TECHNICAL ARTICLE

A Method for Predicting Direct Operating Costs During Aircraft System Design

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This article presents a method of determining direct operating costs to support the design of aircraft and shows the economic consequences of specific parameters. The goal is to give engineers an additional tool for making the optimal choice among different design alternatives and to help control the future operating costs of aircraft systems during early development.

The nonmilitary aircraft market has changed in recent years. Recession and increased competition have created a buyer's market, resulting in aircraft being sold for less than the manufacturer's expenses. Airlines are more interested than ever in low operating costs. Design decisions, from the early development phase on, should be based upon the aircraft's operating costs.

Table 1—Structure of Aircraft Systems by ATA Definition [1]

ATA Chapter	System
21	air conditioning
22	auto flight
23	communications
24	electrical power
25	equipment/furnishings
26	fire protection
27	flight controls
28	fuel
29	hydraulics
30	ice and rain protection
31	indicating/recording
32	landing gear
33	lights
34	navigation
35	oxygen
36	pneumatics
38	water/waste
49	airborne auxiliary power

Aircraft systems that are defined by the Air Transport Association of America (ATA) account for about one-third of the total aircraft price. They are grouped into various "chapters," which are listed in table 1.

In order to control aircraft system costs, a tool is needed that allows operating costs to be estimated during the early design phase.

CHOOSING THE BEST APPROACH TO ESTIMATE AIRCRAFT SYSTEMS' COSTS

The major problem with estimating the cost of an aircraft system is choosing the right estimating method. Many different methods have been proposed; however, a suitable method has to meet the following requirements:

- it has to work with the small quantity of data available in the early development phase;
- it has to show cost elements based on cost origins; and
- the calculation of single cost elements must be as accurate as possible.

Two paths may be taken: making a target retail price the maximum limit for the designer or looking for a cost-performance optimum.

Design-to-cost (DTC) [11] and designing-for-cost (DFC) [6] follow the first path. The problem with these methods is that they depend upon production costs and not upon operating costs, the latter being of greater interest to airlines. Both DTC and DFC also need very detailed data in the early design phases. It is almost impossible in the design phase to provide production data such as lists of parts or production sheets. Table 2 shows a summary of some possible cost estimating methods.

The second path consists of analyzing the costs during development. There are three major methods presently in use. The cost-of-ownership (COO) method [7] was first developed for marketing purposes [8]. It is a very good method for estimating operating costs because it takes the view of the airline into account. The life-cycle cost (LCC) method [9] can be applied to estimate aircraft system costs and is often used in the military sector [5]. Both the COO and LCC require very detailed data, as do the DTC and DFC, which could cause a problem in early design phases. Most commonly used in civil aviation is the direct operating costs (DOC) method [2]. In contrast to other methods, the DOC method is based on equations characterizing the aircraft in its entirety instead of going to the parts level. Airlines can use the DOC method to select an optimum aircraft while manufacturers can use it to optimize the aircraft's design. Direct operating costs have been used to maximize airline profits. This probably explains the method's popularity and the fact that there are so many variants of it in use today [12, 3, 10, 4]. It can be concluded that DOC methods are very suitable for estimating the operating costs of aircraft systems.

Table 2—Summary of Methods for Creating a Cost Estimate

Method	DTC	DFC	COO	LCC	DOC
estimated costs	production costs	production costs	operating costs	costs during the whole life of the aircraft	operating cost
point of view	manufacturer	manufacturer	airline	airline and manufacturer	airline

EVALUATING DIRECT OPERATING COSTS WITH DOC_{SYS}

It is necessary to tailor aircraft DOC methods if they are applied to aircraft systems. When comparing the operating costs of two system design alternatives, it is permissible to look only at those costs directly caused by the systems.

Therefore, the direct operating costs method for aircraft systems proposed here, DOC_{Sys}, consists of cost elements for depreciation ($Depr_{Sys}$), fuel ($Fuel_{Sys}$), maintenance (DMC_{Sys}), dispatch reliability (DR_{Sys}), and stockkeeping costs for holding spares (SHC_{Sys}), only for the system under consideration.

$$DOC_{Sys} = Depr_{Sys} + Fuel_{Sys} + DMC_{Sys} + DR_{Sys} + SHC_{Sys}. \qquad \text{(equation 1)}$$

The insurance costs of aircraft systems account only for a very small percentage of DOC [15] and therefore can be neglected. Cockpit crew costs are fixed as long as the number of cockpit members is not influenced by the design. Other effects, like reduced crew training demands, are neglected in this method.

There are two different considerations in calculating the depreciation of an aircraft system:

$$Depr_{Sys} = \frac{Price_{Sys} - Residual_{Sys}}{N} \times k_N + \frac{Price_{Sys}}{O} \times U(1 - k_N). \qquad \text{(equation 2)}$$

Both utilization and time-dependent depreciation are considered in equation 2. The parameter k_N is the weighting factor for utilization versus time-dependent depreciation. Considering only time-dependent depreciation is the common option ($k_N = 1$). Selection of the residual and the depreciation period N is influenced by tax laws, regulations, and management policies. For example, assume that a system's price is \$200,000. Airline A assumes no residual and a period of only 8 years, which results in a depreciation rate of \$25,000/year. Airline B chooses a more realistic assumption of a 10 percent residual and a period of 12 years, which results in a depreciation rate of \$15,000/year, only 60 percent of airline A. This shows the importance of selecting the right parameters.

Utilization-dependent depreciation considers the technical point of view, and its use often depends on available data. For this reason, it is somewhat difficult to select the utilization (U) and operation time (O) parameters.

The fuel costs are a product of fuel weight, number of flights per year (NFY), and fuel price:

$$Fuel_{Sys} = (m_{Fuel_{fixed}} + m_{Fuel_{variable}} + m_{Fuel_{bleed}} + m_{Fuel_{ram}} + m_{Fuel_{shaft}}) \times NFY \times Price_{Fuel}. \qquad \text{(equation 3)}$$

The method proposed here considers five different causes for fuel consumption. These include the following:

- fuel consumption for the transportation of fixed weight (e.g., system weight);
- fuel consumption for the transportation of variable weight (e.g., potable water);
- bleed-air consumption (e.g., ATA 21, air conditioning [1]);
- ram-air consumption (e.g., ATA 49, airborne auxiliary power [1]); and
- shaft power consumption.

As an example, the mass of fuel required for shaft power is given below in equations 4 and 5.

$$m_{Fuel_{fixed}} = \sum_{i=1}^{7} \left[\left(\frac{m_{i-1}}{m_i} - 1 \right) \times \left(m_{Sys} + \sum_{j=i+1}^{7} m_{Fuel_{Fixed,j}} \right) \right]. \qquad \text{(equation 4)}$$

The following parameters are required: system weight (m_{Sys}), total aircraft weight ($m_{A/C}$), the number of turbines (n), maximum thrust (T_{max}), shaft power consumption (P_i) during different flight segments (i = 1 to7), and fuel fractions (m_{i-1}/m_i) [14]. $K_{p,th}$ is an empirical engine technology-dependent factor.

$$m_{Fuel_{shaft}} = \sum_{i=1}^{6} \left[\frac{K_{p,th} \times m_{A/C}}{n \times T_{max}} \times \left(\frac{m_{i-1}}{m_i} - 1 \right) \times P_i + \left(\frac{m_{i-1}}{m_i} - 1 \right) \times \sum_{j=i+1}^{6} m_{shaft,j} \right]. \qquad \text{(equation 5)}$$

The fuel fractions for the flight segments "climb" (i = 4), "cruise" (i = 5), and "descent" (i = 6) have to be calculated as described in equation 6. For the calculation, the following segment parameters are required: thrust-specific fuel consumption ($SFC_{th,i}$), lift-to-drag (L/D_i), flight path angle (γ_i), and segment duration (τ_i).

$$\frac{m_{i-1}}{m_i} = e^{g \times SFC_{th,i} \times \left(\frac{\cos\gamma_i}{L/D_i} + \sin\gamma_i \right) \times \tau_i} \qquad \text{(equation 6)}$$

Maintenance costs, especially direct maintenance costs (DMC_{Sys}), are difficult to estimate and require insight into airline practices. Normally, they are differentiated between costs for preventative maintenance and repair. For aircraft under development that have no in-service experience, such detailed data is not available, nor can it be estimated easily from scratch. Therefore, in the early development phase a comparison method was chosen. A current one is the "Airbus industrie comparison method," which compares a newly-designed aircraft with an existing system [13, 16]. The results of this method are the maintenance work-hours "on aircraft" and "off aircraft" (MMH_{on}, MMH_{off}) and material costs (MC) for the new system. Together with the labor rate (LR), an estimation for direct maintenance costs can be made:

$$DMC_{Sys} = (MMH_{on} + MMH_{off}) \times LR + MC. \qquad \text{(equation 7)}$$

The failure probability of the system influences the dispatch reliability costs (DR_{Sys}):

$$DR_{Sys} = (D_D \times C_D \times D_C \times C_C) \times NFY.$$

(equation 8)

Equation 8 considers the probability for delay time (D_D) (see figure 1) and the probability of cancellations (D_C) (see figure 2). C_D and C_C introduce the mean airline costs for delay or cancellation, respectively.

An aircraft system also influences the stockkeeping costs (SHC_{Sys}) for holding spare parts. These costs depend on fleet size (FS), interest (r), and required spares (RQS, a function of availability). A factor, k_p, considers the ratio of spare price to the original purchase price, the percentage of system parts in stock, and the redundancy level of onboard systems.

$$SHC_{Sys} = k_p \times Price_{Sys} \times \frac{RQS}{FS} \times r.$$

(equation 9)

CALCULATING DIRECT OPERATING COSTS WITH THE DOC$_{SYS}$ PROGRAM

The program already provides parameters, independent of the investigated aircraft systems, such as failure probabilities, engine data, inflation rates, and delay costs, so it is very easy to use.

A Sample Calculation

To show how the program works, an analysis for a particular system of two different aircraft is presented. The flight controls system was chosen for a new aircraft (Airbus A320) and for an old aircraft (Boeing B727).

This allows the comparison of direct operating costs differences for the flight control system, representing different stages of system evolution. Figures 3 and 4 show three major cost elements for ATA-chapter 27, maintenance, depreciation, and the transportation of fixed weight. A comparison between the old system (B727) and the new one (A320) shows an increase in depreciation and spare-holding costs, which is compensat-

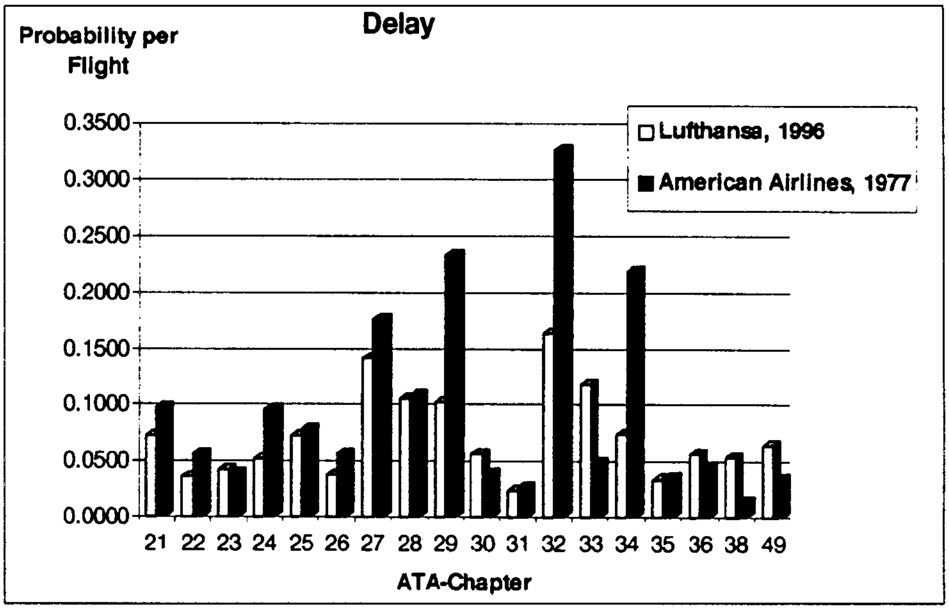

Figure 1—Comparison of Delay Probabilities in % From American Airlines [4] and Lufthansa

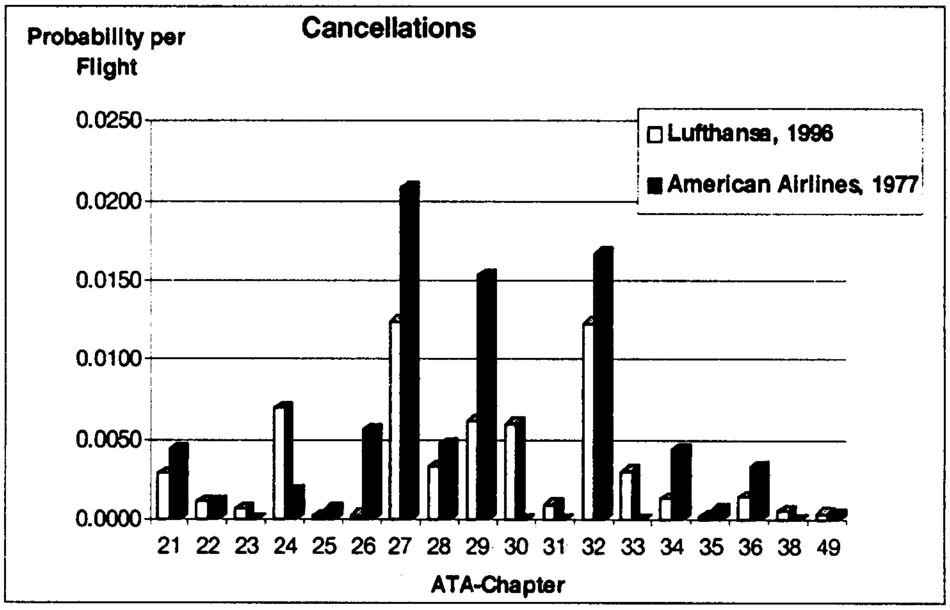

Figure 2—Comparison of Cancellation Probabilities in % From American Airlines [4] and Lufthansa

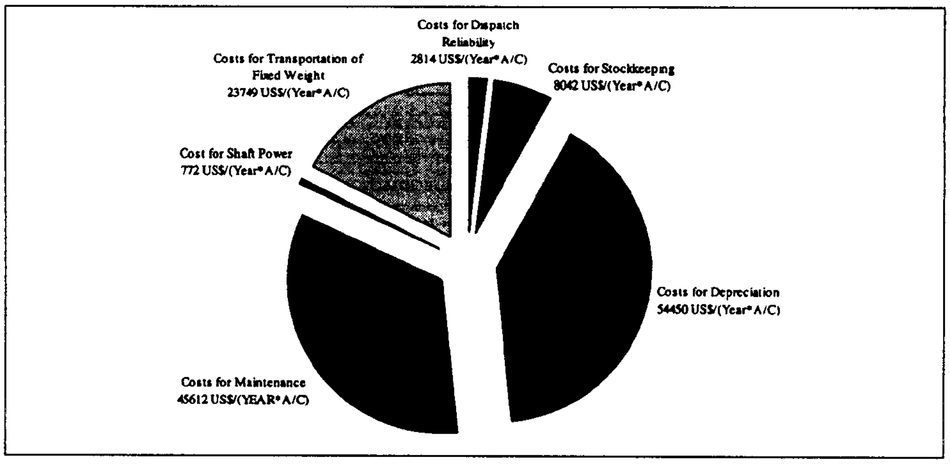

Figure 3—DOC of an Airbus A320/ATA-Chapter 27 [DOC$_{Sys}$ = \$135,439/(A/C*Year)]

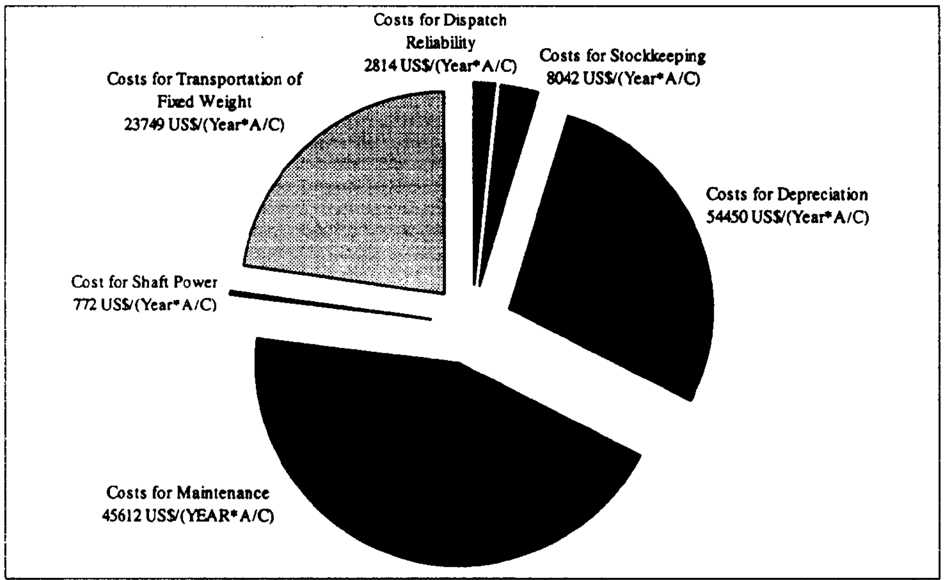

Figure 4—DOC of a Boeing B727/ATA-Chapter 27 [DOC_{Sys} = $175,525/(A/C*Year)]

Table 3—Input Data for the Airbus A320

Data	Value	Data	Value	Data	Value
$Price_{Sys}$	847000 US$	τ_5 (*)	3 h	MC	8720 US$/Year
$Residual_{Sys}$	10 % =84700 US$	γ_4	2 °	LR	36,52 US$ (Germany)
N	14 YEARS	γ_5	0 °	D_D	0,0536
k_N	1	m_1/m_2	0	C_D	15643,62 US$
NFY	1000	m_2/m_3	1/0,995	D_C	0,0208
$Price_{Fuel}$	0,19 US$/kg	m_6/m_7	1/0,996	C_C	3370,61 US$
m_{SysX}	948,367 kg	$m_{A/C}$	70750 kg	RQS (*)	1,117
L/D_4	14	$K_{P,th}$	0,012684 N/W	k_P	1
L/D_5	17,42	T_{max}	111,2 kN	r	8,5 %
SFC_4	0,03366 kg/N/h	n	2	FS	10
SFC_5	0,0612 kg/N/h	P_i	7,246 kW		
SFC_6	0,0 kg/N/h	MMH_{on}	540 h/Year		
τ_4 (*)	26.9 min	MMH_{off}	442,8 h/Year		

*the marked input data can be calculated by further equations. These equations are a part of DOC_{Sys}, but are not necessary for understanding the method.

Table 4—Input Data for the Boeing B727

Data	Value	Data	Value	Data	Value
$Price_{Sys}$	756102 US$	τ_5 (*)	3 h	MC	12636 US$/Year
$Residual_{Sys}$	10 % =75610 US$	γ_4	2 °	LR	36,52 US$ (Germany)
N	14 YEARS	γ_5	0 °	D_D	0,0536
k_N	1	m_1/m_2	0	C_D	15643,62 US$
NFY	1000	m_2/m_3	1/0,995	D_C	0,0208
$Price_{Fuel}$	0,19 US$/kg	m_6/m_7	1/0,996	C_C	3370,61 US$
m_{SysX}	1587,57 kg	$m_{A/C}$	78243 kg	RQS (*)	1,117
L/D_4	14	$K_{P,th}$	0,012684 N/W	k_P	1
L/D_5	17,42	T_{max}	77,4 kN	r	8,5 %
SFC_4	0,03574 kg/N/h	n	2	FS	10
SFC_5	0,06322 kg/N/h	P_i	7,246 kW		
SFC_6	0,0 kg/N/h	MMH_{on}	983 h/Year		
τ_4 (*)	26.9 min	MMH_{off}	806 h/Year		

(*) see table 3

ed for by a decrease in maintenance and fuel costs. Nevertheless, the absolute direct operating costs of the modern aircraft system have been reduced. Tables 3 and 4 show the input data.

The DOC_{Sys} method is able to predict operating costs during the initial design of aircraft systems. The program has been used to estimate the direct operating costs of various aircraft systems. Three general conclusions can be made:

- the system's price, and therefore depreciation, is always a major cost element;
- the system's weight causes fuel costs and reduces the payload, and is a major cost-driver; and
- the complexity of modern aircraft systems causes high maintenance costs.

The implementation of the DOC_{Sys} method as a computer program was successful, and it allows simple and fast calculations.

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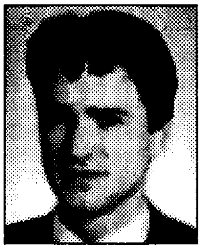

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