DOI 10.21544/1809-3191.v24n3.p735-758

OPERATING AND SUPPORT COSTS FOR NEW VESSELS: ESTIMATES FOR THE PHM ATLÂNTICO BASED ON OPEN SOURCES

Luiz Octávio Gavião[1]
Marcio Magno de Farias Franco e Silva[2]
Emilia Machado[3]
Mariana Petine[4]

ABSTRACT

PHM Atlântico was recently acquired by the Brazilian Navy. The size of the ship indicates that its operating and support costs must be the highest among the conventional vessels of the Force. In general, naval assets remain in active service for 25 to 30 years, although the Navy is extending the working time of some of its main vessels. Knowing the life-cycle costs of ships allows the Force to carry out the appropriate budget planning in the medium and long term. However, the new ships acquired, from construction projects or even directly from the market, lack historical cost records. This makes it difficult to estimate life-cycle costs. This paper aims to apply analogy and parametric methods, associated with Bayesian inference models, to estimate the operation and support costs for the PHM Atlântico. Only open source data was used in the research. The results by different methods were similar, offering interesting alternatives for the calculation of life-cycle costs in a situation of data scarcity.

Keywords: Life-Cycle Costs. Analogy method. Parametric method. Bayesian Inference. PHM Atlântico.

[1] Holds a Bachelor's degree in Naval Sciences from the Naval School, a Master's in Military Studies at United States Marine Corps University (2002-2003), a Master's and PhD in Production Engineering from UFF, and is an Adjunct Professor at the Brazilian War College (ESG), where he conducts research at the Training Center for Defense Acquisition (CCAD). Email: luiz.gaviao67@gmail.com

[2] Rear Admiral (RM1), Superintendent and Dean of Research and Graduate Program in Maritime Studies at the Naval War College (EGN). Rio de Janeiro - RJ). Email: marcio.magno@marinha.mil.br

[3] Graduate student in International Security and Defense, Brazilian War College (ESG). Rio de Janeiro - RJ). Brazil. Email: machado.emilia1@gmail.com

[4] Holds a graduate degree in International Security and Defense at the Brazilian War College (ESG) - (RJ), Brazil. Email: marianapetine@hotmail.com

INTRODUCTION

The management of the life cycle of defense systems is a topic of the highest relevance. In general, defense systems are inherently complex because of the high number of elements that compose them, with various interrelationships between these components and with other systems, requiring advanced technology for their use and maintenance. In this context, it is necessary to know, measure and manage the life cycle of these complex systems, which can remain active for over 40 years (BRAZIL, 2017).

The life cycle includes the whole spectrum of activities related to a system of interest, from the identification of capabilities and requirements, to system design and development, production and/or construction, operational deployment, maintenance support and disposal of materials. At each stage of the lifecycle, a series of processes and models inherent in system acquisition, contracting, development and operating expenditure need to be addressed under best management practices. These various life cycle phases involve time and resources and should receive the utmost attention from managers and advisors, so that efficient life cycle management contributes to the reliability and availability of defense systems employed in each of the Brazilian Armed Forces (BRAZIL, 2017).

Estimating costs of defense systems life cycle phases is essential for efficient management. Government procurement programs require cost estimates for several reasons: supporting decisions about which program to prioritize; annual budget planning; assessing requirements at key decision points during life cycle management; and developing performance benchmarks. In addition, having a realistic estimate of projected costs makes resource allocation effective and increases the likelihood of program success (USGAO, 2009).

However, measuring defense system costs is considerably challenging. The conditions for developing a good cost estimate require stable and accurate development programs, access to detailed documentation and historical data, availability of well-trained and experienced cost analysts, execution of risk and uncertainty analysis, identification of adequate confidence levels and long-term contingency and management reserves under the best of these circumstances. These conditions usually do not exist in the real world. Information is not accurate and fully available to users. Supporting documentation is scarce or classified, there are no similar programs for comparison, or estimation methodologies are based on irrelevant or outdated data (USGAO, 2009). In short, the task of estimating costs requires analysts to use their skills and judgment to produce essentially probabilistic results.

In a recent interview with the Valor Econômico newspaper, the Navy Commander (NC) exposed some concerns related to the life-cycle management of navy ships. Since 2013, Navy resources fell 55% to R$ 2.9 billion. This decrease has affected major ongoing programs, causing delays in submarine construction and extending the useful life of surface vessels that should operate for 25 to 30 years. According to the NC, investments in the re-equipment of the Navy should be of around R$ 1.2 billion per year, but the Force only receives, on average, approximately R$ 600 million (ROSA, 2018).

The budget constraint scenario in the Navy in recent years makes expenditure forecasting even more important to prevent premature depreciation of assets. In the case of new defense products (PRODE), developed in research and development (R&D) projects or even acquired in the market, this forecasting capacity is limited due to the scarcity of historical cost records. In this case, the Force risks acquiring new equipment with a high life-cycle cost (LCC), further aggravating budget constraints. This long-term economic sustainability problem is called "affordability" in the specialized literature (MELESE, 2015).

Managing the life cycle of a defense system requires the use of estimation models, because of the uncertainties involving its useful life. Operative and, eventually, combat activities over decades of active service can result in additional operating and support costs, making budget planning difficult. Modernization programs of equipment, required to keep them up to date with the state of the art of similar systems, may aggravate the difficulty. This uncertainty is expressed in estimation results by ranges of values and associated probabilities. At first glance, an estimate may be depreciated compared with accurate data. However, defense system operation and maintenance data are naturally private and classified by manufacturers and users. Thus, a result, even if estimated, is better than the lack of the information necessary for comparison and decision-making.

Another relevant aspect of the scope of this study concerns the use of open sources. Estimated results based on publicly available information are of interest because they allow anticipated planning and comparison with other systems with potential for development or acquisition. In addition, results based on open sources may serve as a reference when assessing classified data obtained during or after negotiation with supplying countries and firms. For example, estimates based on classified data that are considerably lower than open source results may indicate data omission or miscalculations, seriously impairing long-term budget planning. On the other hand, significantly higher results may warn of high maintenance costs of certain subsystems or components, characterizing the new equipment as atypical. The open sources used in this study are naval architecture data, available in reference publications, official data on HMS Ocean published by the Royal Navy, and information from the specialized media.

In this context, the recent acquisition of PHM Atlântico is the focus of this paper. Because it is the largest ship in the Fleet, it is reasonable to assume that it will require the largest share of resources among conventional vessels, restricted here to those without nuclear propulsion. Considering an useful life of 25 to 30 years, a significant resource consumption is expected for its operation and support. The Royal Navy, which designed and launched the then called HMS Ocean in 1998, spent ₤ 150 million in its acquisition, according to British media reports (ROBERTSON, 2018). However, detailed records of annual operating and support costs (O&S) throughout its useful life cycle from 1995 to 2018 are not available from open sources. These costs represent, in general, the largest share of the total ownership costs of a ship and not knowing them may compromise the readiness of the Force (Gansler & Lucyshyn, 2015).

Thus, the answer to the following research question may contribute to medium- and long-term navy budget planning: How to estimate PHM Atlântico's O&S, within a context of data scarcity, and what is the average annual cost?

This paper has four sections. After exposing the problem in the introductory section, Section 2 presents the adequate LCC estimation methods that can be used in the case study. Section 3 presents the calculation models results for the PHM Atlântico. Finally, Section 4 presents the conclusion and suggestions for further research.

MATERIALS AND METHODS

The mathematical models used to estimate LCC are basically explored by Operational Research (OR). Some authors argue that the term OR was first used in Britain, shortly before World War II, to distinguish applied research for integrating radar technology into air defense operations from research developed in laboratories and workshops. In 1941, OR was found to be useful in decision-making on military issues. Thus, the Armed Forces brought together scientists, engineers and mathematicians, among other professionals, to conduct research directly in support of the Military Chiefs of Staff (THOMAS, 2015).

With the end of World War II, OR developed rapidly in England and the United States. In 1947, the Pentagon implemented the Scientific Computation of Optimal Programs (SCOOP) project to support decision-making in the US Air Force. In this project, mathematician George Dantzig developed the simplex method for solving linear programming problems (DANTZIG, 1987). In Brazil, the first OR symposium took place in 1968, at the Aeronautics Technology Institute (ITA) (ARENALES et al., 2015).

Several definitions for OR have been proposed since its inception. In 1967, the English journal Operational Research Quarterly summarized OR as the development of scientific methods for complex systems to predict and compare strategies or decisions. Other authors define OR as a "scientific approach to problem solving in complex systems management" or, briefly, "a scientific approach to decision making" (ARENALES et al., 2015).

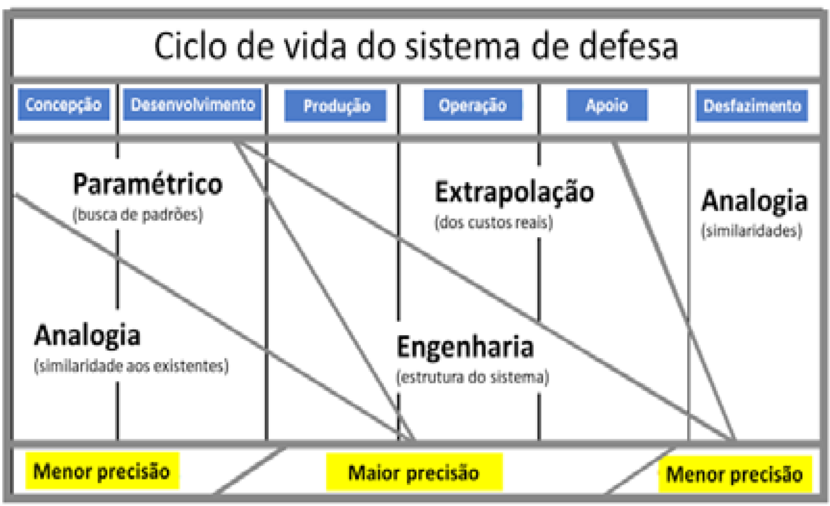

Fig.1: tipologia dos métodos em CCV. Fonte: (OTAN, 2007).

During the six phases of defense systems life cycle, it is possible to group LCC estimation methodologies into four groups, as shown in Fig.1. In the early stages (i.e. design, development and production), OR models by analogy and parameters predominate. Throughout the operating and support phases of the defense system, new performance and cost data can be collected and recorded. This data accumulates over the years of the useful life of vessels, enabling the use of engineering models and extrapolation of the actual data, which ensure greater accuracy of results. Finally, the rarity of cases of disposal of similar vessels suggests the use of analog models for LCC estimates.

Defense systems can be unique in their characteristics and capabilities. For example, the first vessel of a new class may contain subsystems and components from a variety of ships, making it unique among its peers. Therefore, analog models emulate the parameters of interest of similar systems to estimate LCC in the early stages of the process. These models are also common in disposal calculations. Parametric models seek relationships between cost variables and performance or other variables of the new defense system.

Among these models, linear regressions stand out. Given the acquisition of a new vessel for the Navy, this study explored analog and parametric models to estimate the operating and support costs of the PHM Atlântico.

The doctrine of defense life cycle management is still new in Brazil. At the Ministry of Defense (MD), LCC conceptual framework is defined by the Defense Logistic Systems Support Center (CASLODE) (BRAZIL, 2017). In developed countries, the defense procurement agencies have been conducting research and publishing academic works on the topic in the last decades. The theses, dissertations, technical reports and scientific articles produced at the Naval Post-Graduate School (NPS) and at the Defense Acquisition University (DAU), both in the USA, contributed to broaden knowledge on LCC and produce new data and calculation models. Thus, we selected two studies to support our case study, due to the adequacy between the available data on the new vessel and the characteristics of the calculation methods used in the DAU and NPS. Brandt (1999) applied linear regressions to 195 US Navy ships based on their displacement, length and crew. The author categorized the ships by class similarity, in order to differentiate the results based on their similar characteristics.

ESTIMATION BY ANALOGY

Jones et al. (2014) analyzed the ratio of the costs of each phase of the life cycle to the total costs of ownership of different defense systems. This ratio was called the "Golden Ratio" in LCC estimation. This model can also be characterized as analog, in the sense of supporting estimates related to the new vessel based on data on similar systems. Figure 2 shows the general cost structure profile:

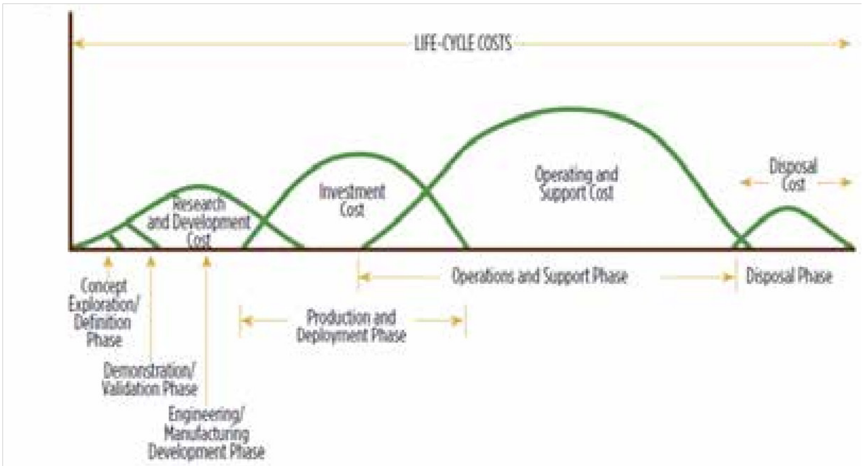

Fig.2: Estrutura genérica dos custos por fases. Fonte: Jones et al. (2014).

The defense procurement community often uses a 70:30 cost ratio of operating and support costs to acquisition costs of an average weapon system (JONES et al., 2014). Using operational data from 37 US Navy and Air Force acquisition programs conducted between 1989 and 2010, the authors estimated the average cost ratio at 55:45, although many weapon systems show a significant deviation from this 55%average. Several factors contribute to this inaccuracy, such as life expectancy and acquisition strategy, which may involve the development of a new system or the modernization of current ones.

In their research, Jones et al. (2014) advise against the use of a single cost ratio for all types of defense systems. Thus, the authors segregated their sample to perform the calculations by category of defense systems. In the specific case of surface vessels, the results from the sample of ten vessels indicated that the O&S averaged 53.26% of the total costs, with a standard deviation of 13.13%.

Two US government reports also set parameters for the use of the "Golden Ratio," but at different percentages from surface vessel's O&S. Recently, the US Department of Defense has published cost percentages for different defense systems (USDOD, 2014). The report presents percentage estimates for three phases: research and development (R&D), investment and operations/support. US DoD estimated R&D costs of 5% of total, 26% for investment and 69% for operations and support. The report did not inform the percentage for defense system disposal.

The R&D phase consists of costs of trade studies of material solution and advanced technology development; system design and integration; development, fabrication, assembly and test of prototype hardware and software and/or engineering development models; system tests and evaluation; system engineering and program management; and product support elements associated with prototypes and/or engineering development models. For some programs, this may include additional development costs associated with later modifications or increments (USDOD, 2014).

The investment phase consists of the costs associated with the production and deployment of primary hardware; system engineering and program management; product support elements, i.e. specific and common support equipment, specific/initial training and equipment, publications/technical data, and initial spare parts and repair parts associated with production assets; contractor's temporary support that is considered as part of the system acquisition and is included in the scope of the procurement program (USDOD, 2014).

The operations and support phase covers maintenance costs incurred from the initial system deployment to the end of operations. It includes all costs of operating, maintaining and supporting a fielded system. Specifically, it encompasses (organic and contracted) costs for personnel, equipment, consumable materials, software, and services associated with operating, modifying, maintaining, providing and supporting a system in US DoD inventory (USDOD, 2014).

In a report by the Government Accountability Office (GAO)[5], the percentages of life cycle costs for surface vessels are similar to those of the US DoD (USGAO, 2009). GAO pays particular attention to the estimation of defense systems costs for auditing purposes in this sector. This body understands that the defense community does not have a formal policy to conduct or revise cost estimates. Thus, GAO guidelines benefit defense procurement by informing the criteria that GAO will use to assess the credibility of a cost estimate. For surface vessels, GAO assumes that operating and support costs exceed 60% of total ownership costs. In the report, this data is credited to GAO itself and to the US DoD, which gives credibility to the use of an estimated 69% of total operating and support costs (USGAO, 2009).

[5] GAO is equivalent to the Federal Court of Accounts (TCU) in Brazil.

PARAMETRIC ESTIMATES

Parametric estimates, like calculations by analogy, are also usually explored in the early stages of the life cycle of defense systems, as indicated in Fig. 2. Most of the academic papers available in the scientific literature show the use of linear regression techniques in this method category (MAZUR, 2006; SANCHEZ et al., 2014; MELESE; RICHTER; SOLOMON, 2015; MISLICK; NUSSBAUM, 2015). Regression analysis is the part of statistics that investigates the relationship between two or more non-deterministically related variables. The goal of this technique is to explore the relationship between two (or more) variables, in order to obtain information about one of them based on known values of the other(s). Stating that variables x and y are related in this way means that knowledge of the value of x implies knowledge of the value of y. The relationship between two variables x and y is linear for $y = ax + b$, considering a and b constants. The relationship is linear because a line defines the graph of the equation of the two variables. The y is called dependent variable and x is called independent variable. Regression analysis calculations also reveal the quality of the relationship between the variables through the correlation coefficient (DEVORE, 2010).

The model developed by Brandt (1999) can be applied to the acquisition or development of a new vessel. The absence of historical data on operations and support for the vessel under analysis is mitigated by using numbers related to the structural (e.g. displacement and length) and operational (e.g. personnel) characteristics of similar vessels with a significant amount of data available. To obtain the regression equations and the variance of results, the author explored the database of the Naval Center for Cost Analysis, a US Navy military organization created in 1985, which manages naval operations and support costs, which is called Navy Visibility and Management of O&S Costs (VAMOSC).

The greater the displacement, length and crew of the ship, the higher the estimated operating and support costs. These parameters were chosen considering the availability of data, both for an existing vessel, acquired in the market, and for a vessel to be developed based on Military Staff's requirements and other project information. Brandt (1999) explored data from VAMOSC, comprising 417 ships of 77 classes between 1984 and 1996. The author's hypothesis is that ships of the same class are similar regarding tasks, operating cycles and maintenance.

VAMOSC data comprise 122 cost elements, divided into four components: (1) direct unit cost; (2) direct intermediate maintenance cost; (3) direct depot maintenance cost; and (4) indirect operating and support costs. The direct costs of each ship include personnel costs (e.g. pay and other labor rights), material (e.g. all kinds of consumables, including food, fuel, spare parts, etc.) and purchased services other than maintenance (e.g., expenses with contractors and outsourced services). Direct intermediate maintenance costs include costs of material and labor involved in the maintenance of the ship that are not characterized as general maintenance, major maintenance or modernization of the shipyard or arsenals, which must be recorded in the third cost category. Finally, indirect operating and support costs include routine operating expenses, for example training, technical services, ammunition loading and unloading, among others not considered as investment (BRANDT, 1999).

The equations developed by Brandt (1999), resulting from the regression analysis using VAMOSC data, established the operating and support cost estimate for the ship classes, the standard error of this measure and the percentages of this estimate for each cost category. Equations (1) to (3) describe the relationships between each parameter of light displacement in tons (D), vessel length in feet (L) and number of crew members (T). These equations also establish the lower (Li) and upper (Ls) limits for annual average operating and support costs (O&S). Equations (4) to (7) present the cost estimates and respective limits for the four components described, considering the US Navy class of ships most similar to the PHM Atlântico class. The ships were categorized as "Amphibious Assault" vessels, composed of the LPD, LSD, LST, LCC, LPH, LHA, LHD and LKA classes for calculation purposes[6]. The statistical procedures that result in these equations are detailed in BRANDT (1999).

$$COA = 111.302(D)^{0,618}, L_i = -31,68\%, L_s = +46,37\% \quad (1)$$

$$COA = 1.223(L)^{1,6}, L_i = -27,53\%, L_s = +37,99\% \quad (2)$$

$$COA = 285.215(T)^{0,75}, L_i = -24,35\%, L_s = +32,18\% \quad (3)$$

$$Conjunto\,1 = 67,89\% \pm 17,53\% \quad (4)$$

$$Conjunto\,2 = 1,16\% \pm 0,88\% \quad (5)$$

$$Conjunto\,3 = 27,55\% \pm 18,40\% \quad (6)$$

$$Conjunto\,4 = 3,4\% \pm 1,95\% \quad (7)$$

[6] Landing Platform Dock (LPD), Landing Ship Dock (LSD), Landing Ship Tank (LST), Landing Ship Command and Control (LCC), Landing Platform Helicopter (LPH), Landing Helicopter Assault (LHA), Landing Helicopter Dock (LHD) and Landing Cargo Amphibious (LKA).

These equations show that the percentage of direct personnel and maintenance costs is the largest among the operating and support costs. This procedure of accounting for pay, allowances and other crew pay expenses, as provided for in VAMOSC, is similar to NATO's life-cycle management doctrine, as described in the reports on the topic (NATO, 2003, 2007). Another aspect to highlight is the variety of results for O&S, due to the use of different input parameters in the equations of BRANDT (1999). In our paper, the results were statistically aggregated, including new data evidence, in order to consider all available information, precisely in the early phases of the defense system's life cycle, for which data are scarce.

STATISTICAL AGGREGATION OF RESULTS WITH NEW EVIDENCE

The estimates presented regarding the "Golden Ratio" and O&S, based on Brandt (1999), are probabilistic, indicating intervals. Statistics deals with data. Generally speaking, the goal of statistics is to make inferences based on data. In statistics, the precise conclusions are rare, since statistical parameters derive from essentially random processes. Thus, we sought a method capable of statistically aggregating the parameters obtained from research and open sources for the operating and support costs of HMS Ocean and similar class ships.

Bayesian inference is a method of statistical inference in which the Bayes' theorem is used to update the probability of a hypothesis as more evidence or information becomes available. Bayesian inference is an important technique in statistics. In general, the goal of Bayesian inference is to represent the prior uncertainty about the model parameters with a probability distribution and to update this prior uncertainty with the new evidence obtained, in order to produce an posterior probability distribution for the parameter, with lower uncertainty. In the case of this study, the parameter θ of interest is the operating and support costs (ANNIS; MILLER; PALMERI, 2017).

Bayes' theorem, expressed in terms of probability distributions, can be described according to Equation (8). The variables in this equation indicate that $f(\theta \mid data)$ is the posterior distribution of the parameter θ for existing data. The function $f(data \mid \theta)$ is the density of the data sample, considered proportional to a likelihood function at the actual unknown density, differing only by a normalizing constant, to reduce it to a density function. The function f (θ) is the prior distribution for the parameter θ and f (data) is the marginal probability of the data. For a continuous sample space, this marginal probability is calculated according to Equation (9), which integrates the sample density function multiplied by the prior distribution, in the domain of the parameter θ. The result of this integral represents a normalizing constant to transform the posterior function into a probability density function. Based on Equation (8), the Bayes' Theorem for probability distributions is often described according to Equation (10), where the symbol "α" indicates rate (ANNIS; MILLER; PALMERI, 2017).

$$f(\theta \mid dados) = \frac{f(dados \mid \theta).f(\theta)}{f(dados)} \qquad (8)$$

$$f(dados) = \int_{\Omega_\theta} f(dados \mid \theta).f(\theta)d\theta \qquad (9)$$

Função "*a posteriori*" α Função de Verossimilhança x Função "*a priori*" (10)

Although Bayes' theorem is conceptually simple, its application to real data and models is complex. On the one hand, the calculation of Equation (9) involves a multivariate integral whose solution may be unworkable with traditional mathematical techniques. On the other hand, for models with only one or two parameters, a posterior distribution can sometimes be calculated directly or estimated by numerical methods. However, as the number of parameters in the model increases, direct mathematical solutions become scarce and traditional numerical methods insoluble (ANNIS; MILLER; PALMERI, 2017). In this sense, due to the multivariate functions generated by the BRANDT's (1999) model applied to Bayesian inference, it was necessary to apply simulation integration techniques, based on Simpson's rule (BAUWENS; LUBRANO; RICHARD, 2000). We used R statistical analysis software for modeling cost estimates (R-CORE-TEAM, 2018).

APPLICATION AND RESULTS

The models presented in Section 2 were applied in two case studies for the calculation of PHM Atlântico's operating and support costs. The first study applied the "Golden Ratio," based on the values available from open sources, about the acquisition costs of HMS Ocean between 1995 and 1998, the year that marks the beginning of the ship's operating life. HMS

Ocean operated for exactly 20 years and was recently acquired by the Brazilian Navy. The second case study explored Brandt's (1999) parametric model to obtain operating and support costs from displacement, length and crew data. These calculations have been updated with new evidence from the UK Freedom of Information Act, obtained from open sources.

CASE STUDY 1

From a mathematical point of view, the "Golden Ratio" is just a simple rule of three. Knowing the cost percentages for each phase of the life cycle, and the value of only one phase, enables the calculation of the other phases' costs. Percentage data is obtained from the cost history of similar systems. This explains the analogy character of this estimation method. As shown in Fig. 1, analogy methods are inaccurate both in terms of using data from other vessels and in the unpredictability of the conditions under which the new vessel will operate throughout its useful life. However, an approximate figure is better than the absence of an estimate for budget planning. At least best and worst case estimation scenarios can be used to assess the Force's economic sustainability in subsequent years.

In this first case study, uncertainty about operating and support costs was mitigated by the use of Bayesian inference. The values projected by US DoD (2014), corroborated by US GAO (2009), were combined with the results of Jones et al. (2014) to obtain a posterior distribution of operating and support costs. These percentages were then applied to the value of £ 150 million, which was the acquisition cost for HMS Ocean, with due inflation correction for 2018 and monetary conversion to the Real. We obtained the value for 1998 from open sources and used it in this case study (ROBERTSON, 2018). The probabilistic approach, which considers data variance in relation to the average parameters, can also mitigate any discrepancy between the estimate of £ 150 million and the actual figures from the Royal Navy.

Regarding surface vessels, Jones et al. (2014) obtained O&S costs equivalent to 53.26% of total costs, with a standard deviation of 13.13%. For US DoD, O&S are estimated at 69% of total costs (USDOD, 2014). Since the US DoD report did not inform the standard deviation, we used the same deviation proposed by Jones et al. (2014) for the Bayesian inference with continuous samples.

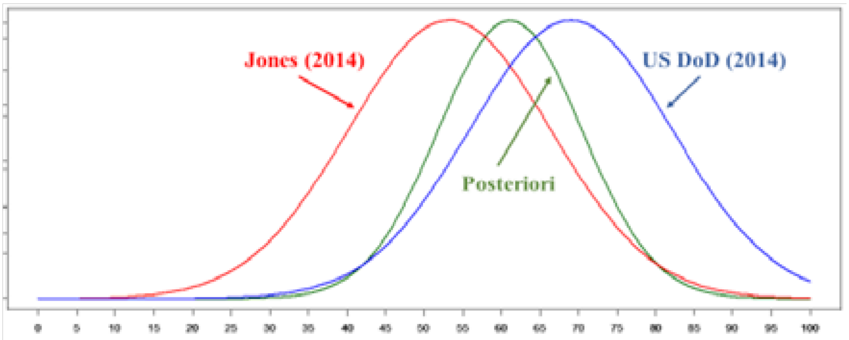

Fig.3: Inferência Bayesiana para a "Regra de Ouro".

The results of the Bayesian inference applied to the data of Jones et al. (2014) and of the US DoD (2014) show the posterior distribution of Fig. 3. The normal distribution shows an average value of 61.13% for the operating and support costs and a standard deviation of 3.8% for the total costs of the ship's life cycle. UK's inflation rate from 1998 to 2018 was 70.91% and one pound sterling was equal to R$ 4.82 in November 2018. Thus, an acquisition cost of £150 million in 1998 is equal to R$ 1,606,383 in 2018 values. We obtained an average annual O&S for PHM Atlântico of R$ 121,833,700 (31% of the acquisition cost), with a standard deviation of R$ 117,208,300 and R$ 126,459,100. It should be noted that these figures represent all O&S costs, including annual personnel expenses, on-board system maintenance, spare parts, and shipyard and armory services, among others accounted for in the VAMOSC database. It is also worth mentioning that the so-called "Brazil cost" was not accounted for in the conversion of values, due to the lack of information on the effect of the costs of Brazilian shipbuilding services in relation to similar services in the United Kingdom or the USA. If, on the one hand, the "Brazil cost" could increase the nominal value of operating and support costs, we could also assume that the operating routine of ships in Brazil is less demanding than in those countries, considering days at sea and the intensity of system use in severe situations. In some ways, the positive effect of the "Brazil cost" on O&S in the country and the negative effect on naval deployment neutralize each other. Thus, we chose not to multiply the results by the "Brazil cost".

CASE STUDY 2

The second case study explored Equations (1) to (7), obtained from Brandt's model (1999), and Equations (8) and (9), referring to the Bayesian inference. Fig. 4 presents the graphs of the probability functions obtained for each parameter: displacement, length and crew of the PHM Atlântico. The equations produced annual mean values and upper and lower limits. The asymmetry of these values required modeling the data with asymmetric probability distribution. In this case, we chose to use the Beta PERT distribution, widely used in risk analysis and project management, due to the modeling with minimum, maximum and median parameters, as those obtained in the case study (VOSE, 2008). Due to the dispersion of the results with the three parameters, we decided to aggregate them under a mixture distribution, composed by the three Beta PERT distributions, in equal proportions. Thus, all values estimated by Brandt's model (1999) are considered for the estimation. Regarding the parameters "D", "L" and "T" applied to the equations, the light displacement of HMS Ocean is 21,200 tons and its length is 667 feet (UKMOD, 2003). PHM Atlântico's estimated crew is 432 members (BRAZIL, 2018).

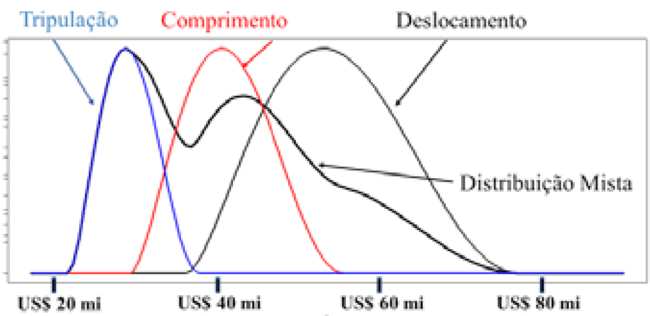

Fig.4: Resultados das equações de Brandt (1999) ao ano fiscal 1998, em US$ milhões/ano.

In 2015, the Royal Navy complied with a public request for data regarding the operating and support costs of its fleet. This request, similar to Brazil's Access to Information Act, disclosed new evidence on HMS Ocean costs. Average costs for fiscal year 2014 were £ 12,345 million. These values were adjusted for the 8.74% English inflation rate between 2015 and 2018, and converted to US dollars, considering £ 1.00 equal to US$ 1.27. At this average converted cost, other parameters for modeling with the Beta PERT distribution were also considered. The minimum and maximum parameters were obtained from the average operating and support costs of the amphibious vessel classes most similar to HMS Ocean. The document published by the Royal Navy identified average operating and support costs of £ 8,170 million for the LSD Bay class and of £ 23,975 million for the LPD Albion class in 2014. These figures were adjusted and converted to US dollars following the same procedure applied to the costs of HMS Ocean.

Fig.5: Resultados da inferência Bayesiana ao ano fiscal 2018, em US$ milhões/ano.

With these parameters, it was possible to model the probability distribution of the new data published by the Royal Navy, as shown in Fig. 5. With the mixture distribution indicating the prior information of Brandt's model (1999), it was possible to apply the Bayesian inference and obtain the posterior information. Thus, PHM Atlântico's average annual operating and support costs are US$ 31.56 million, with a 95% confidence that this average will range from US$ 31.16 million to US$ 33.65 million. Considering US$ 1.00 equal to R$ 3.78, these annual values can be converted to an average of R$ 119.3 million, ranging from R$ 117.78 million to R$ 127.2 million. The same considerations as those described in the results of the first case study applies to this case, regarding the cost categories involved and our option of not taking into account the "Brazil cost."

Table 1 presents the results of the case studies. The upper and lower limit estimates presented in Equations (1) to (7), applied to the results obtained by Bayesian inference to the "Golden Ratio" and Brandt's model (1999) allowed us to estimate the costs for each set. For Set 1, which includes personnel, material and basic maintenance costs, there is still an additional inference to exclude personnel costs. This new estimate makes it possible to simulate maintenance costs in short-term operating cycles, given that HMS Ocean underwent major maintenance and modernization periods in the years preceding its sale to Brazil. Thus, it is reasonable to assume that, in the next two or three years, PHM Atlântico will not incur significant costs related to the other sets. Assuming crew costs for the PHM Atlântico of around R$ 24 million per year, the costs of supply and basic maintenance of the onboard systems may consume approximately R$ 57.58 million per year over this initial period of the ship's operating life.

Tabela 1: Resumo dos cálculos dos estudos de caso em R$ milhões/ano.

Modelos		Conjunto 1	Conjunto 2	Conjunto 3	Conjunto 4
Regra de Ouro (média)	R$ 121,834	R$ 82,713	R$ 1,413	R$ 33,565	R$ 4,142
	Limite inf	R$ 61,355	R$ 0,341	R$ 11,148	R$ 1,767
	Limite sup	R$ 104,070	R$ 2,485	R$ 55,983	R$ 6,518
Regra de Ouro (mínimo)	R$ 117,208	R$ 79,573	R$ 1,360	R$ 32,291	R$ 3,985
	Limite inf	R$ 59,026	R$ 0,328	R$ 10,725	R$ 1,700
	Limite sup	R$ 100,119	R$ 2,391	R$ 53,857	R$ 6,271
Regra de Ouro (máximo)	R$ 126,459	R$ 85,853	R$ 1,467	R$ 34,839	R$ 4,300
	Limite inf	R$ 63,685	R$ 0,354	R$ 11,571	R$ 1,834
	Limite sup	R$ 108,021	R$ 2,580	R$ 58,108	R$ 6,766
Equações de Brandt (média)	R$ 119,300	R$ 80,993	R$ 1,384	R$ 32,867	R$ 4,056
	Limite inf	R$ 60,079	R$ 0,334	R$ 10,916	R$ 1,730
	Limite sup	R$ 101,906	R$ 2,434	R$ 54,818	R$ 6,383
Equações de Brandt (mínimo)	R$ 117,780	R$ 79,961	R$ 1,366	R$ 32,448	R$ 4,005
	Limite inf	R$ 59,314	R$ 0,330	R$ 10,777	R$ 1,708
	Limite sup	R$ 100,608	R$ 2,403	R$ 54,120	R$ 6,301
Equações de Brandt (máximo)	R$ 127,200	R$ 86,356	R$ 1,476	R$ 35,044	R$ 4,325
	Limite inf	R$ 64,058	R$ 0,356	R$ 11,639	R$ 1,844
	Limite sup	R$ 108,654	R$ 2,595	R$ 58,448	R$ 6,805
Médias dos modelos	R$ 121,630	R$ 82,575	R$ 1,411	R$ 33,509	R$ 4,135

CONCLUSION

Complex defense systems involve significant costs to countries. Unlike mass consumer products that cater to the general population, defense products are sometimes unique in their uses and characteristics. In this case, data recording and analysis is scarcer, making cost estimation complex. In this paper, we analyzed some models for calculating life-cycle cost estimates of naval systems, with emphasis on the initial phases of acquiring new systems, both by developing from scratch and by purchasing in the market.

The methods employed in this study enabled us to estimate operating and support costs for PHM Atlântico. The use of the "Golden Ratio," which estimate percentages of the total cost of ownership for each phase of the life cycle, and of Brandt's equations (1999), both modeled with new evidence based on Bayesian inference, led to approximate and similar results. This indicates that the proposed methods are useful for budget planning, at least as long as the Force does not accumulate records in quantity and quality over the useful life of the defense system. In the US Navy, for example, VAMOSC has accumulated data since 1975 on 122 cost categories for all its naval assets. This ensures the best conditions for cost analysis, with more accurate and consistent mathematical models.

Some improvements suggested by this study apply to Brazil, such as the calculation of the "Brazil cost" for defense systems and the proposal for applying an adjustment factor to UK and USA naval systems. The "Brazil cost" may have different values for each industrial activity and should not be generalized to commercial products and defense systems. Thus, it is necessary to determine the "Brazil cost" for defense systems, capable of correcting the estimation for these countries. The second suggested improvement refers to the differences in the use of the vessels between the mentioned countries, due to the intensity of the use of the ships. This indicator could be based on the number of days at sea, for example. Assuming that more days at sea require more resources to be spent on maintenance, support, personnel expenses, etc., it is possible to project a factor for applying to life-cycle costs, adjusting them to the Brazilian pattern of use. These proposed measures increase the accuracy of the models, but do not replace databases dedicated to timely and accurate recording of the various costs for each naval environment. Measuring to manage is the main lesson of the countries that spend the most on defense systems, and this good practice directly contributes to improving different mathematical models for long-term defense planning.

REFERENCES

ANNIS, J.; MILLER, B. J.; PALMERI, T. J. Bayesian inference with Stan: A tutorial on adding custom distributions. Behavior research methods, v. 49, n. 3, p. 863–886, 2017.

ARENALES, M.; MORABITO, R.; ARMENTANO, V.; YANASSE, H. Pesquisa operacional: para cursos de engenharia. [s.l.] Elsevier Brasil, 2015.

BAUWENS, L.; LUBRANO, M.; RICHARD, J.-F. Bayesian inference in dynamic econometric models. London: Oxford University Press, 2000.

BRANDT, J. M. A parametric cost model for estimating operating and support costs of US Navy (non-nuclear) surface ships. 1999. Naval Post--Graduate School, 1999.

BRASIL. Doutrina de Gestão do Ciclo de Vida de Sistemas de Defesa - minuta. Brasilia-DF: Ministério da Defesa - Centro de Apoio a Sistemas Logísticos de Defesa, 2017.

BRASIL. Porta-Helicópteros Multipropósito (PHM) Atlântico chega ao Rio de Janeiro. Disponível em: <https://www.marinha.mil.br/sinopse/porta-helicopteros-multiproposito-phm-atlantico-chega-ao-rio-de-janeiro>. Acesso em: 20 nov. 2018.

DANTZIG, G. B. Origins of the simplex method. [s.l.] Stanford University-CA, Systems Optimization Lab, 1987.

DEVORE, J. L. Probabilidade e Estatística para Engenharia e Ciências. São Paulo: Cengage Learning Edições Ltda., 2010.

GANSLER, J. S.; LUCYSHYN, W. Allocating national security resources. In: MELESE, F.; RICHTER, A.; SOLOMON, B. (Ed.). Military Cost–Benefit Analysis. 1. ed. New York: Routledge, 2015. p. 52–69.

JONES, G.; WHITE, E.; RYAN, E. T.; RITSCHEL, J. D. Investigation into the ratio of operating and support costs to life-cycle costs for DoD weapon systems. Defense ARJ, v. 21, n. 1, p. 442–464, 2014.

MAZUR, D. J. Defense mergers and acquisitions: in the name of efficiency. 2006.

MELESE, F. The economic evaluation of alternatives. In: Military Cost–Benefit Analysis. Charlotte: Routledge, 2015. p. 108–144.

MELESE, F.; RICHTER, A.; SOLOMON, B. Military Cost–Benefit Analysis: Theory and practice. [s.l.] Routledge, 2015.

MISLICK, G. K.; NUSSBAUM, D. A. Cost estimation: methods and tools. [s.l.] John Wiley & Sons, 2015.

OTAN. RTO TECHNICAL REPORT TR-SAS-058 - Cost Structure and Life Cycle Costs for Military Systems. [s.l: s.n.].

OTAN. RTO TECHNICAL REPORT TR-SAS-054 - Methods and Models for Life Cycle Costing. [s.l: s.n.].

R-CORE-TEAM. R: A language and environment for statistical computing.http://www. R-project. orgVienna, Austria, 2018. .

ROBERTSON, A. Ritain "sells Royal Navy's flagship HMS Ocean to Brazil for £84million" even though new aircraft carrier HMS Queen Elizabeth won't be fully operational until 2020. Daily Mail, p. 2, 2 jan. 2018. Disponível em: <https://www.dailymail.co.uk/news/article-5228991/Britain-sells-Royal-Navys-flagship-HMS-Ocean-Brazil.html>.

ROSA, J. L. Submarinos podem atrasar mais se houver novos cortes. Valor Econômico, v. 1, n. 1, 2018. Disponível em: <https://www.valor.com.br/brasil/5810051/submarinos-podem-atrasar-mais-se-houver-novos-cortes>.

SANCHEZ, S. M.; MORSE, M. M.; UPTON, S. C.; MCDONALD, M. L.; NUSSBAUM, D. A. A Robust Design Approach to Cost Estimation: Solar Energy for Marine Corps Expeditionary Operations. [s.l.] Naval Postgraduate School Monterey CA - Graduate School of Business and Public, 2014.

THOMAS, W. Rational Action: The Sciences of Policy in Britain and America, 1940-1960. [s.l.] MIT Press, 2015.

UKMOD. The Royal Navy Handbook: the Definitive MoD Guide. 1. ed. London: Conway Maritime Press, 2003.

USDOD. Operating and Support Cost-Estimating Guide: cost assessment and program evaluation. [s.l: s.n.].

USGAO. Cost Estimating and Assessment Guide: best practices for developing and managing capital program costs. [s.l: s.n.].

VOSE, D. Risk analysis: a quantitative guide. New York: John Wiley & Sons, 2008.