SUMMARY

Good cost estimates contribute significantly to an effective acquisition policy. RAND has a long history of producing cost-estimating methodologies for military jet engines.[1] Two of RAND's more recent studies of turbine engine costs are Nelson (1977) and Birkler, Garfinkle, and Marks (1982). This report updates those earlier studies by incorporating cost and technical data on recent engine development and production efforts. We analyzed this information and produced a set of parametric relationships to estimate turbofan engine development costs, development schedules, and unit production costs.

In this analysis, we have extended and improved upon earlier RAND analyses in two key ways:

- The previous RAND studies grouped turbojet and turbofan engines into the same population. To provide a more homogeneous population, we focused exclusively on parametric relationships for turbofan engines in this study (because pure turbojet engines are largely no longer used in modern aircraft).
- In the previous studies, it was often not clear how the data from a particular engine family was treated. In our analysis, we treat each model (or "dash number") as a separate observation. We explicitly consider how derivative engines relate to first-of-a-kind engines.

[1]For instance, Watts (1965); Large (1970); Anderson and Nelson (1972); Nelson and Timson (1974); Nelson (1977); Nelson et al. (1979); and Birkler, Garfinkle, and Marks (1982) are RAND studies focused exclusively on jet engine costs.

In our statistical analysis, we explore most of the possible performance, programmatic, and technology parameters that affect development and production costs and the development schedules of engines. We employ least-squares regression methods to develop a series of parametric relationships for forecasting the development cost, development time, and production cost of future military turbofan engine programs.

TECHNICAL BACKGROUND

The first part of this report provides basic concepts on how engines operate, the parameters used to compare engines, development process alternatives, and likely future trends in jet engine technologies. An understanding of these concepts, alternatives, and trends should help both program managers and cost analysts to employ the cost-estimating relationships (CERs) described in the second part of this report and should facilitate conversations about jet engines and what affects their costs.

We describe various engine performance parameters and development approaches. The engine community uses these parameters to rate the quality and performance of individual components used as independent variables in CERs. In addition, we discuss other factors such as environmental requirements (for pollution control, noise abatement, and such), new performance requirements (stealth and thrust vectoring), and maintenance requirements (such as prognostic health monitoring systems and reliability and maintainability improvements programs) that influence an engine's life-cycle costs and have implications for the engine CERs explored in this report.

While these factors and other new technologies could increase or decrease costs, it is nearly impossible to identify every future cost driver when a CER is being developed. However, because the CERs are often based on historical data and performance metrics, they do not reflect the influences of these new factors on costs. Therefore, an analyst should consider the influence of these new factors when forecasting the cost of future military engines.

COST-ESTIMATING METHODS

The second part of this report presents a discussion on how cost-estimating methods are developed. We discuss the principal cost-estimating methods—i.e., *analogy, bottom-up,* and *parametric.* The bottom-up approach relies on detailed engineering analysis and calculations to determine a cost estimate. Another approach related to the bottom-up method is estimating by analogy. With this approach, an analyst selects a system that is similar to the system undergoing the cost analysis and makes adjustments to account for the differences between the two systems. The third approach is the parametric method, which is based on a statistical technique that attempts to explain the changes in the dependent variable (e.g., cost or development schedule) as a function of changes in several independent variables, such as intrinsic engine characteristics (e.g., size, technical/performance characteristics, or risk measures). We selected the parametric method for our analyses in this study.

We next focus on the estimation of parameters for the various turbofan engines in our database, data normalization and our efforts at validating the data, and the addition of new observations to update a series of parametric cost-estimating relationships published in earlier RAND studies. Finally, we describe a series of technical risk and maturity measures that we applied to each engine in our database.

We describe our statistical analysis and present a series of parametric estimating methods for aircraft engine acquisition costs and development times. We determine each of the cost-estimating relationships through a series of stepwise and ordinary least-square regression methods. We present cost-estimating relationships for aircraft turbofan engine development cost, development time, and production cost.

Finally, to illustrate how the various estimating relationships presented in this report can be used to generate cost projections, we provide examples of two notional engines—a new engine with advanced technologies and a derivative engine that employs more-evolutionary technological advances.

RESULTS AND FINDINGS

Our results indicate that rotor inlet temperature is a significant variable in most of the reported cost estimating relationships. Full-scale test hours and whether an engine is new or derivative are significant drivers of development time estimating relationships.

Our projections also indicate that a new advanced-technology engine design would have significantly higher development costs and would take longer to develop than a derivative engine using evolutionary technologies.

Disappointingly, the residual error for the development-cost and development-time estimating relationships remains rather high, particularly for the derivative engines. Therefore, these relationships are most useful at the conceptual stage of a development program. On the other hand, the parametric relationship presented for estimating the production costs can be used with more confidence. However, we still recommend this approach only for the conceptual phase or in the event quick estimates are required and detail information is lacking.

In all cases, simple performance parameters and technical risk measures, such as full-scale test hours and new-engine-versus-derivative-engine parameters, were the most significant factors. However, residual errors for development time and engine development costs are high, and readers are cautioned from using these CERs anywhere other than at the conceptual stage of aircraft development.