costs for defense systems and consider whether the proposed model is a useful alternative to the current method of determining the life-cycle costs for EO/IR sensors on surface ships. Finally, we consider whether the developed model can be applied to cost estimating in other sectors of DoD cost projections.

Research Summary

While executing a standard life cycle–based TOC analysis, we assume that, before the system is operational, there are substantial acquisition costs. These costs are usually referred to as Year 0, followed by the operational years where operation and maintenance costs will apply. The final price analyzed is the salvage cost, or the cost to properly dispose of, sell, or render the system inoperable. The sum of these three expenses is called the life-cycle cost. Unfortunately, the accurate calculation of these costs is not as straightforward as their descriptions. To accurately incorporate these three factors, it is essential to consider economic theory. The elements of time valuation of money are critical in the analysis of alternatives. The economic growth, annual discount rate, inflation, and opportunity cost of investing in a specific system are essential to our study. Other factors include budgetary cutbacks and changes in technology. The model will allow the user to input these changes to manually adjust for each of these. Utilizing this model will serve as a proof of concept to understand how this approach could be used to reduce cost overflow and prevent budget overruns. It will provide greater insight into the true nature of the cost of cash outflow and the life cycle of the product and its associated costs. These results would give leaders a more effective metric to analyze TOC under uncertainty, therefore allowing leadership to make more informed decisions in the DoD acquisition process.

Literature Review

Introduction

This background and literature review provide a comprehensive overview of the topics pertinent to our project. We first examine the concepts and best practices in the field of cost and cost estimation and their application inside of the DoD. We then investigate the DoD's acquisition process as a whole to analyze how the DoD can utilize cost estimation to influence decision-making. After covering basic cost estimation and the acquisition system, we then discuss TOC and life-cycle cost estimations and how these factors play a role in calculating the overall cost of a system. The review also covers the topics of risk and uncertainty to explain the relationship and the differences between the two as well as to highlight the importance of properly accounting for both factors. We conclude with an overview of our model's subject, the EO/IR sensor. We give a brief rundown of the capabilities as well as the applications that these sensors have on Navy surface vessels, along with their rapidly changing technology, and state why it is imperative that the Navy continues to buy these sensors while ensuring the cost stays at a rational price point.

Cost Estimation

The DoD receives a limited amount of funds every fiscal year and must decide how those funds are used in support of U.S. national strategies and goals. Specifically, those decisions fall into one of three categories: long-term planning, budgeting, or choosing among alternatives (Mislick & Nussbaum, 2015). The government is tasked with spending taxpayers' dollars effectively and efficiently. This means that the DoD decision-makers must ensure they make strategic investments, including the acquisition of new programs and systems. Before a program is implemented or a system is purchased, decision-makers must understand the full cost that will be incurred and its effect on the DoD's limited budget.

The projected costs of major acquisitions are produced through a process known as *cost estimation*. Cost estimation is defined as "the process of collecting and analyzing historical data and applying quantitative models, techniques, tools, and databases in order to predict an estimate of the future cost of an item, product, or task" (Mislick & Nussbaum, 2015, p. 11). In basic terms, cost estimation is performed by running relevant data from the past through a model or database to predict what an item will cost in the future. It is important to note that reliable historical data are fundamental to this process.

In order to produce cost estimates, we must first gather available historical data. Collecting data is often the most time-consuming and costly step of the entire cost estimation process (Mislick & Nussbaum, 2015). Only after the historical data have been obtained can the cost analyst start the "organization, normalization, and management of that historical data" (Mislick & Nussbaum, 2015, p. 11). *Normalization* refers to taking the historical data and "applying adjustments to that data to gain consistent, comparable data to be used in your estimates" (Mislick & Nussbaum, 2015, p. 78). Normalizing the data set allows the analyst to compare data across different periods of time by adjusting for different factors. The data set must be normalized three different ways: for content, for quantity, and for inflation (Mislick & Nussbaum, 2015). Normalizing for content ensures comparison across the same category or type of data (Mislick & Nussbaum, 2015). Normalizing for quantity ensures comparison of data at the same point on the learning curve of production and of equal quantities (Mislick & Nussbaum, 2015). Finally, the data are adjusted to account for inflation when comparing data from different years (Mislick & Nussbaum, 2015).

The second component of cost estimation is the quantitative model that is used to turn normalized historical data into a future cost estimate. Mislick and Nussbaum (2015) explain that the "profession of cost estimating is scientifically grounded by using transparent, rationally defensible and reviewable quantitative methods" (p. 12). The development of a high-quality quantitative model is key in cost estimation. If a poor quantitative model is used, then the quality and reliability of the cost estimate will also be poor. This highlights the importance of the quality cost models for EO/IR sensors.

The third part of Mislick and Nussbaum's (2015) definition of cost estimation is to predict. The ultimate goal of cost estimation is to predict a future cost. The prediction is based on the information available at the time. We can only "estimate the conditions that will pertain later when the project is executed" and must rely on the information available in the present (Mislick & Nussbaum, 2015, p. 12). While no one can forecast the future with 100% accuracy, through historical data and quantitative models, we are able to provide a more accurate prediction that, while not perfect, is still a useful tool for decision-makers in the acquisition process.

One of the most important characteristics of a quality cost estimate is that it must be understandable to the user or decision-maker in order to be an efficient decision-making tool (Mislick & Nussbaum, 2015). To this end, a complex approach to cost estimation should be avoided and a simpler approach should be used (Mislick & Nussbaum, 2015). An understandable estimate also clearly lays out the assumptions and ground rules that were used in the process (Mislick & Nussbaum, 2015). With the diversity among people's background and experiences, there can be differing underlying assumptions in the cost estimation process. Therefore, the assumptions used must be clearly stated, and a sensitivity analysis should be performed to accommodate additional variations of assumptions (Mislick & Nussbaum, 2015).

Cost Overview

Before comprehending cost estimation methods, it is important to become familiar with the terms associated with cost estimation. To begin with, an understanding of "cost" provides a solid foundation in the cost estimation process. If we do not understand what we are trying to predict, then we will not produce a quality or credible estimation. The term *cost* is often used interchangeably with the term *price*; however, they do not have the same meaning. There is an important distinction between the two terms. Mislick and Nussbaum (2015) define cost as the total amount of money needed to produce a certain item, or a quantitative measurement that accounts for all resources needed to produce an item. However, they refer to price as the amount of money that a person must pay for an item. When we go into a store, we normally ask the salesperson "What does this item cost?" Answering the literal question of what an item costs would encompass every resource that went into the development and production of that item. Instead, the accurate question is, “What’s the item’s price?” or “How much money must I exchange to receive that item?”

Because the term *cost* can refer to a number of different types or categories, the type of cost is important to understand during the cost estimation process. One of the first distinctions is between recurring and nonrecurring costs. A recurring cost is “repetitive and occurs each time a company produces a unit” (Mislick & Nussbaum, 2015, p. 26). When a bottling company produces a bottled beverage, each bottle cap has an associated cost. The cost of each bottle cap is recurring. In contrast, a nonrecurring cost is “not repetitive and cannot be tied to the quantity of the items being produced” (Mislick & Nussbaum, 2015, p. 26). The cost associated with purchase of the bottling machine would be considered nonrecurring. Closely related to recurring and nonrecurring costs are fixed and variable costs. Variable costs are associated and vary with the level of production (Mislick & Nussbaum, 2015). The more units produced, the more the total variable cost. However, fixed costs are unaffected by the level of production and are “generally associated with nonrecurring costs” (Mislick & Nussbaum, 2015, p. 27). No matter how many units are produced, the fixed cost will remain unchanged.

Another distinction between types of cost is direct and indirect costs. A direct cost can be “reasonably measured and allocated to a specific output, product, or work activity” (Mislick & Nussbaum, 2015, p. 26). The material used to produce an item is a direct cost. An indirect cost “cannot be attributed or allocated to a specific output, product, or work activity” (Mislick & Nussbaum, 2015, p. 27). The maintenance required for the upkeep of a machine used in production is indirect. Operating costs that are not direct labor or material, such as electricity and property taxes, are classified as overhead costs (Mislick & Nussbaum, 2015).

The Theory of Predictive Modeling in Cost

Generally, forecasting can be divided into quantitative and qualitative approaches. Qualitative forecasting is used when little to no reliable historical, contemporaneous, or comparable data exist. Several qualitative methods exist, such as the Delphi or expert opinion approach (a consensus-building forecast by field experts, marketing experts, or internal staff members), management assumptions (target growth rates set by senior management), and market research or external data or polling and surveys (data obtained through third-party sources, industry and sector indexes, or active market research). These estimates can be either single-point estimates (an average consensus) or a set of prediction values (a distribution of predictions). The latter can be entered into Risk Simulator as a custom distribution, and the resulting predictions can be simulated (i.e., running a nonparametric simulation using the prediction data points as the custom distribution).

For quantitative forecasting, the available data or data that need to be forecasted can be divided into time series (values that have a time element to them, such as revenues at different years, inflation rates, interest rates, market share, failure rates, and so forth), cross-sectional (values that are time independent, such as the grade point average of sophomore students across the nation in a particular year, given each student’s levels of SAT scores, IQ, and number of alcoholic beverages consumed per week), or mixed panel (mixture between time-series and panel data; e.g., predicting sales over the next 10 years given budgeted marketing expenses and market share projections, which means that the sales data are time series, but exogenous variables such as marketing expenses and market share exist to help to model the forecast predictions). Here is a quick review of each of the most commonly used forecasting methodologies.

Life-Cycle Cost

In developing a cost estimate, we first must understand a program’s or project’s life cycle. A life cycle follows the project or program from its inception to its disposal, or “cradle to grave.” It includes “the various stages of activity or phases through which the project progresses on its way from beginning to completion" (Rendon & Snider, 2008, p. 3). The life cycle starts at a program's development; flows through its production, operation, and maintenance; and finally concludes after proper disposal. The costs associated with this process are classified as the program's life-cycle cost.

The Defense Acquisition University (DAU) defines *life-cycle cost* as the direct cost of the acquisition program as well as the indirect cost that can be logically attributed to the program over the entire life cycle (Defense Acquisition University [DAU], n.d.-b). It includes the cost to the government to "acquire, operate, support (to include manpower), and where applicable, dispose" of a system or program (DAU, n.d.-b). There are multiple stakeholders in the DoD—such as Congress, the program manager and office, and contractors—that view a program's life-cycle cost from different perspectives. These multiple perspectives have led to three different methods of breaking down and displaying life-cycle cost.

The first method is breaking down program life-cycle costs by five different appropriation categories (DAU, n.d.-b): research, development, test, and evaluation (RDT&E); procurement; operations and maintenance (O&M); military construction (MILCON); and military personnel (MILPERS). This method is used to develop and submit budget requests to Congress (DAU, n.d.-b).

However, program managers and program offices would not find the first method as useful as Congress does. Instead, they utilize program life-cycle costs that are broken down by Work Breakdown Structure (WBS; DAU, n.d.-b). The DAU describes a *Work Breakdown Structure* as a framework that displays "the total system as a product-oriented family tree composed of hardware, software, services, data, and facilities" (DAU, n.d.-b). The WBS relates all of the work elements to each other and eventually to the final product (DAU, n.d.-b). A WBS encompasses all of the work necessary to produce a product (Huynh & Snider, 2008). This breakdown shows the relationship between costs and different elements of a system, which is a useful tool for program managers and contractors.

The Office of the Secretary of Defense for Cost Assessment and Program Evaluation (OSD CAPE) outlined the third life-cycle cost display method in its *Operating and Support Cost-Estimating Guide* (Office of the Secretary of Defense for Cost Assessment and Program Evaluation [OSD CAPE], 2014). The OSD CAPE defines a program's life-cycle cost as the summation of four different cost categories or phases: research and development (R&D), investment, operating and support (O&S), and disposal. Figure 1 provides a graphical representation of the four cost categories over a program's life cycle.

R&D is the initial cost category or phase in a program's life cycle. These costs are the first incurred in the research, design, and development of a new system or program. They can also include the "system design and integration; development, fabrication, assembly, and test of hardware and software for protypes and/or engineering development models" (OSD CAPE, 2014, pp. 2–3).

Following R&D is the investment cost category. These costs are incurred from "procurement and related activities from the beginning of low rate initial production (LRIP) through completion of deployment" (OSD CAPE, 2014, pp. 2–3). *Low rate initial production* refers to the production of the minimal number of a product or system that is required for initial operational test and evaluation (IOT&E; DAU, n.d.-c). Investment costs can include program management, initial spares, technical publications, and equipment training (OSD CAPE, 2014).

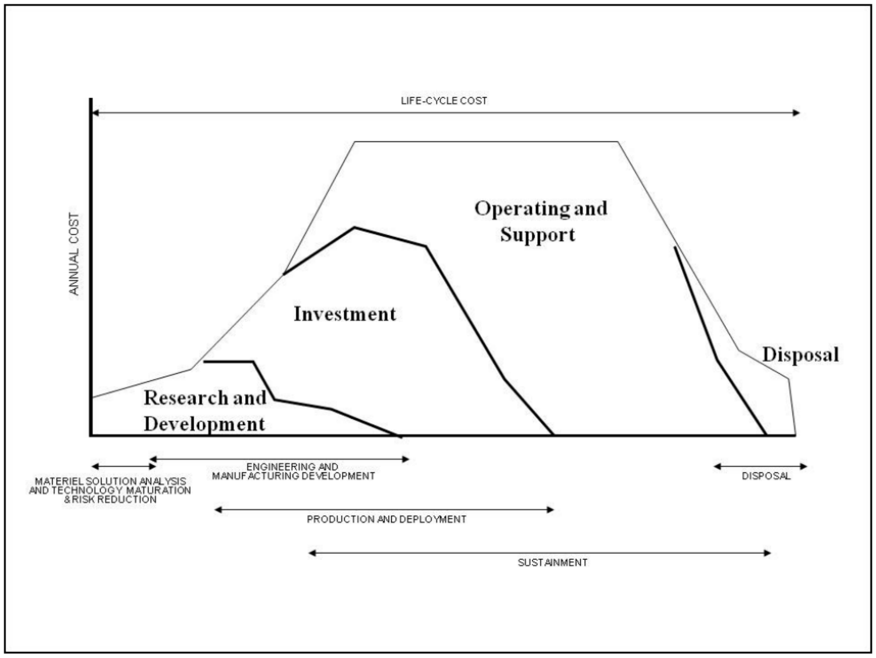

Figure 1. Notional Profile of Annual Program Expenditures by Major Cost Category over the System Life Cycle. Source: OSD CAPE (2014).

The O&S phase is the third phase in the OSD CAPE definition of life-cycle cost. The O&S phase normally accounts for a majority of a project's life-cycle costs (OSD CAPE, 2014). O&S consists of all of a system's operation and sustainment cost from initial deployment to the end of its operational life. This includes all the costs associated with "operating, maintaining, and supporting a fielded system" (OSD CAPE, 2014, pp. 2–3). Specifically, costs can include "personnel, equipment, supplies, software, and services associated with operating, modifying, maintaining, supplying, and otherwise supporting a system" (OSD CAPE, 2014, pp. 2–3).

The fourth and final OSD CAPE cost category is disposal. Disposal costs are those associated with the proper disposal or demilitarization at the end of a system's operational life (OSD CAPE, 2014). These costs can include "disassembly, materials processing, decontamination, collection/storage/disposal of hazardous materials and/or waste, safety precautions, and transportation of the system to and from the disposal site" (OSD CAPE, 2014, pp. 2–5). However, disposal costs can also be incurred during the sustainment phase due to unplanned system losses (OSD CAPE, 2014). We revisit this method of life-cycle costing in our discussion of total ownership costing.

Cost Estimation in the Department of Defense

Cost estimation is an important and required tool used by decision-makers in defense acquisitions. The requirement for a cost estimation is outlined in Department of Defense Instruction 5000.02, *Operation of the Defense Acquisition System*. Specifically, the instruction mandates that the

> DoD Component will develop a DoD Component Cost Estimate that covers the entire life cycle of the program for all Major Defense Acquisition Programs (MDAPs) prior to Milestone A, B, and C reviews and the Full-Rate Production Decision; and for all Major Automated Information System (MAIS) programs at any time an Economic Analysis is due. (DoD, 2017, p. 135)

This means that before the acquisition process can move beyond the MSA, TMRR, and EMD phases and ultimately continue on to full production, a cost estimate encompassing the entire program life cycle must be produced. In addition to the DoD's Component cost estimate, a separate, independent cost estimate is also required. *DODI 5000.02* requires the Milestone Decision Authority to consider an "independent estimate of the full life-cycle cost of a program, prepared or approved by the Director of Cost Analysis and Program Evaluation (DCAPE)" (DoD, 2017, p. 135). The DoD Component and DCAPE cost estimates are typically classified as Life-Cycle Cost Estimations (LCCEs). Mislick and Nussbaum (2015) describe an LCCE as a "a cost estimate for the totality of the resources that will be necessary throughout the product's life cycle" (p. 18).

There are four main cost estimating techniques used in the DoD to develop an LCCE, and they can be used in different phases of a program's life cycle (Ambrose, 2017). The first method is parametric cost estimating and involves the use of statistical inferences to generate an estimate based on system performance and design (Ambrose, 2017). Using historical data from similar systems, cost estimation relationships (CERs) and patterns are identified. Those patterns are assumed to hold true in the future and are used to predict cost (Mislick & Nussbaum, 2015). The second method is analogy cost estimating, whereby a new system is compared to a similar existing system. The analogy method is a relatively quick and inexpensive method; however, it may not be as precise as other methods (Ambrose, 2017). The parametric and analogy methods are normally used early on in the acquisition process during the materiel solution analysis (MSA), technology maturation and risk reduction (TMMR), and engineering and manufacturing development (EMD) phases (Ambrose, 2017). The third and most time-consuming method is engineering cost estimation. In this method, the system is broken down into its WBS elements in which individual detailed estimates are conducted. These estimates are then summed together to create the overall estimate (Mislick & Nussbaum, 2015). The engineering method is used during the TMMR phase and through the remaining acquisition process (Ambrose, 2017). The last main method used by the DoD is actual costing. This method uses the actual costs from a system that were incurred in the past to predict the cost of producing that system in the future (Ambrose, 2017). This method can be used after a program has entered the production and deployment (P&D) phase.

Total Ownership Cost

While LCCEs are a useful tool for decision-makers, they present a narrower scope when a broader perspective may be more beneficial (Kobren, 2014). Thus, we introduce the concept of total ownership cost (TOC). The DAU defines *total ownership cost* as including the "elements of life-cycle cost as well as other infrastructure or business process costs not normally attributed to the program" (Kobren, 2014). Infrastructure refers to "all military department and defense agency activities that sustain the military forces assigned to the combatant and component commanders" (Kobren, 2014). The major infrastructure categories are support to equipment, support to military personnel, and support to military bases (Kobren, 2014). Not normally included in a traditional LCCE, other support activities to consider in a cost estimate are recruiting, environmental and safety compliance, management headquarters functions, and logistics infrastructure activities (Kobren, 2014).

DoD Directive 5000.01 states that

> DoD Components shall plan programs based on realistic projections of the dollars and manpower likely to be available in future years. To the greatest extent possible, the MDAs shall identify the total costs of ownership, and at a minimum, the major drivers of total ownership costs. (DoD, 2003)

This requires the DoD to expand beyond the basic life-cycle cost estimation and include the support activities and infrastructure costs. To support the DoD directive, the Department of the Navy (DoN) issued its *Total Ownership Cost (TOC) Guidebook* in which it describes "new departmental and naval processes" that support the DoD policy of the identification of total costs of ownership (DoN, 2014, p. 6). Specifically, the guidebook assists the DoN and its organizations in developing, understanding, and applying the TOC requirements of the DoD.

The DoN outlines the importance of TOC: "As the DoD (and Navy) funding remains constant or declines, and as Navy's purchasing power declines as a result, increasing the decision weight priority for alternatives that can mitigate and reduce TOC becomes our clearest path to a capable an optimally affordable Fleet" (DoN, 2014, p. 8). For this reason, we focus our model on TOC instead of a standard life-cycle cost.

Risk and Uncertainty

A key point that we need to understand in cost estimating is that the future is uncertain. Therefore, an essential pillar in developing a defensible and credible cost estimate is ensuring that risk and uncertainty are incorporated. A cost estimate can be severely affected by factors such as technological maturity, schedule slips, software requirements, or any other unforeseen event (Mislick & Nussbaum, 2015). Unknown factors make any "point estimate" or any exact answer extraordinarily unlikely (Mislick & Nussbaum, 2015). A more accurate estimate uses a central tendency centered on the original point estimate and a range both higher and lower to define the bounds of the estimate.

Though similar and related, risk and uncertainty are not synonymous. In the simplest terms, *risk* is the "probability" of the occurrence of a negative or unfavorable event, while *uncertainty* is the lack of certainty, or the realization that definitively knowing the outcome of any future event is completely impossible (Mislick & Nussbaum, 2015). Unlike with risk, with uncertainty we are not able to predict the possibility of any future outcome. In Johnathan Mun's book, *Readings in Certified Quantitative Risk Management (CQRM),* he states,

> The concepts of risk and uncertainty are related but different. Uncertainty involves variables that are unknown and changing, but uncertainty will become known and resolved through the passage of time, events, and action. Risk is something one bears and is the outcome of uncertainty. Sometimes risk may remain constant while uncertainty increases over time. (Mun, 2015, p. 28)

A good way to think about risk and uncertainty is to imagine going on a sky diving trip with a friend. As the plane takes off, you and your friend realize that there is only one parachute and that the parachute is looking like it is somewhat past its service life. Your friend, being slightly more adventurous than you, decides to grab the parachute and take the jump. Both you and your friend share the same level of uncertainty about whether the parachute will open and whether your friend will live to tell the story. However, only your friend will assume the risk of jumping out of the plane and falling to his death.

Electro-Optical Infrared Sensors

Electro-optics (EO) are the field systems that convert electrons into photons (Driggers & Nichols, 2012). These systems are designed to respond to wavelengths within the 0.4–0.07 micrometer wavelength (Driggers & Nichols, 2012). They deliver images that are analogous to human vision; some EO systems are even capable of processing the near or short infrared spectral region (Driggers & Nichols, 2012). Figure 2 shows the basic components of an EO/IR sensor system.

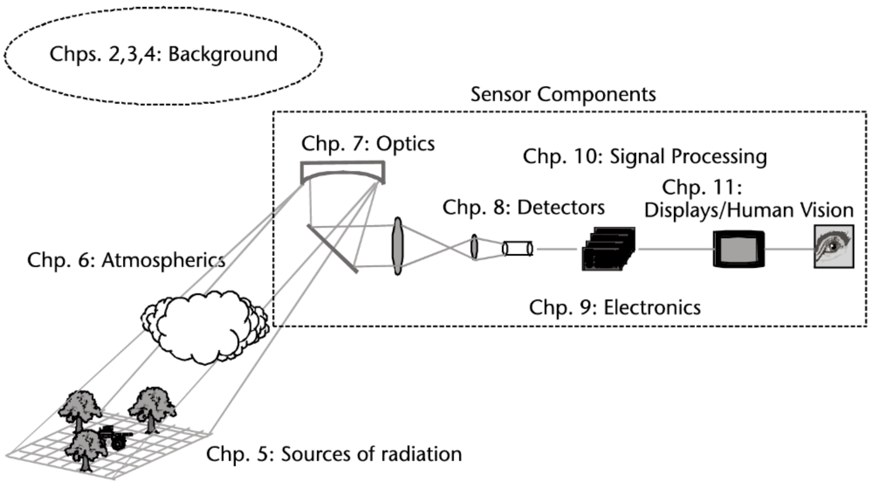

Figure 2. EO and IR Sensors (Driggers & Nichols, 2012)

The term *target* is used to describe the desired image that we are looking for with an EO sensor. The signal from a target usually has a large reflective component typically in the EO wavelength band. The target is provided this reflective component by moonlight, starlight, sunlight, or any artificial light source (Driggers & Nichols, 2012). The light sources reflecting off of the background and the target are known as external radiation. Radiation reflected by targets and background does not go directly to the EO sensor. The reflected radiation must first transition through the atmosphere, where it experiences scattering, before being processed by the EO sensor (Driggers & Nichols, 2012). Scattering is a phenomenon where particles in the atmosphere such as smoke, smog, or mist interfere with the reflection. Once the reflected radiation meets the EO sensor, it is passed through the sensing element, which could be detectors, tubes, or image intensifiers (low light situations; Driggers & Nichols, 2012). Next, the output of the sensor element is digested by the electronics and sent to a human interface for the operator (human) to gather some information from the process. This information could take a myriad of shapes such as detection, recognition, or identification of targets such as a warship. In short, EO sensors are essentially products of the light reflected from the scene (Driggers & Nichols, 2012). Figure 3 represents a typical EO sensor scenario.

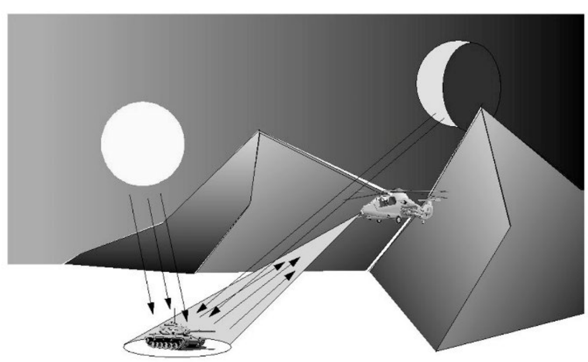

Figure 3. Typical EO Sensor Scenario (Driggers & Nichols, 2012)

Infrared is able to digest the spectral region from 0.7 to 14 micrometer wavelengths and is divided into four subregions:

> The near-infrared (NIR) region is from 0.7 to 1.1 mm, the short-wave infrared (SWIR) region is from 1.1 to 3 mm, the midwave infrared (MWIR) region is from 3 to 5 mm, and the long-wave infrared (LWIR) region is from 8 to 14 mm. Infrared is primarily used in night operations. (Driggers & Nichols, 2012)

The science of infrared is based on the science supporting Planck's law, which states that all bodies above the temperature of absolute zero emit electromagnetic radiation. The electromagnetic radiation is exploited to uncover the electromagnetic signatures given off that do not correlate to the wavelengths visible by the human eye or EO sensors.

> As the temperature of the object gets hotter, the peak wavelength moves to shorter wavelengths so that at very hot temperatures the radiation is perceived by the eye as light. The emissive surface characteristics of the hot object determine the spectral emission weighting of the radiation. The radiation emitted travels through the atmosphere, where it will then meet the aperture of the sensor. (Driggers & Nichols, 2012, p. 7)

EO/IR Sensors on Surface Ships

Before the advent of EO, direct optics were a commander's main resource in support of tactical decision-making. Binoculars, stadimeters, and periscopes were the keys to situational awareness and obtaining fire control solutions for torpedoes and gun engagements (Davidson, 2015). With the invention of EO, warfighters are no longer restricted to the limitations of the human eye. The application of using television cameras and the discovery of light-sensitive semiconductor materials allow images to be converted into electrical signals that are fed into displays for humans to process information. EO sensors paired with the ability of infrared detection allow warfighters to discern a target in the most vast and unlit environments (Davidson, 2015).

In Stefan Nitschke's (2007) article, "New Generation Naval Electro Optics," he states, "Electro Optical/Infrared technology is an invaluable aid for the 21st century battlespace arena. It provides surface warships, submarines, and maritime aviation operating in the varying naval environment with extensive image gathering, navigational, and targeting capabilities" (p. 87). The constant advances in EO/IR systems have led to the development of sensors with integral lasers that are used to measure distances with extreme accuracy and are a fraction of the size of the range finders of legacy ships (Davidson, 2015). In the report given by the Institute of Defense Analyses entitled *A Tutorial on Electro-Optical/Infrared (EO/IR) Theory and Systems*, it is stated that "the performance of an EO/IR sensor depends on the optics, detector, display, target-background contrast, and the intensity of the illumination source" (Koretsky et al., 2013, p. 5).

Technological advances have emphasized the importance of the opportunity and the necessity to reinvest in the newest technologies and systems. These advances in technology will drive future EO/IR systems purchases by the DoD. These system acquisitions will require credible and reliable cost estimations to ensure that the DoD manages its budget effectively. With the complexity and uniqueness of EO/IR systems, an efficient cost estimation model is needed to account for all life-cycle costs. The additional aspect of uncertainty should also be considered in the estimation. The cost estimation model we are proposing considers TOCs and uncertainty for the acquisition of EO/IR systems for U.S. Navy surface ships. This model will serve as a proof of concept to help future DoD decision-makers understand the cost associated with EO/IR systems so they can make strategic investments.

Model Application and Results

The inputs for this model were sourced from the program components lists provided by the research sponsor, NAVSEA, for the (generic or specific) EO/IR sensor.

The cost estimates for this model were sourced using rough of order magnitude (ROM) values. The values fluctuate slightly between the five different systems to illustrate the differing systems' costs between contract estimates. These values were explicitly created to further the proof of concept of the model and, therefore, do not necessarily reflect the accurate value for component, part, or salary of support team members. However, these values do show how the simulation can provide an estimate of an entire system and demonstrate how much impact each variable will have on the overall life-cycle cost estimate. In this example, we simulate a cost estimate of an EO/IR system being implemented on 55 platforms with a service life of 20 years.

Model Inputs and Data

The Total Ownership Cost is calculated by summing the initial Acquisition Cost, Operation Cost, Maintenance Cost, and Disposal Cost. The model accounts for these four phases, beginning with the Acquisition Cost. In a real-world scenario, a cost analyst would utilize the technical specifications given by the program office to enter the required values. From the technical specifications, the analyst would insert two crucial metrics. The first is the number of platforms that will receive the system, and the second is the number of components required in each system. Since real-world data are not available for this notional model, this research uses the ROM system to fill in the blanks. In Systems A–E, the model uses 55 as the number of platforms.

The Acquisition Unit Cost accounts for all of the planning, design, and construction costs to make each component possible. The model also considers the estimated cost for a replacement component. The estimated cost for replacement parts should be considerably lower than the initial Acquisition Cost because developed technology will only need to be reproduced instead of being redeveloped. The Operational Cost per year is an estimate of the amount required to run the component for a year. The Operation Cost includes equipment depreciation, costs of the energy source used to power the component, cost of damage due to use, and so on. Similarly, the Maintenance cost is an estimate based on the amount required to maintain the equipment every year. Figure 4 shows the categories for Acquisition and Operation and Maintenance Costs.

Once the cost analyst has entered the acquisition cost for the hardware and software required for the system, the analyst must remember to account for the human element. The analyst will need to ensure that the cost required to pay for those responsible for the design, logistics, management, and technology are represented in the model. This model uses the Acquisition Cost column to record the initial salary of each job. The Number of Platforms column describes the number of teams required for each system. The Number of Units per System column describes the number of people required on each team. The Operation Cost column is used to annotate the continuing salary for the human element for the remainder of the program's life. Essentially, this is how an analyst would annotate a recurring salary payment. Throughout the five systems, the number of people per team and the amount requested per salary will vary. Figure 5 shows an example of where salaries are inputted into the model.

All of the costs mentioned previously are recurring costs, costs that will be multiplied by the number of years of the program and summed to get the total cost. Analysts must be sure not to forget to account for all of the one-time costs associated with the origins of any project. Figure 6 shows the list of nonrecurring costs accounted for in the model.

Finally, we account for all of the disposal and end-of-life-cycle costs that will also be one-time costs. Figure 7 shows the nonrecurring end-of-life-cycle costs.

Categories	Number of Units per System	Number of Platforms	Acquisition Cost (Unit)	%	Operational Costs (Unit) Per Year	%	Maintenance (Unit) Per Year	%	Replacement (Unit) Per Year	%	Total Acquisition Cost	%	Total Annual O&M	%
Grand Total			##############		**$217.00**		**$1,164.00**		**$42,391.00**		**$45,863,500.00**		**$15,308,443.00**	
Narrow-Medium Field of View (NFOV) Sensors	**43**	**935**	**$7,110.00**	**0.2%**	**$73.00**	**33.6%**	**$594.00**	**51.0%**	**$4,880.00**	**11.5%**	**$960,850.00**	**2.1%**	**$753,720.00**	**4.9%**
NF-DIR (NFOV Director)	2	55	$400.00	0.0%	$5.00	2.3%	$30.00	2.6%	$300.00	0.7%	$44,000.00	0.1%	$36,850.00	0.2%
NF-TIS (Thermal Imaging Sensor) - TIS #1	3	55	$350.00	0.0%	$6.00	2.8%	$23.00	2.0%	$150.00	0.4%	$57,750.00	0.1%	$29,535.00	0.2%
NF-TIS (Thermal Imaging Sensor) - TIS #2	2	55	$460.00	0.0%	$7.00	3.2%	$25.00	2.1%	$300.00	0.7%	$50,600.00	0.1%	$36,520.00	0.2%
NF-EOS (Electro-Optic Sensor) - EOS #1	3	55	$230.00	0.0%	$5.00	2.3%	$34.00	2.9%	$200.00	0.5%	$37,950.00	0.1%	$39,435.00	0.3%
NF-EOS (Electro-Optic Sensor) - EOS #2	3	55	$340.00	0.0%	$3.00	1.4%	$45.00	3.9%	$220.00	0.5%	$56,100.00	0.1%	$44,220.00	0.3%
NF-EOS (Electro-Optic Sensor) - EOS #3	3	55	$450.00	0.0%	$2.00	0.9%	$56.00	4.8%	$250.00	0.6%	$74,250.00	0.2%	$50,820.00	0.3%
NF-LRF (Laser Rangefinder)	2	55	$560.00	0.0%	$3.00	1.4%	$45.00	3.9%	$560.00	1.3%	$61,600.00	0.1%	$66,880.00	0.4%
NF-LDR (Laser Designator/Rangefinder)	2	55	$430.00	0.0%	$4.00	1.8%	$34.00	2.9%	$220.00	0.5%	$47,300.00	0.1%	$28,380.00	0.2%
NF-LDRFI (Laser Designator/Rangefinder/Illuminator)	2	55	$460.00	0.0%	$5.00	2.3%	$23.00	2.0%	$140.00	0.3%	$50,600.00	0.1%	$18,480.00	0.1%
NF-LP (Laser Pointer)	5	55	$450.00	0.0%	$6.00	2.8%	$45.00	3.9%	$270.00	0.6%	$123,750.00	0.3%	$88,275.00	0.6%
NF-LOI (Laser Optical/Ocular Interrupter)	1	55	$560.00	0.0%	$6.00	2.8%	$65.00	5.6%	$320.00	0.8%	$30,800.00	0.1%	$21,505.00	0.1%
NF-LI (Laser Illuminator)	3	55	$430.00	0.0%	$3.00	1.4%	$43.00	3.7%	$540.00	1.3%	$70,950.00	0.2%	$96,690.00	0.6%
NF-IRU (Inertial Reference Unit)	2	55	$430.00	0.0%	$3.00	1.4%	$34.00	2.9%	$450.00	1.1%	$47,300.00	0.1%	$53,570.00	0.3%
NF-BSM (Boresight Module)	1	55	$230.00	0.0%	$3.00	1.4%	$23.00	2.0%	$220.00	0.5%	$12,650.00	0.0%	$13,530.00	0.1%
NF-EU (Electronics Unit)	2	55	$670.00	0.0%	$3.00	1.4%	$23.00	2.0%	$330.00	0.8%	$73,700.00	0.2%	$39,160.00	0.3%
Ancillary Material (cabling, mounting hardware, etc.)	3	55	$430.00	0.0%	$3.00	1.4%	$23.00	2.0%	$200.00	0.5%	$70,950.00	0.2%	$37,290.00	0.2%
Other: __________	4	55	$230.00	0.0%	$6.00	2.8%	$23.00	2.0%	$210.00	0.5%	$50,600.00	0.1%	$52,580.00	0.3%
Wide Field of View (WFOV) Sensors	**23**	**385**	**$25,600.00**	**0.6%**	**$24.00**	**11.1%**	**$245.00**	**21.0%**	**$14,200.00**	**33.5%**	**$4,240,500.00**	**9.2%**	**$2,487,100.00**	**16.2%**
WF-DIR (Director)	2	55	$4,500.00	0.1%	$4.00	1.8%	$35.00	3.0%	$2,000.00	4.7%	$495,000.00	1.1%	$224,290.00	1.5%
WF-TIS (Thermal Imaging Sensor)	3	55	$3,500.00	0.1%	$3.00	1.4%	$43.00	3.7%	$1,200.00	2.8%	$577,500.00	1.3%	$205,590.00	1.3%
WF-EOS (Electro-Optic Sensor)	1	55	$4,500.00	0.1%	$2.00	0.9%	$23.00	2.0%	$3,200.00	7.5%	$247,500.00	0.5%	$177,375.00	1.2%
WF-IRU (Inertial Reference Unit)	2	55	$5,300.00	0.1%	$6.00	2.8%	$22.00	1.9%	$2,300.00	5.4%	$583,000.00	1.3%	$256,080.00	1.7%
WF-EU (Electronics Unit)	4	55	$1,000.00	0.0%	$3.00	1.4%	$55.00	4.7%	$1,000.00	2.4%	$220,000.00	0.5%	$232,760.00	1.5%
Ancillary Material (cabling, mounting hardware, etc.)	5	55	$2,300.00	0.1%	$2.00	0.9%	$45.00	3.9%	$2,100.00	5.0%	$632,500.00	1.4%	$590,425.00	3.9%
Other: __________	6	55	$4,500.00	0.1%	$4.00	1.8%	$22.00	1.9%	$2,400.00	5.7%	$1,485,000.00	3.2%	$800,580.00	5.2%
EO/IR Sensor Manager (ESM)	**17**	**330**	**$1,910.00**	**0.0%**	**$45.00**	**20.7%**	**$124.00**	**10.7%**	**$1,400.00**	**3.3%**	**$282,150.00**	**0.6%**	**$275,990.00**	**1.8%**
Processing Equipment	3	55	$340.00	0.0%	$4.00	1.8%	$15.00	1.3%	$150.00	0.4%	$56,100.00	0.1%	$27,885.00	0.2%
Processing Software	4	55	$230.00	0.0%	$6.00	2.8%	$23.00	2.0%	$230.00	0.5%	$50,600.00	0.1%	$56,980.00	0.4%
Recording Equipment	5	55	$240.00	0.0%	$5.00	2.3%	$40.00	3.4%	$430.00	1.0%	$66,000.00	0.1%	$130,625.00	0.9%
Docking Station Equipment	2	55	$350.00	0.0%	$5.00	2.3%	$21.00	1.8%	$230.00	0.5%	$38,500.00	0.1%	$28,160.00	0.2%
Ancillary Material (video converters, encoders, ethernet switches, racks, cabling, etc.)	1	55	$210.00	0.0%	$12.00	5.5%	$10.00	0.9%	$210.00	0.5%	$11,550.00	0.0%	$12,760.00	0.1%
Other: __________	2	55	$540.00	0.0%	$13.00	6.0%	$15.00	1.3%	$150.00	0.4%	$59,400.00	0.1%	$19,580.00	0.1%

Figure 4. Categories for Acquisition and Operation and Maintenance Costs

Categories	Number of Units per System	Number of Platforms	Acquisition Cost (Unit)	%	Operational Costs (Unit) Per Year	%
Grand Total			$4,202,920.00		$1,907,716.00	
Manpower and Personnel	30	6	$321,000.00	7.6%	$240,000.00	12.6%
Program Management Office Team	8	1	$80,000.00	1.9%	$80,000.00	4.2%
Manning and military occupational series training	6	1	$40,000.00	1.0%	$40,000.00	2.1%
Depot Activation	5	1	$60,000.00	1.4%	$55,000.00	2.9%
Software Sustainment	4	1	$40,000.00	1.0%	$35,000.00	1.8%
Initial Fielding Support	4	1	$56,000.00	1.3%	$30,000.00	1.6%
Other: __________	3	1	$45,000.00	1.1%	$0.00	0.0%

Figure 5. Manpower and Personnel Salary Input Section

Nonrecurring Acquisition and End of Lifecycle Costs	Total	%
Acquisition and Procurement	$467,800.00	
Bid Specifications Development	$10,000.00	2.1%
Proposal Evaluation	$2,000.00	0.4%
Data Collection	$40,000.00	8.6%
Data Analysis	$12,000.00	2.6%
Contracts Development	$3,000.00	0.6%
Program Planning	$4,000.00	0.9%
Hardware Purchases	$10,000.00	2.1%
Personal Computers	$10,000.00	2.1%
Peripherals	$15,000.00	3.2%
Storage	$60,000.00	12.8%
Networking	$23,000.00	4.9%
Related Equipment	$35,000.00	7.5%
Other costs	$10,000.00	2.1%
Administrative Cost	$34,000.00	7.3%
Asset Management	$15,000.00	3.2%
Overseeing Contractor Services	$4,000.00	0.9%
In-House Training for Staff	$5,000.00	1.1%
Product Maintenance	$2,000.00	0.4%
Help Desk Support	$10,000.00	2.1%
IT Support for Database Management	$20,000.00	4.3%
Network Management Support	$42,000.00	9.0%
Software Upgrades	$12,000.00	2.6%
Hardware Upgrades	$2,100.00	0.4%
Internet and Network Access Cost	$14,000.00	3.0%
Furniture and Equipment	$10,000.00	2.1%
Energy Costs	$3,400.00	0.7%
Informal Training	$4,300.00	0.9%
Downtime Support and Outsource	$24,000.00	5.1%
Other costs	$32,000.00	6.8%

Figure 6. Nonrecurring Acquisition and Procurement Costs

Nonrecurring End of Lifecycle Costs	Total	%
End of Lifecycle	$109,000.00	
Administrative Cost	$40,000.00	36.7%
Asset Management	$20,000.00	18.3%
Vendor Contract Procurement	$4,000.00	3.7%
Staging, Sanitizing, Testing	$10,000.00	9.2%
Follow-Up Support	$10,000.00	9.2%
Recycling and Disposal Fees	$5,000.00	4.6%
Value of Sold Products and Materials	$20,000.00	18.3%

Figure 7. Nonrecurring End-of-Life-Cycle Costs

Results and Analysis

Once the data have been manually inputted into the model, the cost analyst can utilize the multitude of charts, graphs, and tools to analyze the TOC of the systems.

These graphs, charts, and tools allow the analyst to compare multiple cost estimates over the entire life of the system at the same time. This research analyzed the following tables and charts to highlight the functionality of the model: Total Net Life-Cycle Cost, Present Value of Discounted Total Net Life-Cycle Cost, Cash Total Net Cost at 5-Year Increments, Total Ownership Cost Forecast Statistic Table, Simulation Probability Charts, and the Tornado Analysis.

Total Net Life-Cycle Costs and Cash Total Net Cost at 5-Year Increments

Figure 8 shows the Total Net Life-Cycle Cost for all five systems over a span of 30 years. The table and graph show the cost for the systems broken down into 5-year estimates. The model projects the life span of the system past the 20-year expected service life. This extension allows the cost analyst to consider cost out to the 30-year point, as many DoD systems tend to exceed their expected service lives. However, the 5-year increments also allow a decision-maker to understand the total net cost of disposing of a system before its 20-year service life. The side-by-side comparison enables a decision-maker to graphically perceive the potential differences between the cost estimates of the multiple systems. When choosing between alternatives, Figure 8 can be a beneficial decision aid.

In the analysis table in Figure 8, the 20-Year Cash Total Net Cost ranges from $554 million (System C) to $771 million (System D). If cost were the determining factor, a decision-maker could quickly determine that System C should be selected. To make the comparison even easier to analyze, Figure 9 provides a side-by-side comparison of all five systems at each of the 5-year increments. Looking at the 20-Year Total Net Cost Graph, it can be clearly seen that System C has the lowest Total Net Cost.

Cost analysis should only be one part of the picture when it comes to making the correct strategic decision. For example, each system's specifications and capabilities—its military benefits or returns—should also be computed, such that each system will have its own return on investment (ROI). Nonetheless, the major component of any ROI analysis is cost. The focus of this research is to determine this cost computation. Another aspect of TOC analysis is its use in cost mitigation, cost savings, and cost deferred, which constitute another point of view of cost-based decision analytics.

Analysis Period/Type	System A	System B	System C	System D	System E
5 Year Cash Total Net Cost	$192,078,759.39	$199,950,888.59	$158,074,801.16	$206,656,401.49	$161,982,378.15
10 Year Cash Total Net Cost	$348,972,742.05	$366,909,094.54	$280,489,136.93	$381,039,284.24	$291,014,854.14
15 Year Cash Total Net Cost	$517,992,119.86	$546,770,499.13	$412,364,142.71	$568,899,174.37	$430,019,476.51
20 Year Cash Total Net Cost	$700,073,991.93	$740,532,313.22	$554,430,976.94	$771,277,628.99	$579,766,932.65
25 Year Cash Total Net Cost	$896,227,880.11	$949,268,816.09	$707,477,304.94	$989,296,700.88	$741,087,471.77
30 Year Cash Total Net Cost	$1,107,541,326.15	$1,174,137,311.67	$872,351,665.95	$1,224,165,159.57	$914,875,508.07

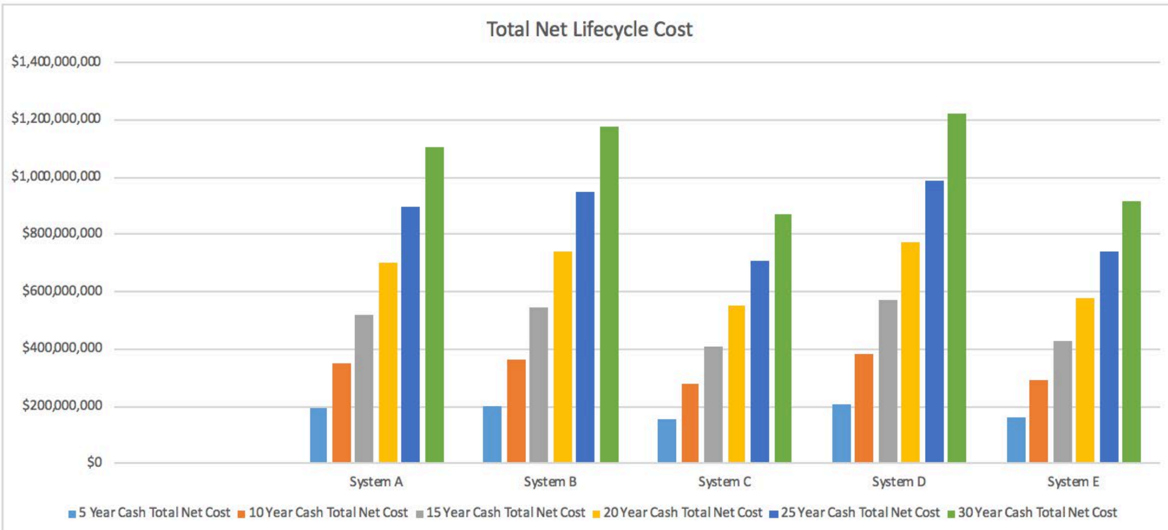

Figure 8. Total Net Life-Cycle Cost

Present Value of Discounted Total Net Life-Cycle Cost

While Figure 10 shows the Total Net Life-Cycle Cost, it does not include consideration of economic factors such as the time value of money and uncertainty risk. To mitigate these factors in the model, Figure 10 incorporates a Net Present Value Life-Cycle Cost estimate using a discount rate of 3% (i.e., the government's cost of money, where we can use 20-year and 30-year Treasury bond yields as proxies). In the analysis table in Figure 10, the 20-Year Total Net Cost ranges from $554 million (System C) to $771 million (System D), but when looking at the more realistic Present Value Discounted Net Life-Cycle Cost, the range between Systems C and D decreases to $418 million and $577 million. Not only do the estimates for the minimum and maximum values decrease when the discount factor is applied, but the delta of the range between the values also shrinks by $57.8 million. Incorporating the discount rate into the model gives the decision-maker a complete analysis of the costs. Specifically, it shows the value of the lifetime cost of a system in today's money, thereby putting all systems with different life cycles and life spans on an equal footing with each other for a better cost comparison.

Analysis Period/Type	System A	System B	System C	System D	System E
5 Year Cash Cost in Present Values	$179,704,285.34	$186,783,594.12	$148,416,499.73	$192,904,219.83	$151,802,725.35
10 Year Cash Cost in Present Values	$303,544,126.37	$318,568,174.68	$245,037,964.84	$330,549,870.97	$253,648,577.73
15 Year Cash Cost in Present Values	$418,626,211.89	$441,033,105.19	$334,826,703.72	$458,461,345.77	$348,292,207.24
20 Year Cash Cost in Present Values	$525,569,818.93	$554,837,402.90	$418,265,845.06	$577,326,978.99	$436,242,875.34
25 Year Cash Cost in Present Values	$624,950,442.22	$660,593,492.07	$495,804,364.31	$687,786,438.92	$517,973,842.03
30 Year Cash Cost in Present Values	$717,302,888.41	$758,870,497.06	$567,859,497.04	$790,434,167.10	$593,924,909.86

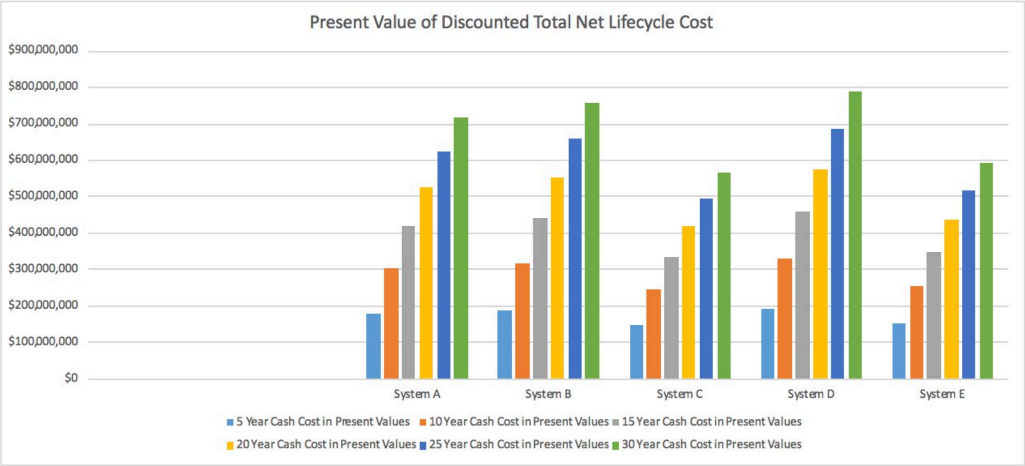

Figure 9. Present Value of Discounted Net Life-Cycle Cost

Forecast Statistics Table - TOC Model

Cell	Total Lifetime Cost for System A (20 Years)	Total Lifetime Cost for System B (25 Years)	Total Lifetime Cost for System C (20 Years)	Total Lifetime Cost for System D (10 Years)	Total Lifetime Cost for System E (15 Years)	Total PV Lifetime Cost for System A (20 Years)	Total PV Lifetime Cost for System B (25 Years)	Total PV Lifetime Cost for System C (20 Years)	Total PV Lifetime Cost for System D (10 Years)	Total PV Lifetime Cost for System E (15 Years)
Name	S42	S42	S42	S42	S42	S43	S43	S43	S43	S43
Number of Datapoints	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Mean	$700,128,499.57	$740,532,963.43	$554,392,425.60	$771,338,025.77	$579,775,293.62	$525,611,374.46	$554,838,179.48	$418,238,633.17	$577,371,510.62	$436,248,097.08
Median	$700,141,006.85	$740,535,580.46	$554,384,371.67	$771,364,875.28	$579,759,448.54	$525,610,342.27	$554,835,058.62	$418,245,556.21	$577,382,472.47	$436,233,772.78
Standard Deviation	$6,257,100.80	$5,845,829.50	$4,467,888.27	$7,611,267.45	$4,630,641.37	$4,594,559.43	$4,292,302.35	$3,283,147.51	$5,583,858.78	$3,400,790.39
Coefficient of Variation	0.89%	0.79%	0.81%	0.99%	0.80%	0.87%	0.77%	0.78%	0.97%	0.78%
Maximum	$721,408,465.72	$760,794,257.46	$568,380,140.14	$792,265,719.52	$595,514,481.66	$541,361,082.89	$569,528,468.16	$428,545,963.69	$592,883,001.86	$447,659,644.97
Minimum	$679,850,811.09	$719,523,385.66	$540,339,232.67	$748,640,296.95	$564,025,304.82	$510,709,204.65	$539,393,598.53	$407,787,597.45	$560,676,945.01	$424,678,356.35
Range	$41,557,654.63	$41,270,871.80	$28,040,907.47	$43,625,422.57	$31,489,176.84	$30,651,878.24	$30,134,869.63	$20,758,366.24	$32,206,056.85	$22,981,288.62
Skewness	-0.0032	-0.0042	-0.0148	-0.0026	0.0087	-0.0023	-0.0028	-0.0144	-0.0026	0.0091
Kurtosis	-0.4009	-0.2633	-0.3281	-0.5003	-0.3088	-0.3995	-0.2616	-0.3249	-0.4998	-0.3093
25% Percentile	$695,719,253.67	$736,446,455.02	$551,284,478.55	$765,796,106.33	$576,509,002.84	$522,378,543.35	$551,839,791.47	$415,958,053.49	$573,311,007.82	$433,851,693.64
75% Percentile	$704,532,335.37	$744,600,466.38	$557,526,620.08	$776,618,455.92	$582,946,797.53	$528,851,703.11	$557,822,109.37	$420,545,180.57	$581,253,957.83	$438,577,466.99
Error Precision at 95%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
5% Percentile	$689,682,929.25	$730,959,587.63	$546,946,259.66	$758,769,396.90	$572,144,154.21	$517,951,178.33	$547,793,197.77	$412,759,859.00	$568,154,901.40	$430,640,138.12
10% Percentile	$691,747,640.51	$732,794,898.81	$548,533,001.64	$761,225,549.84	$573,689,454.88	$519,468,239.36	$549,181,125.39	$413,946,175.50	$569,990,913.70	$431,776,478.59
20% Percentile	$694,602,871.32	$735,367,935.12	$550,510,692.26	$764,515,420.38	$575,778,821.69	$521,563,700.07	$551,045,883.57	$415,386,396.82	$572,378,313.33	$433,315,521.79
30% Percentile	$696,704,619.98	$737,452,394.84	$551,979,547.59	$767,095,731.78	$577,226,617.51	$523,096,629.77	$552,578,355.90	$416,460,293.34	$574,253,331.14	$434,382,267.57
40% Percentile	$698,493,546.06	$739,011,582.52	$553,233,344.80	$769,309,931.15	$578,543,844.11	$524,394,394.43	$553,713,041.68	$417,379,609.28	$575,880,312.72	$435,341,189.38
50% Percentile	$700,141,006.85	$740,535,580.46	$554,384,371.67	$771,364,875.28	$579,759,448.54	$525,610,342.27	$554,835,058.62	$418,245,556.21	$577,382,472.47	$436,233,772.78
60% Percentile	$701,843,734.05	$742,099,383.62	$555,579,609.61	$773,403,235.14	$580,989,590.40	$526,887,691.99	$555,979,070.58	$419,103,492.37	$578,891,015.17	$437,139,948.28
70% Percentile	$703,601,587.76	$743,714,003.76	$556,847,632.09	$775,491,755.81	$582,222,603.44	$528,161,141.23	$557,172,586.27	$420,044,672.96	$580,410,041.35	$438,057,186.64
80% Percentile	$705,593,527.64	$745,597,406.41	$558,265,766.20	$778,104,442.05	$583,805,528.28	$529,626,241.70	$558,543,630.43	$421,090,371.98	$582,332,648.63	$439,205,172.05
90% Percentile	$708,345,917.64	$748,088,346.78	$560,256,120.90	$781,498,101.24	$585,875,474.23	$531,647,003.55	$560,385,422.61	$422,546,755.03	$584,823,963.64	$440,711,757.31
95% Percentile	$710,307,855.95	$750,205,085.99	$561,774,937.44	$784,001,472.92	$587,517,826.61	$533,116,251.14	$561,929,004.53	$423,658,279.36	$586,692,336.33	$441,943,293.84
99% Percentile	$713,991,274.06	$753,529,283.26	$564,370,570.06	$787,642,529.91	$589,971,521.84	$535,763,348.04	$564,406,101.50	$425,570,623.73	$589,320,737.18	$443,747,515.40

Figure 10. Total Ownership Cost Forecast Statistics Table

Stochastic Total Ownership Cost Forecast Statistics Table

The Forecast Statistics Table, shown in Figure 10, summarizes the distribution of the Total Life-Cycle Cost and the Total Present Value (PV) Life-Cycle Cost for the five systems at different points in the life cycle of the system based on risk-based simulation and stochastic TOC models used to value the alternative cost paths. Figure 10 highlights the outcomes of running 10,000 trials using the Monte Carlo Risk Simulator. The takeaways from this figure are the mean, standard deviation, maximum, minimum, and range data points. These metrics provide a decision-maker with a better understanding of how uncertainty can affect the Total Life-Cycle Cost and Total PV Life-Cycle Cost of a system.

System C looks at the cost over a 20-year life span. Using the Monte Carlo Risk Simulator, the maximum Total Life-Cycle Cost of the system is $568 million, while the minimum is $540 million. These values represent the worst- and best-case scenarios, respectively. The simulations produced a Total Life-Cycle Cost range of $28 million and a mean value of $554 million. The standard deviation of Total Life-Cycle Cost simulations for System C is $4.5 million, meaning that 68.2% of the estimates will fall within ±$4.5 million of the mean if the distribution is somewhat normally distributed. Figure 10 also shows the same metrics for the PV of the Total Life-Cycle Cost for all systems.

Simulation Probability Charts

A simulation probability chart is a histogram or frequency distribution of all of the total life-cycle costs of a system based on 10,000 simulation runs or trials. The probability chart produces a graphic representation of the information contained in the forecast statistics table. Figure 11 shows the frequency distribution of the total life-cycle cost for System A over a 20-year life. In the figure, System A’s frequency distribution is shaped as a roughly symmetrical bell curve centered on a mean of $700 million. Using this chart, an analyst could confidently conclude that the total life-cycle cost for this system will fall between $679 million and $721 million. The figure also shows the 90% confidence interval of the TOC to be between $690 million and $710 million. This means that there is a 90% chance that given all uncertainties that exist in each of the input assumptions, the 20-year total lifetime cost for System A will be between these two values. In addition, there is only a 5% chance that the cost can be below $690 million and a 5% chance it can exceed $710 million. Figure 12 uses the same frequency distribution over the same 20-year system life as in Figure 11; however, Figure 12 takes into account the discount rate to better illustrate the economic factor of inflation over time. Similarly, the 90% confidence interval in present values is between $518 million and $533 million.

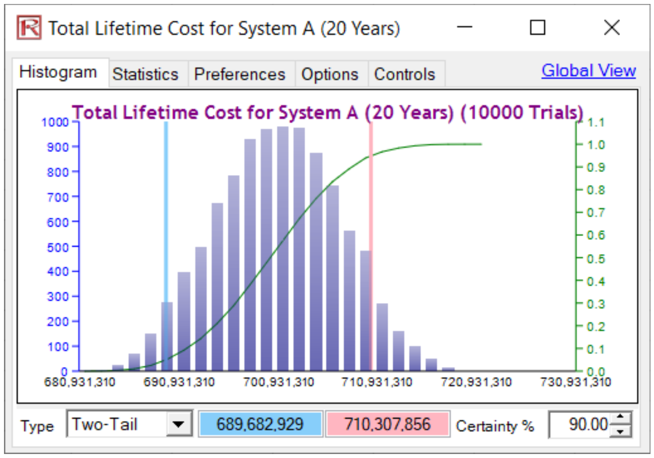

Figure 11. Total Life-Cycle Cost for System A (20 Years)

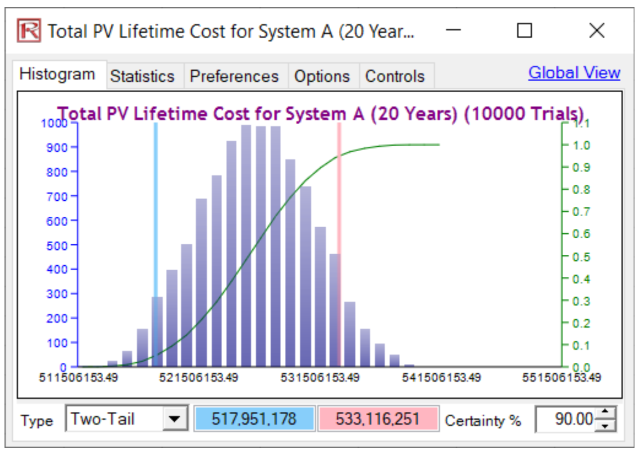

Figure 12. Total Present Value Life-Cycle Cost for System A (20 Years)

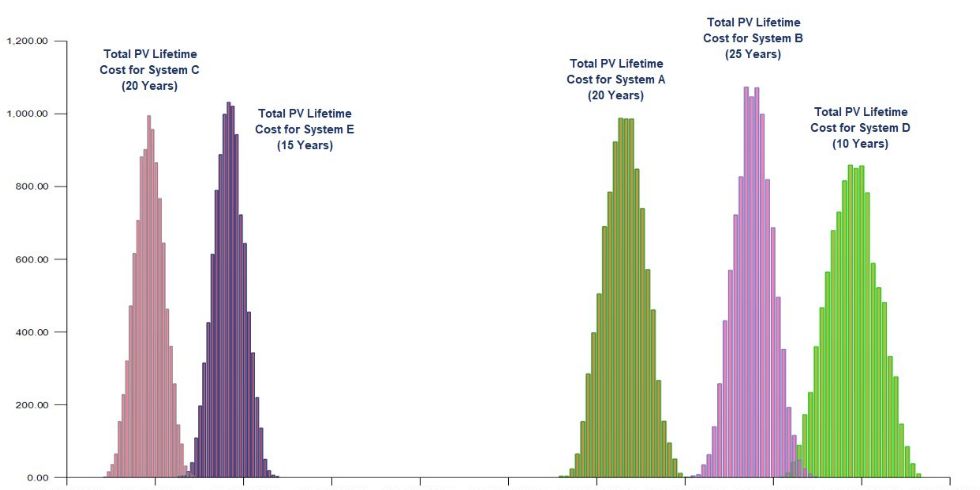

Figure 13. Probability Distribution Cost Overlay of the Five Systems

Tornado Analysis

The tornado analysis chart gives decision-makers the ability to break down which variables have the most significant impact on the overall outcome of the simulation. By focusing on the top critical factors, decision-makers can focus on cost reduction techniques in places that will have the most effect. The tornado analysis allows the decision-makers to adjust how many critical variables to display. Figure 14 shows the tornado analysis chart detailing the 20 most impactful variables on the TOC model. Based on the notional cost values inputted into the model, the number of platforms containing that ancillary material is the most critical factor.

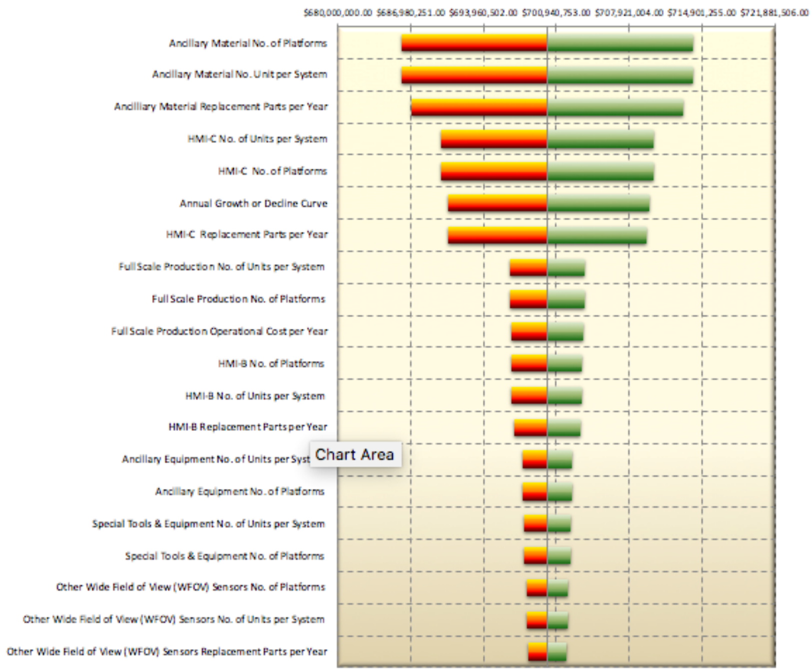

Figure 14. Tornado Analysis

Conclusion

Key Conclusions

The purpose of this report was to develop a total ownership with life-cycle cost model while considering uncertainty for EO/IR sensors on U.S. Navy surface ships. Through the examination of TOC modeling over the life cycle of EO/IR sensors, including the inception phase of acquisition costs, followed by annual O&M expenses, along with a final set of Disposition Costs, we were able to develop a useful model for TOC estimations. Using Monte Carlo risk simulation, our model accounts for risk and uncertainty when producing cost estimates. The model also provides analysts with a more realistic estimate by factoring in economic theory, such as economic growth, annual discount rate, and inflation.

As discussed, the cost analysis models presented should be only one part of a larger picture when it comes to making the correct strategic investment decisions. For example, each system's specifications, capabilities, military benefits, or financial and noneconomic returns should also be computed, such that each system will have its own return on investment (ROI). Nonetheless, the major component of any ROI analysis is cost. The focus of this current research is to determine a suitable method to compute critical life-cycle cost. Another use of TOC modeling is in determining cost mitigation, cost savings, and cost deferred, that is, what the cost differential might be or an Analysis of Alternatives, which constitutes another point of view of cost-based decision analytics. The model allows decision-makers to have better decision analytics of the costs of surface EO/IR sensors. These analytics can be used in subsequent cost comparisons between different sensor platforms, Analysis of Alternatives, and portfolio allocation of resources. Specifically, Program Executive Office Integrated Warfare Systems (PEO IWS) and NAVSEA can utilize this model in future program cost estimation development. Since the model is tailorable to different sensor configurations, it can provide clarity in analyzing different and complex alternative sensor systems to develop and outfit the fleet. The results of this model give decision-makers a more effective metric to analyze TOC under uncertainty; this can reduce cost overflow and prevent budget overruns. Ultimately, the model allows leadership to make more informed decisions in the DoD acquisition process and maximize the use of its limited resources.

Current Research Limitations and Follow-on Research

The main limitation of the current study is that notional cost data were used to provide a proof of concept that the model functions as designed. However, this presents an opportunity for future research whereby additional follow-on research with empirical data should be conducted. This model can analyze cost data in past, present, and future EO/IR models.

Beginning with historical data, a cost analyst could compile a list of program components associated with a system that is either retired or currently in use. Once the list of components is obtained, the analyst can then associate the estimated historical cost assigned to each component during the program's initial cost estimate (e.g., a program cost estimate developed in 1992). Using the original cost data and component list, the analyst could then run the new total ownership with life-cycle cost model under uncertainty. This would produce a new cost estimate for the program, which could then be compared to the original estimate and the actual life-cycle cost of the program. Executing this study would determine whether the TOC model developed in this thesis is a superior method of cost estimation for the DoD.

Another follow-on study could be done using the data from a program that is currently undergoing its initial cost estimation. The cost estimate could be done in conjunction with the DoD's current methods of cost estimation. Another researcher could partner with PEO IWS and the new system's program office to complete a cost estimate using the TOC model developed in this thesis. This process would allow for real-time cost comparisons at different stages in the acquisition process. The comparison between the two estimates would provide decision-makers with another method of verifying assumptions and validating that their cost estimates are reasonable and credible. Concurrently conducting the cost estimates allows researchers and cost estimators to compare their estimates to actual cost data at the different increments throughout the program's life cycle. This comparison would determine which method of cost estimation was more accurate at different points in the system's life cycle.

These follow-on studies require real-world cost data from historical or current EO/IR programs. While data collection may prove difficult and time-consuming, this research would be beneficial to the DoD and well worth the investment. Working with PEO IWS and the program office's cost estimation teams could result in model improvements and provide an even more robust total ownership with life-cycle cost model under uncertainty.

Other Applications and Conclusions

This research focuses specifically on the application of this TOC model with regard to EO/IR sensors on surface ships; it barely scratches the surface of the model's potential. This model could be applied to any one of the thousands of acquisition projects in the DoD. The model's use is not confined to EO/IR sensors on surface ships but can be adjusted and developed for various programs. The process and the strength of the results that the model would provide would be the same; the only necessary change a cost analyst would need to make is to alter the list of components to reflect whichever system or program is being analyzed. In the same fashion, this model could also provide contractors and non-DoD organizations with an additional method of cost estimation.

Cost estimation is not an exact science; however, this model provides a coherent method of estimating the total ownership with life-cycle costs under uncertainty for EO/IR sensors on surface ships. It gives a decision-maker another tool when evaluating alternative programs and courses of action. The ultimate goal of this model is to provide a more effective tool in determining how the DoD spends its limited resources on competing priorities. While follow-on research needs to be conducted to validate the efficacy of the model, this thesis offers a proof of concept and takes a step toward DoD portfolio optimization.

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