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Life Cycle Costing of Military Equipment

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Abstract **-** Military assets are generally appraised at the acquisition stage on the basis of their total life cycle costs. This study provides a theoretical foundation and a parametric cost model for forecasting the life cycle cost for any kind of heavy military equipment. In the model, the asset operating and maintenance (O&M) costs are estimated as a function of its age over its optimal operational life. The methodology is applied to the Canadian Arcturus fleet. The results show that O&M costs account for approximately 70.81% of the overall life cycle cost of this fleet. Uncertainty is introduced in the developed model using a sensitivity analysis.

Keywords**:** Life cycle costing, optimal assessment horizon, dynamic programming.

1. Introduction

Accurate cost estimation of military equipment plays a crucial role in any military acquisition strategy. Military assets are generally appraised at the acquisition stage on the basis of their total life cycle costs (LCC). Life cycle costing is an economic assessment that looks beyond the initial purchase cost of an item. It also includes the cost of operating and maintaining the item over its entire operational life. This technique was designed in the early 1960s for procurement purposes in the US Department of Defence. This concept is becoming a central concern and increasingly being considered in many military procurement processes (Korpi and Ala-Risku, 2008).

The purpose of a LCC model is to estimate the overall costs of an item. It can be used as an evaluation tool in two situations. The first situation occurs when assessing the economic impact of a given investment such as the procurement of new equipment. If the decision has already been made, LCC can assist in budget allocation (Liu, 2006). The second takes place when comparing various alternative courses of action with the objective of choosing the best way to use scarce resources (Fabrycky and Blanchard, 1990). In this case, LCC assists in selecting the alternative that ensures quality at minimal cost (Fuller, 2010).

From the perspective of the equipment user, LCC may be subdivided into three categories: Acquisition cost, ownership cost, and disposal cost. The acquisition cost includes the purchase price and the cost of potential equipment improvements. Ownership cost is composed of operation and maintenance (O&M) costs. O&M costs may include consumables, engineering services, repairs, overhaul and spares. Maintenance cost can be grouped in two categories: anticipated and unanticipated maintenance costs. Anticipated maintenance is generally programmed and suggested by the manufacturer for prevention purposes. Unanticipated maintenance is not programmed. It can be caused by equipment failures. Disposal cost occurs when equipment is withdrawn from service (Enparantza et al., 2006).

O&M is an important facet of the total ownership costs of military equipment. The cost of operating and maintaining equipment can exceed the cost of capital over the life of the equipment (Solomon and Sokri, 2013). With greater national interest in reduced public spending, emphasis would be placed on O&M from the cost standpoint. However, when attempting to apply life cycle costing concepts, analysts have been thwarted by the lack of accepted methodology to arrive at appropriate decisions (Al-Hajj, 1998).

1. 1. Aim

The main objective of this research is to develop a forecasting model of O&M costs for military equipment. The sub-objective includes the following:

- Develop a methodology for predicting the ownership cost of military equipment;
- Optimise the LCC of acquiring, operating, and maintaining military assets; and
- Enhance the understanding of life cycle costing both theoretically and practically.

1. 2. Methodology

This modelling procedure can be summarized by the following three-stage process:

1. Estimate the relationship between the O&M cost and equipment's age;
2. Compute the optimal replacement age of the equipment;
3. Compute the O&M LCC of the equipment over its entire optimal life.

The methodology is aimed to be clear, general, and applicable to old and new asset generations.

1. 3. Structure

This paper is organized into five sections. Following the introduction, Section 2 provides a review of literature on LCC analysis. Section 3 sets up the employed model and presents its mathematical derivations. In Section 4, an example using the Canadian Arcturus fleet is used to illustrate the methodology. In Section 5, some concluding remarks are made.

2. Literature Review

LCC analysis has been an active research area in the military sector as well as in the construction industry. The other sectors appear to make acquisitions of capital items simply on the basis of initial purchase cost (Woodward, 1997). This literature can be divided along methodological lines into three main approaches to estimating LCC: (i) engineering approach, (ii) analogy, and (iii) parametric method (Fabrycky and Blanchard, 1990).

2. 1. Engineering Approach

The engineering approach assigns costs to each element of the asset and then combines them into a total for the whole asset. This approach is time consuming and requires a huge amount of detailed data to perform the calculations. Sandberg et al. (2005), for example, presented a model for LCC prediction in the conceptual development of jet engine components. The model evaluates manufacturing and post-manufacturing activities and gives LCC feedback on potential design changes.

2. 2. Analogy Approach

The analogy approach uses similar systems to estimate cost when needed data are not available. This method is used to gain a rapid assessment of the LCC of a new system. Compared to the engineering approach, this cost comparison method has the significant advantage of exploiting relatively few data. But it has the drawbacks of being relatively inaccurate and requiring a high degree of judgment to draw analogies. To study how the costs of maintaining military aircraft change as aircraft age, Dixon (2006), for example, used an analogy between commercial aviation and military aviation. The author found that airline maintenance costs grow at a fairly sharp rate in the first six years of age, increase moderately between 6 to 12 years, and grow slightly after the 12 years of aircraft ownership. This study also suggests that different types of aircraft maintenance costs, e.g., airframe maintenance versus engine maintenance, may show different cost patterns. Even if one can assume that the commercial airlines' experience is meaningfully analogous to the Air Force's experience, there are limits to this analogy. No profitable commercial airline would operate an aircraft like the military do. For instance, military aircraft commonly fly 500 hours per year whereas commercial aircraft fly thousands of hours per year.

2. 3. Parametric Approach

The parametric approach applies econometric techniques to historical data to identify the major cost drivers of a given system and determine their effects on its LCC. The estimated parameters are then used in the cost estimating relationships of the analyzed systems. A growing body of literature recognizes the parametric method as an effective approach to forecast the LCC. Brandt (1999), for example, formulated a parametric cost model to determine the annual O&M costs of U.S. Navy surface ships. Using standard regression and data analysis techniques, the author developed cost estimating relationships for three major cost drivers: ship light displacement[1], ship overall length, and ship manpower. Kiley (2001) used regression analysis to estimate the relationship between an aircraft's characteristics and operating tempo and its O&M costs. Results indicate that spending on O&M for aircraft increases by 1% to 3% for every additional year of age, after adjusting for inflation. Younossi et al. (2002) explored most of the possible performance and technology parameters that affect the development and production costs and the development schedules of engines. These authors employed least-squares regression methods to develop a series of parametric relationships for forecasting the development cost, development time, and production cost of military turbofan engine programs.

Other methods have also been suggested for life cycle costing. Emblemsvag (2001), for example, suggested the activity-based costing (ABC) method to estimate the life cycle cost. This accounting-oriented methodology identifies activities and segregates their direct and indirect costs to identify their respective cost drivers. ABC has mostly been used in fixing the price of products and improving production processes. However, ABC requires extensive activity-cost data and is not easily employed to forecast the life cycle cost. The literature has also used the proportional models to estimate the life cycle cost. These models predict the future O&M costs of aircraft, for example, simply by multiplying the historical cost per flying hour and the estimated number of flying hours (Wallace et al., 2000). Wallace et al. (2000) showed that these models are not able to adequately predict future costs during periods of radically different flight behaviour. They indicated that during the First Gulf War proportional models overestimated removals by more than 200%. Unger (2007) stated that the proportional models may misestimate budgets when the relationship between cost and usage is either nonlinear or includes nontrivial fixed costs. The presence of fixed costs in the average cost factor would cause an exaggeration in estimated budget for a given number of flying hours. More recently, Maybury (2011) showed that the forecast of national procurement spending could not be improved using flying hours as an explanatory variable.

The literature has also used multimethodology or mixed methods to enhance forecasting quality. Parker (1991), for example, used an accounting model and a parametric model to evaluate alternative configurations within the same life cycle cost model. The accounting model was used to examine activities such as planning, engineering design, production, distribution, maintenance, and equipment disposal. The parametric method was utilized to determine cost estimating relationships during the cost determination phase of life cycle costing. More recently, Desmier (2012) used analogy and parametric approaches to forecast national procurement costs for F-35A aircraft. The author based his analogy on the assumption that the F-35A fleet fulfills the same mission profiles as the CF-18 fleet. Considering life cycles of 20 and 30 years, the parametric approach used the spending and usage history of the CF-18 fleet to define the trend in spending for the F-35 fleet. An interesting review of published case studies can be found in Korpi and Ala-Risku (2008). This paper also provides directions for further research on the LCC concept.

While many important findings have been reported in the military sector, the existing models on LCC still suffer from a lack of generality and simplicity. The existing models are usually tied to specific systems. These models cannot generate general insights because their validity, assumptions and results need to be tied to data from these specific systems. The lack of generality and simplicity also seems to be an unavoidable consequence of the use of time series theory while building models. Another feature of the existing models is that the project horizons remain highly arbitrary. LCC is not always bound to the

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[1] Light displacement describes the weight of water in tons that a ship displaces under light load conditions.

optimal replacement horizon. A key implication of the arbitrary horizon is that overall costs of equipment are reduced (amplified) if the horizon is considerably shorter (longer) than the optimal age.

Building on the existing literature, this paper seeks to address these deficiencies. Generality and simplicity are achieved by developing a minimal model that focuses on the most relevant aspects of equipment. As discussed in Greenfield and Persselin (2003), Maybury (2009), and Sokri (2011), age is thought to replace all related factors affecting the equipment O&M costs. For an aircraft, examples of such factors include (but are not limited to) engine cycles, number of sorties and flying hours. The range of applicability of such formalism is very large. It can be applied to any kind of heavy military equipment. A dynamic programming procedure is also developed in this paper to identify the optimal planning period. This planning period, referred to below as the optimal assessment horizon, is the length of time costs are accumulated. It actually corresponds to the optimal replacement horizon of military equipment.

3. The Model

To understand the concept of LCC and how it can be used in a military context, let's first examine the O&M cost for a given asset. Let *m* denote the asset O&M costs and *a* its age. O&M costs are assumed to depend on *a* through an increasing continuous function, i.e.,

$$m'(a) > 0. \tag{1}$$

As in Greenfield and Persselin (2003) and Sokri (2011), this relation is based on the assertion that the longer equipment stays in service, the higher its maintenance cost. It is commonly specified by the following parametric relationship

$$m(a) = Ce^{ga}, C > \text{ and } g > 0, \tag{2}$$

where *C* represents the initial O&M cost of the asset and g denotes the growth rate of its O&M costs. In this model, *C* can be regarded as a technological parameter characterizing each asset generation.
The regression model to be estimated is therefore

$$ln[m(a)] = ln(C) + ga + \varepsilon,\ C > \text{ and } g > 0. \tag{3}$$

This cost estimating relationship shows how maintenance costs change as equipment grows older. As stated in the existing literature, one virtue of this log formulation is that the regression coefficient estimate on the age variable is in percentage terms (Dixon, 2006). The random error ε in this parametric relationship is also relative and not absolute.

To forecast O&M costs of a new asset generation, one can use historical data of a comparable old asset to estimate the slope g. The initial cost of O&M at age zero of the new asset can be observed or estimated in collaboration with the manufacturer. Ordinary least-squares (OLS) regression can be used to undertake the parameter estimation. A probabilistic simulation can be conducted to analyze the uncertainty surrounding the parameters. Confidence intervals on the slope and the intercept can be used to specify the range of possible values of the parameters. A Program Evaluation and Review Technique (PERT) distribution can be used to determine their likelihood of occurrence. All current dollar values need to be converted into constant dollars to remove the effects of inflation and allow easy comparisons between periods.

To compute the optimal assessment horizon, let *M* be the equipment O&M costs per availability, *s* its retirement age, and *p* its acquisition cost. We assume, as in Keating and Dixon (2004) and Sokri (2011), that the military objective is not only to minimize expenditure but also to control the average cost per available year. For each available year, the total cost of acquiring, operating, and maintaining the asset during its life cycle can be written as

$$c(s) = p + \int_0^s e^{-ra} M(a) da, \tag{4}$$

where r is a positive discount rate. Consider the problem where we try to minimize the total discounted cost over an infinite number of replacements. For a discount factor,

$$\beta = e^{-r}, \tag{5}$$

the optimality equation for this infinite horizon problem is defined by

$$v = \min_s\{c(s) + \beta^s v\}, \tag{6}$$

where v is the stationary value function; that is, v is common to all time periods (Bertsekas, 2005). The total discounted cost is finite because $c(s)$ is assumed to be bounded for every s and $0 < \beta < 1,\ i.e., r > 0$.

Solving Eq. (6) for *v* gives the following optimal value

$$v^* = \min_s \left\{\frac{c(s)}{1-\beta^s}\right\}. \tag{7}$$

The minimum of this function and the corresponding optimal assessment horizon can be determined both graphically and numerically by plotting the expression on the right-hand side as a function of the variable s. This LCC model provides multiple benefits. In addition to the advantage of being general to several types of fleets, this model can be used to forecast LCC of old and new asset generations.

4. Illustration

The long range maritime patrol CP-140 Arcturus aircraft was built for the Canadian Armed Forces by Lockheed Corporation. It was mainly deployed to search out pollution violations, drug trafficking, illegal fishing and immigration. This aircraft was acquired in 1993 with a unit acquisition cost of approximately 79.6M. The acquisition costs include the purchase price and various improvements on the asset. These improvements represent approximately 0.32% (or $.25M) of the acquisition cost.

In this section, the data used in the analysis is described, O&M costs of the aircraft are estimated as a function of its age, and the optimal assessment horizon is determined. A sensitivity analysis is also carried out to assess the impact of some key model parameters on the basic result.

4. 1. Data and Assumptions

The historical data used in this study were provided by the Canadian Department of National Defence. O&M costs are defined as the costs of operating the asset and keeping it in good working condition. These costs include petroleum, oil and lubricants, engineering services, repairs and overhaul, and spares. In this study, these costs do not include the costs of civilian and military personnel. Current dollar values were converted into constant dollars to remove the effects of inflation and allow easy comparisons between periods. Constant dollars are computed at age zero. The real military discount rate is assumed to be approximately 1% (Sokri, 2013). The age of the asset is assumed to influence the need for maintenance and repair. Older age is assumed to generate not only higher O&M costs but also higher safety risks.

4. 2. Cost Estimating Relationship

To estimate the cost estimating relationship one should estimate the unknown parameters in Eq. 3 that are most likely to have generated the observed data. Using historical data in Table 1, Eq. 8 estimates the natural logarithm of O&M cost as a function of age.

$$ln[m(a)] = 14.598 + 0.036a. \tag{8}$$

The intercept term is the natural logarithm of the initial O&M cost. It indicates that the initial O&M cost amounts to

$$C = \exp(14.598) \approx \$2{,}186{,}910. \qquad (9)$$

The coefficient 0.036 captures the effect of age on O&M costs. It indicates the percentage change in O&M costs of Arturus when its age increases by one year. Its positive value confirms that older aircraft are more expensive to operate and maintain. Each more year would generate a 3.6% increase in O&M costs in terms of constant dollars.

Table 1. Arcturus O&M costs per aircraft (in 1993 constant dollars).

Year	Age (in year)	O&M cost (in $1993M)	Availability
1994	1	2.73	62.75%
1995	2	2.43	67.76%
1996	3	1.93	55.76%
1997	4	2.49	43.37%
1998	5	2.85	30.72%
1999	6	2.55	43.96%
2000	7	2.74	46.78%
2001	8	2.93	59.53%
2002	9	2.93	55.22%
2003	10	2.92	24.02%
2004	11	3.82	16.41%
2005	12	2.77	19.94%
2006	13	4.08	32.15%

Table 2 gives the properties of the least-square adjustment. It shows that the explanatory variable is statistically significant and therefore a meaningful term. The Ljung-Box portmanteau test was used to check the residuals (Yaffee and McGee, 2000). This test returned a p-value greater than 0.05 for all numbers of lags to be tested, giving no indication of autocorrelation between errors.

Table 2. Adjustment of O&M costs.

	Coefficients		95% CI for B		Tests	
	B	Std. Error	Lower Bound	Upper Bound	Sig.	Durbin-Watson
Constant	14.598	.078	14.427	14.770	.000	2.43
Age	.036	.010	.014	.057	.004	

The cost estimating relationship in Eq. 8 is equivalent to the following parametric relationship

$$m(a) = 2{,}186{,}910\, e^{0.036a}. \qquad (9)$$

This last equation has the advantage of directly providing the values of the model parameters.

4. 3. Optimal Assessment Horizon

After estimating the cost estimating relationship, it is worth to determine the analysis optimal horizon. The optimal assessment horizon corresponds to the equipment optimal replacement age. To identify this value, the natural logarithm of O&M cost per available year is estimated as a function of age.

The O&M cost per available year is obtained by dividing the O&M cost of each year by the corresponding operational availability (Sokri, 2011). Eq. 10 estimates the natural logarithm of O&M cost per available year as a function of age. The properties of this least-square adjustment are provided in Table 3.

$$ln[M(a)] = 14.943 + 0.12a. \tag{10}$$

Results indicate that the growth rate of O&M costs per available year amounts to 12%. The initial O&M cost per available year is given by

$$C_a = \exp(14.943) = \$3{,}087{,}894. \tag{11}$$

Table 3. Adjustment of O&M costs per available year.

	Coefficients		95% CI for B		Tests	
	B	Std. Error	Lower Bound	Upper Bound	Sig.	Durbin-Watson
Constant	14.943	.218	14.463	15.424	.000	1.37
Age	.120	.028	.059	.180	.001	

Using an acquisition cost of $79.6M and a real discount rate of 1% (Sokri, 2013), we get the following optimal value

$$v^* = \min_s \left\{ \frac{79.6 + \int_0^s 3.087894 e^{(0.12-0.01)a} da.}{1 - e^{-0.01s}} \right\}. \tag{7}$$

As shown in Figure 1, the optimal horizon can be derived graphically and numerically by plotting the expression optimal value as a function of the variable *s*. Its minimum and, therefore, the optimal horizon is estimated to be 13 years. This result corresponds exactly to the estimated life expectancy provided by the manufacturer.

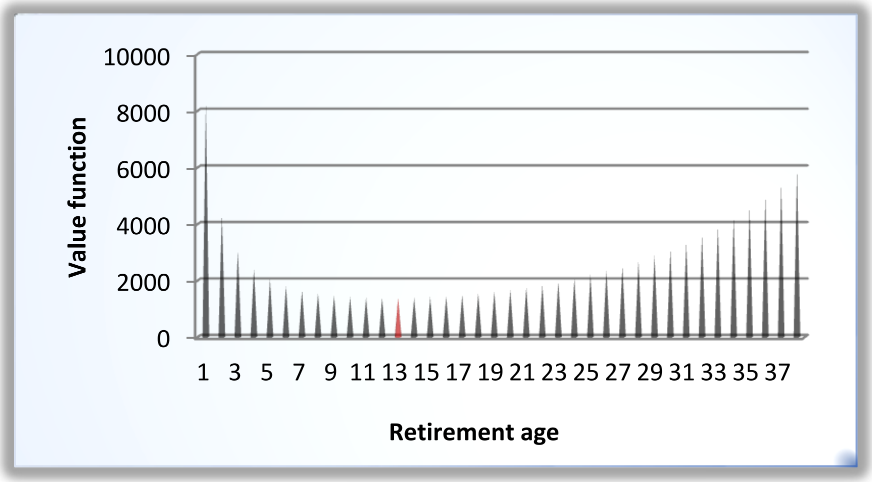

Fig. 1. Optimal horizon.

As shown in equations 8 and 9, O&M costs of Arcturus started at approximately $2.2M and grew at the rate of 3.6% resulting in a bill of approximately $193M over the optimal operational horizon, i.e., from 0 to 13 years. This bill accounts for approximately 70.81% of the overall LCC of this aircraft. It is, therefore, a serious shortcoming to ignore the present value of future O&M costs when conducting equipment appraisals.

4. 4. Sensitivity Analysis

Sensitivity analysis is a very useful tool whereby the major factors of uncertainty can be identified. This technique computes the pairwise relationship between the outcome and the key model parameters. It is generally performed by analyzing a single parameter while all other parameters are held constant. Sensitivity results can be generated using numerical simulation, bivariate correlation, or regression analyses. In this study, a sensitivity analysis was performed using a numerical simulation to determine the impact of varying the model parameters on the results. The possible magnitude of each parameter was allowed to vary over a range of potential values. For example, the range of each estimated parameter was derived from its own confidence interval. This what-if analysis indicates that the optimal horizon is very sensitive to variations in the growth rate of O&M costs per available year. The shorter the growth rate, the larger is the optimal horizon. For example, a decrease in this parameter from 12% to 5.9% would increase the optimal horizon from 13 to 20 years. This analysis also shows that the optimal horizon is very insensitive to changes in the purchase price and discount rate. Any variation of these parameters does not significantly affect the optimal horizon. This sensitivity analysis also shows that the life cycle O&M cost is very sensitive to changes in the growth rate and the initial value of O&M costs. As expected, it was found that any increase in these parameters would push the life cycle O&M cost upward.

5. Conclusion

Ageing assets experience a decline in value and productivity over the course of several years of use. The purpose of a LCC model is to estimate the asset overall costs. LCC can assist in budget allocation and comparing various alternative courses of action. O&M is an important facet of the LCC costs of military equipment. This component can exceed the cost of capital over the equipment lifetime. The aim of this study was to develop a methodology for predicting the ownership cost of military equipment. It provided a theoretical foundation for forecasting O&M costs and computing the optimal replacement horizon.

In this study, O&M costs were estimated as a function of age. A dynamic programming model was developed to identify the optimal equipment life cycle. The model was applied to the Canadian Arcturus fleet. Results indicated that the initial O&M cost of an aircraft amounted to approximately $2.2M with 3.6% increase each more year. This cost estimating relationship shows how O&M maintenance costs change as an aircraft grows older. Results also suggested that the optimal assessment horizon for this fleet was approximately 13 years. This optimal horizon corresponds to the aircraft optimal operational life. This result is consistent with the existing literature and the estimated life expectancy provided by the manufacturer.

A sensitivity analysis was also carried out to assess the impact of some key model parameters on the result. This what-if analysis indicates that the shorter the growth rate of O&M costs per available year, the larger is the optimal horizon. As expected, it was also found that any increase in the growth rate and the initial value of O&M costs would push the life cycle O&M cost upward.

This LCC model provides multiple benefits. In addition to the advantage of being general to several types of fleets, this model can be used to forecast LCC of old and new asset generations.

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