# Engine Life Cycle Cost Modeling in the Conceptual Phase

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**The rising cost of weapon systems in a time of declining purchasing power of the defense budget has forced new procurement practices to tradeoff system and major component performance, with cost at the earliest moment. Major elements of weapon systems such as aircraft engines are prime candidates for such cost/performance evaluations during the conceptual phase of the procurement cycle. This paper deals with life cycle cost modeling techniques that use parametric data to derive information necessary for study by the Defense Acquisition Review Council for decision making. Typical examples of parametric cost/performance tradeoffs are highlighted.**

## I. Introduction

A MAJOR consideration faces manufacturers of aircraft engines and their customers in today's marketplace. This consideration deals with proving and selling an engine concept that will provide the necessary performance at the lowest life cycle cost (LCC). A great burden rests on the procuring agency, i.e., properly defining a needed mission, establishing or identifying a technology base, and acquiring adequate amounts of hardware within ever-diminishing purchasing power. The burden grows heavier and more difficult as the program passes through very critical reviews, where each one exacts more detail than the last step and requires that differences from the previous review must be defended. This paper deals primarily with the conceptual phase of procurement in the review sequence and discusses one means for the manufacturer/customer to evaluate an aircraft engine offering from a LCC standpoint. This evaluation method is defensible and can become the baseline for measuring progress of each phase as the program naturally matures toward operational use.

## II. DOD Requirements

The Department of Defense (DOD) requires that a Defense Systems Acquisition Review Council (DSARC) pass on major new programs before the conceptual phase (DSARC I), full-scale development (DSARC II), and production (DSARC III).[1] A recent DOD directive (5126.22) requires that the Assistant Secretary of Defense for Installation and Logistics (ASD/I&L) be a primary member of the DSARC. This logical and necessary participation mandates LCC predictions prior to as well as during the conceptual phase of procurement. Figure 1 summarizes the foregoing discussion. The opportunity for design/cost tradeoff shown on the ordinate is compared with the development time on the abscissa. Typical milestones that illustrate the progress of an item through the first production unit are shown. It can be seen that the greatest opportunity for meaningful change exists during the design concept and the design definition portion of the program. Once layouts and detail drawings are made, the designer's opportunity for substantial cost-effective changes is reduced greatly. By the time the first unit is produced, the program has progressed past the point of diminishing return for any great breakthrough in cost savings. The long lead time for procurement, the expense and time required for qualification testing, and the added time required to backfit production items only combine to represent a real hurdle that has to be overcome for a LCC savings to occur.

## III. Engine Life Cycle

A typical functional system flow is shown in Fig. 2. A systems requirement is published (i.e., required operational capability or specific operational requirement) to outline the engine life cycle. Once the systems requirement is established, design teams develop a concept to answer the stated operational need. This concept generally includes a mission analysis, performance characteristics, a schedule interface, and any other design-related elements to answer the operational requirements. The design concept then begins to mature and take shape during the design definition.

The handling of design parameters, gas-path studies, layouts, drawings, etc., continues and becomes the basis for a development program. As the program proceeds through the

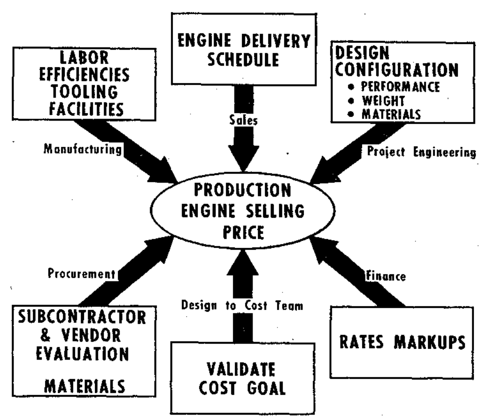


Fig. 1 Design tradeoff vs development time.

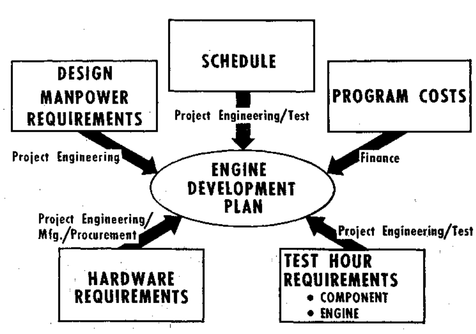


Fig. 2 Typical program activity flow.

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development cycle of making hardware, component tests, and end article tests preparatory to production, more and more of the feasible opportunities to do meangful cost tradeoffs disappear. Hard tooling is committed, long-lead time items ordered, and major procurement sources nailed down. Production begins at a relatively low rate and proceeds as a function of time to some predetermined rate called out in the contract. Production then normally extends for some years. Overlapping this production phase is the operation and maintenance portion of the cycle. The early operation and maintenance elements often become what they are simply because of service use, together with their logistic support. This phenomenon will happen whether there is a plan or not.[2] Full realization of this fact has led to the application of integrated logistic support consideration before production. Hopefully, user considerations were recognized, predicted, and incorporated into the program at least during the development program.

Detroit Diesel Allison (DDA) long has held that these latter considerations (service use and integrated logistics support) must be recognized fully during development and planned for during the design concept/definition.[3] The design community at DDA needed formal help during this early part of their work. The ability to make intelligent, innovative cost-effective decisions required an appropriate data base and a means to exercise it. The output from such activities can be called "sensitivity tables." Such sensitivity information provided to the designer then became a useful tool in the resulting design tradeoffs, which become engine design definitions, detail drawings, and finally hardware. Cost considerations then become an equal partner with performance predictions.

The formal design aid developed at DDA was a computer math model. Work was started in 1968 to program a company-funded operating and support (O&S) maintenance model. After many iterations, a model was developed and is in active use at DDA for all new engine programs and for some other applications. Subsequent to the O&S model, work was begun on a way to calculate production costs of aircraft engines accurately at the conceptual level.[4] DDA expanded on the pioneering of the late R.J. Mauer (NAVAIRSYSCOM) in addition to subsequent work by T.J. Brennan and others at the Naval Air Development Center.[5] The principal elements that must be addressed in a LCC study (even at the conceptual phase) are given in Table 1

Potential program modeling inputs include many different items, some of which are listed in Table 1. The development, acquisition, and operational maintenance considerations must be identified and sized. The general relationship to calendar time also must be known.[6] The O&S model gathers dynamic portions of the various elements into five major groups (mission definition, engine design definition, engine development plan, production engine selling price, and logistic support) that coincide with the activity flow just discussed.

Some items are not modeled within these five categories. For example, the support equipment with spares, publications, training, and training equipment does not affect the first pass of this particular math model. However, there is a plateau where support equipment and training requirements can be sized as a first approximation so that they may be added to obtain a LCC overview. Predicting cost of publications at the conceptual design is still a mystery. Fortunately, publication costs are a very low percentage of LCC and for the moment can remain a mystery without creating undue concern during the conceptual phase.

This model features input and output data computed with random number and Monte Carlo techniques. A typical problem would be described by 300 to 400 data elements. These data would be sufficient to describe the aircraft and engine delivery schedule, premature removal rates, aircraft utilization, time-between-overhaul (TBO) schedule, pipeline time for repair, intermediate support, and overhaul, attrition rates, labor application for each maintenance level, parts application at each maintenance level, chargeable inspection, fuel usage, fuel cost, engine pricing data, and the time frame for computation.

The computer program calculates from these parameters and yields three major summaries. Monthly summaries include aircraft service status, grounded aircraft, engine situation represented by overhaul, intermediate support, repair-and-ready for issue, and the type of premature removal. Tables that show premature engine repairs and overhauls as well as TBO overhauls are generated showing a summary by month and year. Finally, summary tables showing the various elements of applied man hours, applied labor cost, parts cost, flight time, fuel cost, and annual acquisition cost are displayed.

**Table 1 Potential program modeling elements**

| | |
|---|---|
| Development | |
| Program definition | Mission definition |
| End item direct support program(s) | |
| Acquisition | |
| End item production and delivery rate | Engine design definition |
| End item spares and delivery rate | |
| Support equipment | |
| Support equipment spares | |
| Publications | Engine development plan |
| Deployment schedule | |
| Training | |
| Training equipment | Production engine selling price |
| Operation and maintenance | |
| Operating parameters (SFC, MTMA, TBO, etc.) | |
| Labor costs | Logistics support |
| Materials (including cost) | |
| Skill mix and turnover | |
| Deployment schedule | |

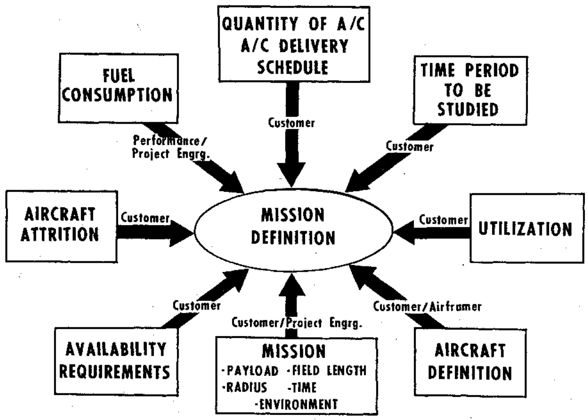


**Fig. 3 Mission definition information elements.**

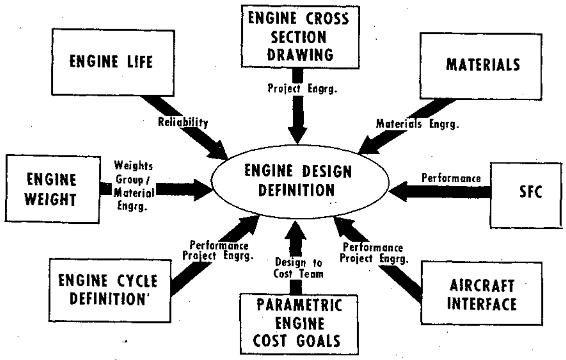


**Fig. 4 Engine design definition elements.**

A program summary then is computed which shows cost per flight hour, man hours per flight hour, and number of events in each maintenance level and calculates the total maintenance cost. This summary is the principal one used to describe the relative merit of an engine concept. The program has additional features to allow correlation of proposed design changes to support tradeoff studies. A portion of the basic program may be exercised to depict these remaining values and benefits at any level of the five definition areas.

The first term (mission definition) occurs during the design concept phase and extends into the design definition (Figs. 3 and 4). The outer ring of data says what is needed, whereas the inner ring shows the probable source. The time period to be studied represents the cycle length for the comparison. Utilization identifies the number of units as well as flight hours per month that the customer wishes to apply to the system. Aircraft definition may define only the number of engines per aircraft but should provide a general layout of the proposed installation, together with an understanding of maintenance accessibility. Mission considerations, i.e., payload, landing field, length, mission length, what kind of flight environment, etc., have to be decided. The customer may apply criteria for aircraft availability. He may define a loss rate or aircraft attrition that must be recognized over a 10- or 15-yr life cycle. He may also define specific fuel consumption limits, as well as an aircraft quantity, together with his delivery schedule. These items make up data elements necessary to define the design parameters so that the total engine design definition may proceed.

Design groups begin tradeoff studies by reviewing proposed engine cross-sectional drawings and imposing engine life, engine weight, specific fuel consumption, material properties, cycle definition, and aircraft interface considerations.[7] Many functional groups must participate in an extensive fashion to bring the engine design to a reasonable definition. In the toughest of marketplaces, a poor engine design definition probably will have two chances of winning any hard-nosed competition: slim and none.

After starting the engine development plan (Fig. 5), new information has to be added to that which already has been developed. Schedule information program commodities and a test plan must be brought together. The estimated cost of this total development activity becomes a significant driver in any sizeable LCC study. Progress in each phase of development demands iterations from preceding studies as a natural and necessary item of the work.

Production considerations impact the O&S model in many ways (Fig. 6). All of the commodities necessary to manufacture end items are estimated. A profit is included. Vendor interfaces are established. Configuration management must be maintained. Cost improvement techniques are applied. Each of these elements must be compatible with an engine delivery schedule. There are a substantial number of dollars on the table during this phase. In the past, this phase has been the one reviewed most critically by "higher headquarters." All of the foregoing efforts and modeling iterations have been aimed at minimizing the performance risk during this and succeeding phases while helping maximize the probability of meeting all cost bogeys.

Often more than five years passes after publishing the original requirement document before the engine is in the hands of the user. Support equipment requirements have been defined in response to modeling outputs. The training needs have been determined in conjunction with the customer. Full sets of publications have been provided to support the planned maintenance concept. Contracting people have been furnished with engine parts data in a manner that adequate space parts can be provisioned. The secret, however, to achieve long-term logistic support (Fig. 7) is continuous monitoring and updating of reliability and maintainability information and feedback of those data to the design team to provide a realistic data base for the next conceptual design.

## IV. Program Example

The XT701 engine contract [DDA J01-73-C-0175 (P6A)] contained an award fee section for design-to-cost (DTC). This turboshaft engine powers the Army heavy lift helicopter (HLH). There were two award fee periods defined which dealt with the DTC aspect of the contract. Early in the first period of the program DDA briefed AVSCOM concerning the potential for including cost-of-ownership considerations in the award fee structure. Consequently, the second award fee period contained cost-of-ownership as one of four rating areas, with its portion of the potential exceeding $100,000, or about 30% of the total award fee. The principal outputs were twofold. First, an extensive set of sensitivity tables and charts for the XT701 was developed. (Sample charts without units are shown in Figs. 8 and 9.) These data were used as a baseline to suggest potential design and/or program tradeoff studies. The second output was a series of calculations done for each formal DTC study. These calculations expanded the basic DTC computations, which concentrated on the unit production cost.

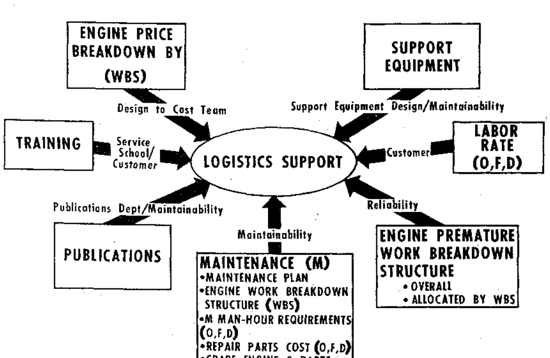


Fig. 5 Engine development program elements.

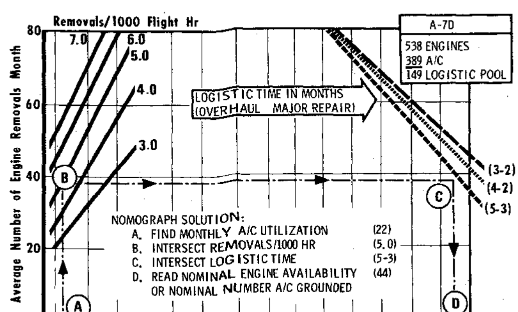


Fig. 6 Production program elements. Engine availability nomograph.

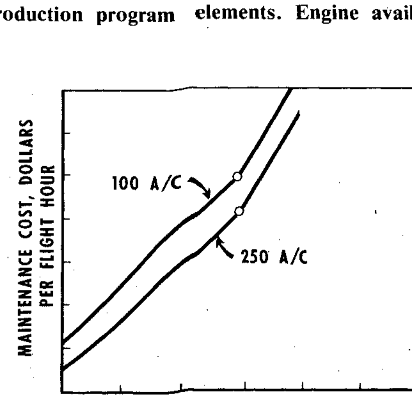


Fig. 7 Logistics support elements. XT701 sensitivity study, cost-of-ownership.

Let us look at an example that illustrates fully this point between the layout and detail drawing stage on the development time scale. The engine design features an inner-shaft center bearing assembly that is buried deep within the engine. This assembly includes an aircraft bearing, its carrier, and a lubricant system. The question was, "Can we eliminate that bearing?" If so, "What savings to the program might be gained?" An analysis using the O&S model was conducted. The following four design-related constraints were imposed, in addition to a main assumption (Table 2) of one depot and five intermediate support maintenance locations for the HLH fleet situated at widely separated geographic locations:

1) The removal of the center bearing would require balance of turbine wheel with its blades whenever any removal and repair of the shaft assembly occurs. This analysis considered no blade replacement or balance capability other than at depot level.

2) The study considered blade replacement using matched pairs of blades, but without rebalance at the intermediate support maintenance level.

3) The study considered blade replacement at the intermediate support level, but required balance of the shaft assembly.

4) The study considered exchanging balanced wheel and shaft assemblies stocked at the intermediate support maintenance level.

A 10-yr life cycle savings summary is given for each of the four conditions in Table 3. Two conditions appeared to yield the best choices from a dollar standpoint. These two are discussed in more detail to illustrate the tradeoff rationale that the designer must consider.

The first condition indicated that the work would be accomplished at the depot and would require balance of the wheel and shaft assembly (Table 4). Calculations were made recognizing development costs, average production savings, maintenance charges, and the requirement for special support equipment. To achieve the big savings in production, a front-end ticket of admission totaling over $700,000 for development must be paid. The total price of admission is increased further by requireing over $300,00 of support equipment at the depot level. Probably, the real test would be to determine the production rate of the large engine quantity, then find the length of time necessary to pay back the development program and to offset the added capaital investment. Evaluation indicated a favorable prediction, or early payback, for the study at hand.

In the second possibility (Table 5), the designer has the same problem presented except that it is presumed that some blade replacement can be done at the intermediate support maintenance level using matched pairs of blades. The blade replacement will not require that the wheel and shaft assembly be rebalanced. A statistical approach is laid on to determine how many of the actions would be avoided at the depot and intermediate support maintenance levels. This cost avoidance approach actually increases the amount of money spent in intermediate support maintenance but achieves a substantial decrease at the depot level. The reason for this effect is that five of 16 units can be turned around at the intermediate support maintenance level and avoid the higher cost of repair at the depot. This simplified example illustrates the depth of information which must be considered and made available to

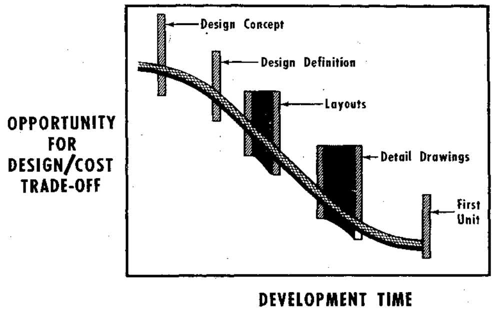


Fig. 8 Maintenance cost vs overhaul rate.

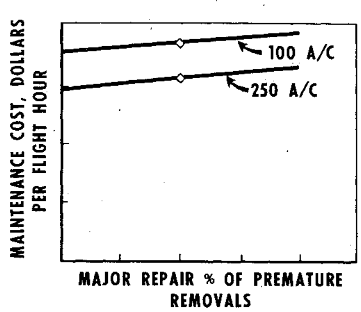


Fig. 9 Maintenance cost vs major repair rate. XT701 sensitivity study cost-of-ownership.

**Table 2 Center bearing removal: DTC 289**

| Assume |
|---|
| 1) Three-level maintenance system:<br>Aviation unit maintenance (AVUM)<br>Intermediate support (IS)<br>Depot (D) |
| 2) Center bearing related work is a capability at depot, or possible intermediate support, with appropriate support equipment |
| 3) Development program required |
| 4) Capital (special) equipment acquisition required. |
| 5) Improvement in removal rate chargeable to proposed design-to-cost change |

**Table 3 Center bearing removal: DTC 289 life cycle summary[a]**

| Premise | 10-yr LCC saving, $ |
|---|---|
| 1) 16 fewer premature removals; no blade replacement or balance lower than depot maintenance | 2329 |
| 2) 16 fewer premature removals; blade replacement without rebalance at intermediate support maintenance | 2539 |
| 3) 16 fewer premature removals; blade replacement requiring rebalance at intermediate support maintenance | 979 |
| 4) 16 fewer premature removals; turbine wheel and shaft assembly replacement at intermediate support maintenance | 1569 |

[a]Assume one depot and five intermediate support maintenance locations.

**Table 4 Center bearing removal: DTC 289 life cycle summary[a]**

| Summary | Initial saving/$ | 10-yr LCC saving/$ |
|---|---|---|
| Development | (704) | (704) |
| Average production engine price using 1125 engines | 2678 | 2678 |
| Maintenance | | |
| Depot | 68 | 670 |
| Intermediate support: | | |
| 5 locations | N/A | N/A |
| Aviation unit | N/A | N/A |
| Peculiar support equipment | | |
| AGE | N/A | N/A |
| Depot | (325) | (325) |
| Relative LCC saving/($) in $ | | 2329 |

[a]Premise: proposed design should result in 16 fewer premature removals in a 10-yr life cycle with work being done at depot maintenance.

Table 5 **Center bearing removal: DTC 289 life cycle summary**[a]

| Summary | Initial saving/($) | 10-yr LCC saving/($) |
|---|---|---|
| Development | (704) | (704) |
| Average production engine price using 1125 engine baseline | 2678 | 2678 |
| Maintenance | | |
| Depot | 90[b] | 900 |
| Intermediate support: | | |
| 5 locations | N/A[b] | N/A[b] |
| Aviation unit | N/A | N/A |
| Peculiar support equipment | | |
| AGE | N/A | N/A |
| Depot | (325) | (325) |
| Relative LCC saving/($) in $ | | 2549 |

[a]Premise: proposed design should result in 16 fewer premature removals in a 10-yr life cycle with some work (e.g., blade replacement) being done at intermediate support maintenance.
[b]$53 saved from 11 O/H at DM and $37 net from five major repairs at ISM.

the designer early in the concept phase of the product life cycle.

## V. Parametric Studies

Conceptual studies benefit from parametric analysis. Accumulated experience provides a data base for realistic LCC predictions during the conceptual phase. DDA has used LCC techniques successfully to describe the relative value of engine and mission families. The study results become a benchmark from which to measure the relative value of new engine offerings in the light of existing or previously planned programs. Parametric study capability can be superimposed on existing programs to show "What if?" Figure 10 is typical of such a study. This nomograph allows an assessment of spare engine need based on anticipated program boundary conditions. (Note that different conditions yield different slope and intersect point.) Given an aircraft fleet, quantity of spare engines, and a range of logistic support times, select a utilization value (hours per month), move vertically to an expected premature removal rate, find the average number of engine removals per month on the left-hand ordinate and move to the right to find the intersection with the logistic time, and then move vertically to the abcissa to indicate the number of ready-for-issue spare engines (or grounded aircraft). The relative impact of variations in utilization, removal rates, and logistic support can be sized during the conceptual phase. This sizing directly responds to the planning need contained in the requirements document for review at DSARC I.

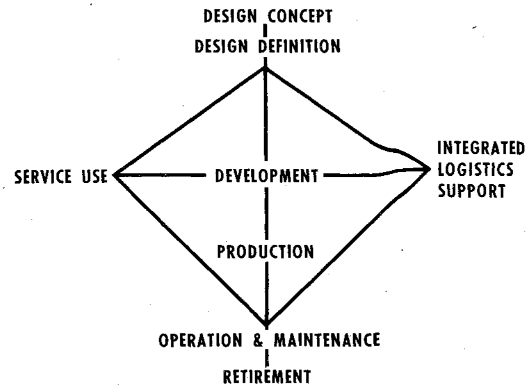

**Fig. 10 Engine availability nomograph. Systems requirement ROC, SOR, etc.**

## VI. Benefit

LCC works during the concept formulation phase if minimum requirements can be stated, a data base exists or can be extrapolated reasonably, a proven analysis tool is available, and a rational schedule is contemplated. The competitive spirit then may prevail in a natural way to provide an affordable, functional product.

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